UWROV

2023 Technical Documentation

Underwater Remotely Operated Vehicles Team (UWROV)
at the University of Washington
Seattle, WA, United States

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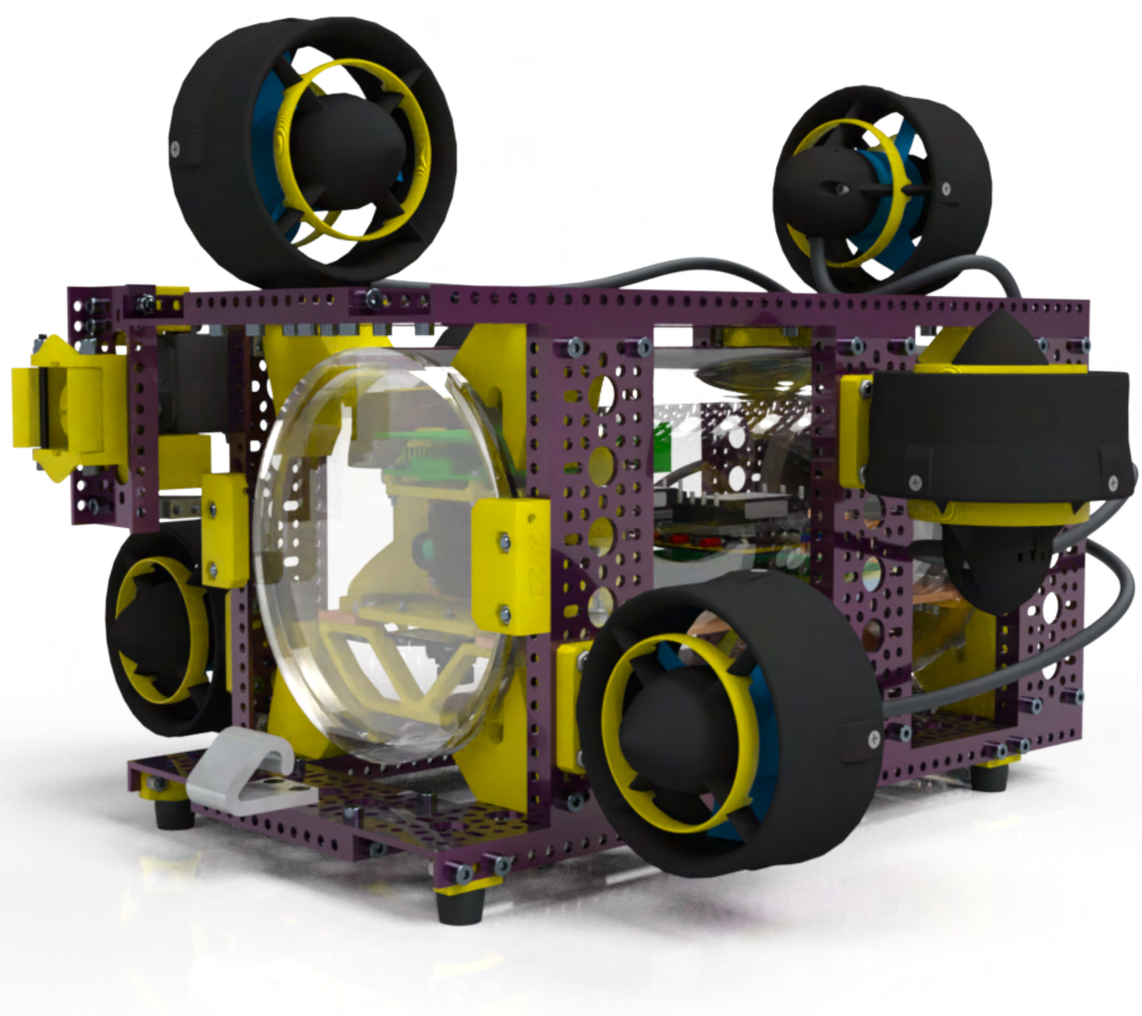


Abstract

This year, the Underwater Remotely Operated Vehicles Team at the University of Washington (UWROV) is excited to present ***Barreleye***, a remotely operated vehicle (ROV) **designed to complete tasks for the MATE 2023 Explorer Challenge**, including maintaining marine renewable energy, healing corals, and preserving blue carbon infrastructure. The name *Barreleye* originates from the real-life barreleye fish (*Macropinna microstoma*), which is distinctive for its deepwater vision and transparent head. Applying inspiration from the barreleye fish and taking lessons from previous year's designs, 2023's *Barreleye* is the product of rigorous innovation, iteration, and testing.

The main objectives of the 2023 UWROV team were to create a ROV with consistent performance, no unnecessary complexity, and safe operation. To achieve these objectives, *Barreleye* was designed modularly with a philosophy of continuous improvement. With a focus on MATE task performance, and **unceasing iteration and innovation on mechanical, electrical, and software systems**, this is UWROV's most focused and reliable ROV in history. The result of this modular development model is an ROV that features precise movement, versatile manipulation capabilities, and excellent vision. ***Barreleye* is ready to be deployed at the MATE World Championship and demonstrate its mission capabilities.**

Table of Contents

Teamwork

Project Management

Company and Personnel Overview:

UWROV is a registered student organization (RSO) at the University of Washington affiliated with the College of the Environment's School of Oceanography. Our team of undergraduate students designs, builds, markets, and competes with underwater robots at the MATE ROV Competition. The team is divided into four **subgroups**: mechanical, electrical, software, and business. Members of different subgroups work together in interdisciplinary project-based teams which focus on specific components of the ROV and MATE ROV Competition.

For a full list of employees and their roles and responsibilities, see the Title page.

Schedule:

The majority of onboarding for the team occurs in October, where returning members support new members in becoming familiar with vehicle systems as well as team structure. November, December, and January were periods of innovation, welcoming a variety of new ideas. The most feasible and effective ideas became the focus for engineering efforts, which took place through April. April and May were our primary months in the water, where we refined new features.

Planning ahead, staying on top of deadlines, and progressing forward with the engineering process are this year's priorities for the UWROV team. Subgroup leads and members decide on broad, long-term plans for the season at the start of the season in September. Broader subgroup objectives are reflected in the short-term goals of flexible **interdisciplinary project subteams** using an **Agile** development model. For our testing schedule, we chose to adopt a dynamic system. Instead of having a dedicated day we start testing, UWROV planned to **test throughout the entire season**. Taking a modular approach to ROV design, we planned to test in-water based on minor iterations.

UWROV's weekly schedule consists of two weekly meetings. Saturday meetings are dedicated to testing while Sunday meetings are concerned with administration, project work time, and resolving blockers.

Upcoming weeks/demo prep

Saturday	**Sunday**
Apr 15, 2023 - Lab work	Apr 16, 2023 - Regular meeting, prop building for demo, ask members to fill out Worlds interest form, find volunteers for outreach and Regionals
Apr 22, 2023 - In-water/recording video demonstration	Apr 23, 2023 - **Record safety video**, finalize safety documentation, potentially in-water test after meeting time, recommend members to update documentation
Apr 29, 2023 - In-water/recording video demonstration	Apr 30, 2023 - Record safety video if need be, finalize safety documentation, have every team/project update technical documentation
May 6, 2023 - In-water/recording video demonstration	May 7, 2023 - Recording if need be, SID/documentation work time
May 13, 2023 - In-water/recording video demonstration	May 14, 2023 - Team and individual photos, SID/documentation work time if need be

Figure 1 (above). An example of UWROV's scheduling over the span of several weeks.

Resources, Procedures, and Protocols

UWROV employees work in their respective **subgroups** and **interdisciplinary project subteams** to work on MATE objectives. Subgroup work provides members to gain an overview of all systems while project subteams collaborate between subgroups to complete tasks at hand. For example, mechanical subgroup members spend a portion of their time working with each other on broader mechanical systems while spending the remainder of their time with electrical members to complete specific projects such as the GO-BGC float.

We also employed a number of software resources to improve team organization and communication. We used **Trello.com** as a kanban board, where employees can collaboratively track and update the status of all UWROV projects. Trello improves the team's workflow by allowing easy identification of project priorities and progress, where projects essential to mission objectives are granted the highest priority. Having projects clearly laid out reduces operational problems through visualizing progress, bandwidth, and goals.

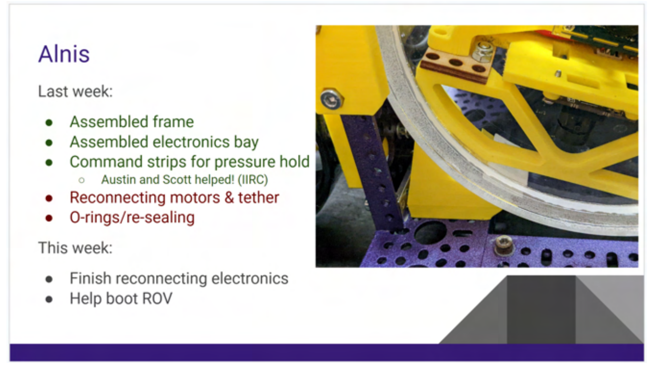


Figure 2 (right): An example of a member-made slide presented at a UWROV team meeting.

In UWROV team meetings, employees prepare **slideshow slides** about their ongoing projects, detailing recent accomplishments, current tasks, blockers, and a plan for the next week. Transparency in workflow between all employees creates an open forum for feedback, insight, and blocker resolution. By providing an open forum where raising concerns about designs and plans is encouraged, we rapidly address operational problems. Our team emphasizes an **Agile** approach with a focus on communication and collaboration, enabling employees to take initiative and solve day-to-day issues without needing to go through time-consuming procedures.

Google Suite was used for file storage through Google Drive, email communication through Gmail, and a teamwide calendar through Google Calendar. For remote communication, we used **Discord** for subgroup and project communication. We also used **Zoom** for live remote collaboration. **Onshape CAD** and **KiCAD EDA** were used for mechanical and electrical design work, respectively. These two design software allowed experienced employees to build off their prior skills with computer-aided design (**CAD**) and gave new employees the opportunity to learn.

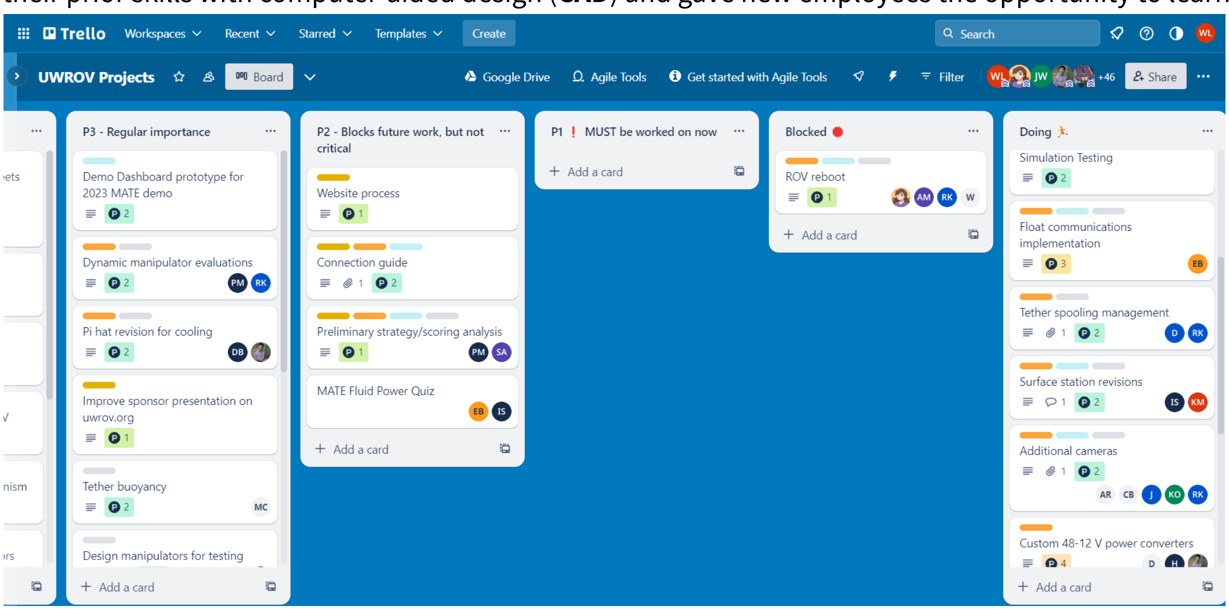


Figure 3 (above). Screenshot of our Trello project organization Kanban board.

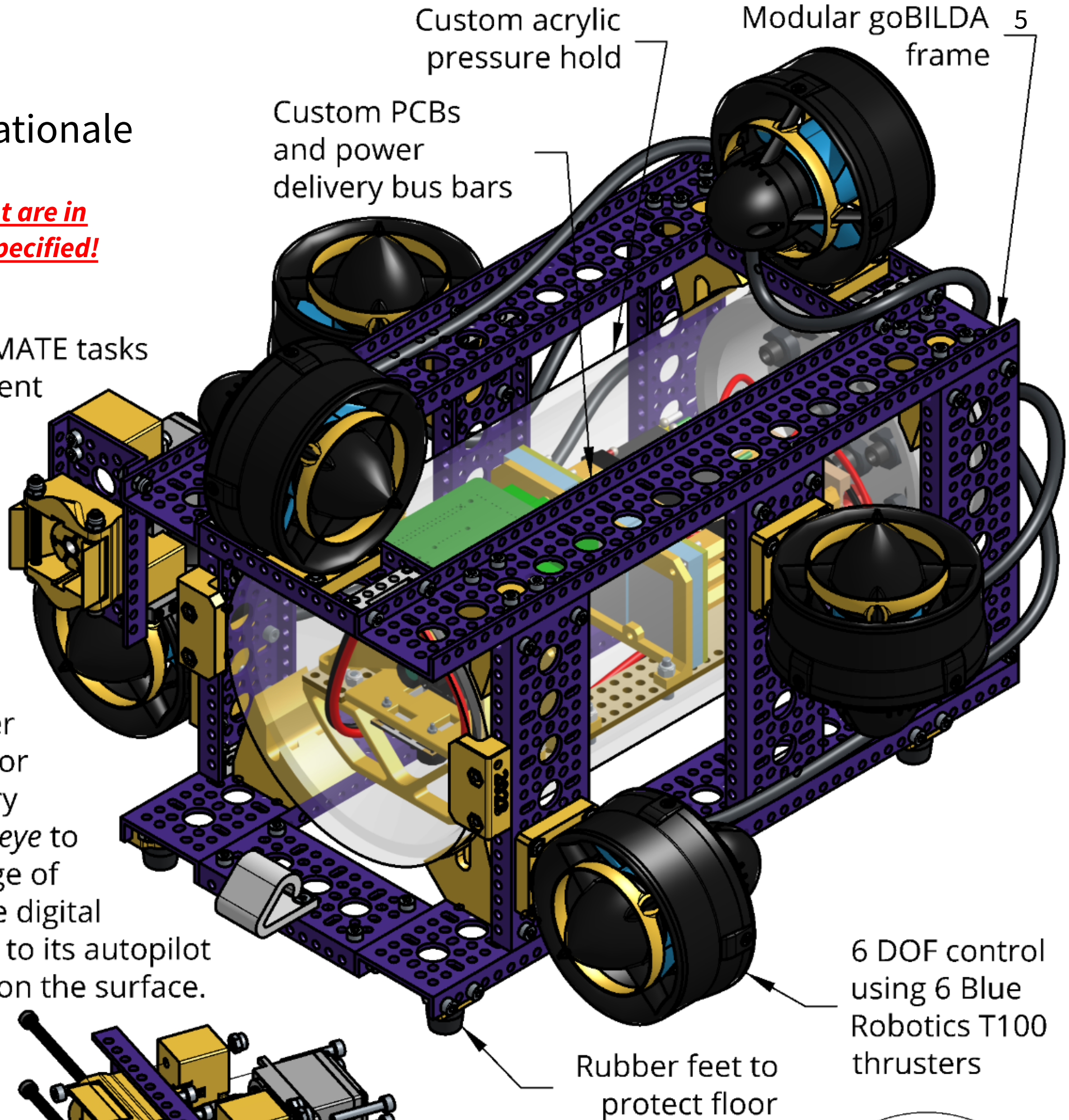
Design Rationale

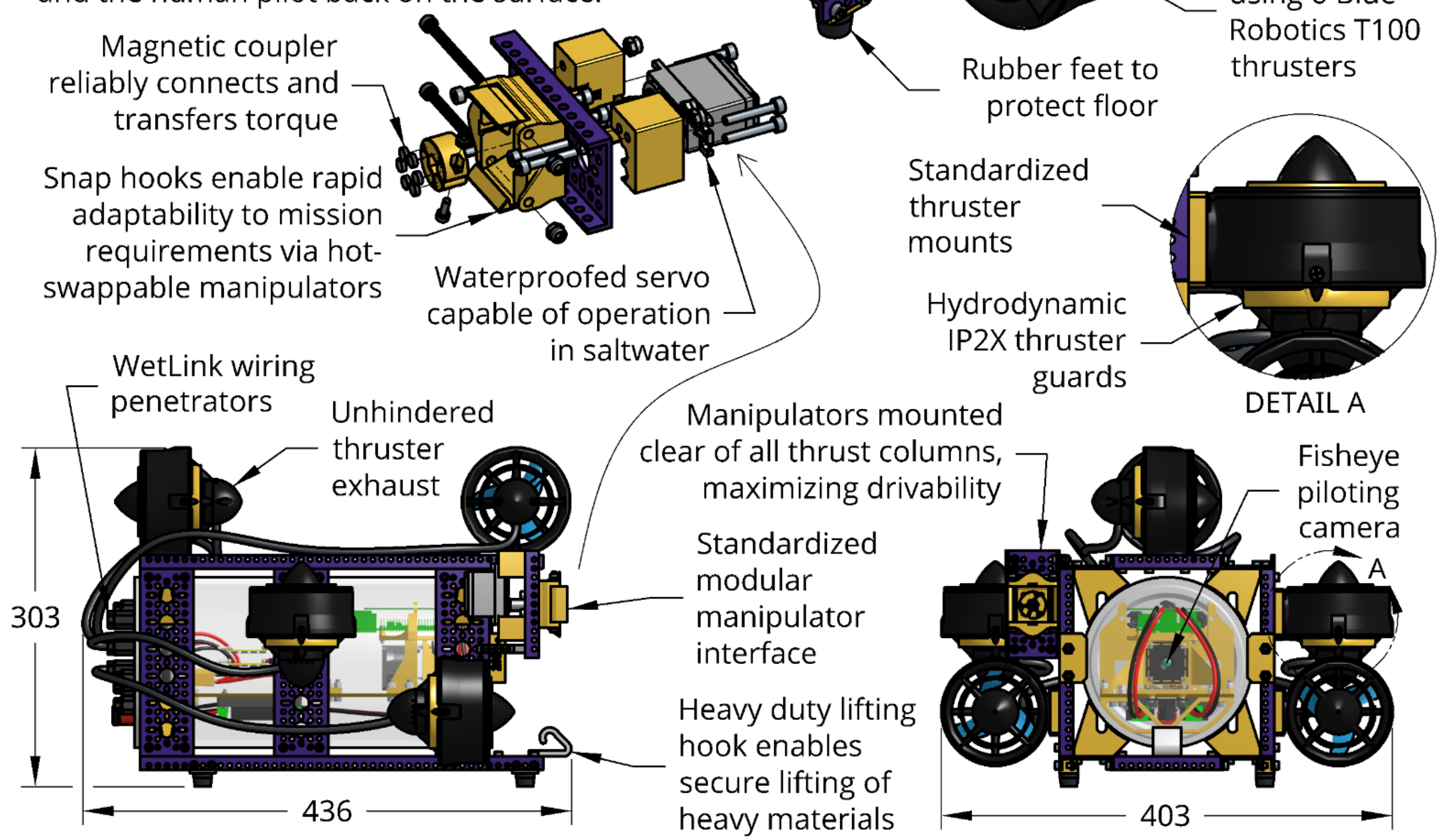
Engineering Design Rationale

Design Overview

All dimensions in this document are in millimeters unless otherwise specified!

Barreleye is optimized for MATE tasks while minimizing deployment challenges. Its ruggedized chassis protects its 2-in-1 acrylic buoyancy module + electronics bay, while the risk of damage to the ROV's environment is minimized through protective features like thruster guards and rubber feet. A modular manipulator allows specializing for every MATE task, enabling *Barreleye* to effectively complete a range of challenging missions, while digital cameras provide guidance to its autopilot and the human pilot back on the surface.





Conceptual Ideation and Selection Process

Reflecting on the experiences of the previous season, the UWROV team reevaluated the design direction of the ROV. Considerations such as competition success, testing success, and system familiarity were paid close attention to when deciding on an overall direction. The company also revisited old concepts and market research for a new perspective.

The first design decision was determining what components of the ROV the team wished to keep. Components that the team believed were **effective in competition, testing, and adaptability were kept** the same from the previous season. Thus, the ROV frame, pressure hold, thruster layout, and tether components were reused on *Barreleye.* The team does not necessarily believe these components were perfect, but rather that they are effective to the point that developing a new component from scratch would have **diminishing returns**.

With these components deemed satisfactory, it was decided that all other portions of the ROV should be subject to innovation and revision: if these components can be improved based around the existing satisfactory “core” components, the end product ROV will be substantially improved. UWROV employees were advised to have wide-spanning goals when initially innovating on these parts. At the same time, they were advised to maintain simplicity for actual implementation. The hope was that ambitious projects could be refined during testing and simplified into a modular component with flexible, yet simple implementation.

The UWROV team narrowed the scope of the new ideas to be within the functional bandwidth of the team, focusing on which ideas were worth pursuing the most. Considering the technical and financial limitations of the team as it stood was a large part of this process. The main question asked was: “which elements would contribute to the ROV’s success in the mission tasks?” The UWROV team defines success as creating a final ROV product that by the end of the season, has **substantial and tangible improvements** in design and performance over previous ROVs. Some elements deemed necessary were to streamline software systems to improve ease of making revisions, integrate more sensors for autonomous work, a more robust electrical system, ergonomic pilot controls, and creating adaptive, modular mechanical systems.

A foundational element for many of these changes was the software system architecture. We redesigned it from the ground up, evaluating which configuration of computers is best-suited to development and MATE tasks.

Table 1 (below): Trade study of alternatives for ROV control system electronics configurations.

Option	Performance			Ease of Development		
	Tether	**Compute**	**Latency**	**Simplicity**	**Redeploy**	**Simulatability**
Onboard computer only	Thick	Limited	Low	Good	Moderate	Moderate
Surface computer only	Thick	Good	Low	Good	Fast	High
Surface computer and onboard computer	Thin	Good	High	Moderate	Fast	High
Surface computer and onboard computer + microcontroller	Thin	Good	High	Poor	Slow	Low

It was determined that, similar to previous years, having a surface computer with an onboard computer would be the most effective for completing mission tasks. An onboard computer allows for simpler electrical connections to components as its proximity to motors, cameras, and sensors reduces the complexity of the tether. However, the computing power of onboard computers is often limited by space and power needs—for our onboard computer, we chose to use a Raspberry Pi 4, which is not as powerful as standard computers. To remedy this issue, utilizing a more powerful second computer at the surface station allows for increased computational power. Having a surface computer also makes connecting peripherals simpler: wires for monitors and controllers do not need to run through the tether. The Pi’s GPIO pins also make up for the lack of a microcontroller as the Pi is capable of outputting PWM values and reading sensor input.

After making the decision to use two computers, the next step was to determine the most effective method of communication between the devices.

Table 2 (below): Trade study of alternatives for communication methods between the ROV and surface station.

Option	Performance			Ease of Development		
	Bandwidth	**Latency**	**Range**	**Setup**	**Learning Curve**	**Simulatability**
ROS & Docker/Ethernet	Moderate	Moderate	Long	Complex	Hard	Good
Websockets/Ethernet	High	Low	Long	Moderate	Moderate	Fair
Serial/USB	Moderate	Low	Moderate	Simple	Moderate	Poor

Websockets over Ethernet using a custom protocol meets our range, latency, and performance requirements, without having any significant drawbacks for ease of development. In previous years, we have used ROS & Docker, but have encountered hard-to-debug transient latency and bandwidth issues as well as introducing unnecessary complexity and development challenges. Serial runs into bandwidth & range issues in the context of ROV tethers, and is challenging to fully emulate in a simulation. Therefore, we chose websockets over ethernet with a custom protocol.

Systems Approach

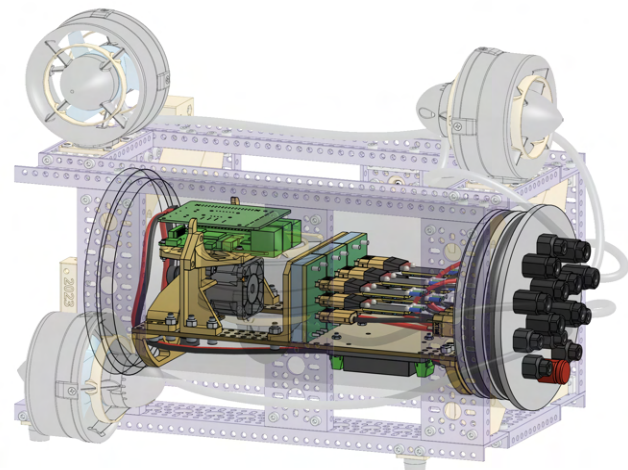


Figure 4 (right): Our ROV's CAD model, which includes all electronics.

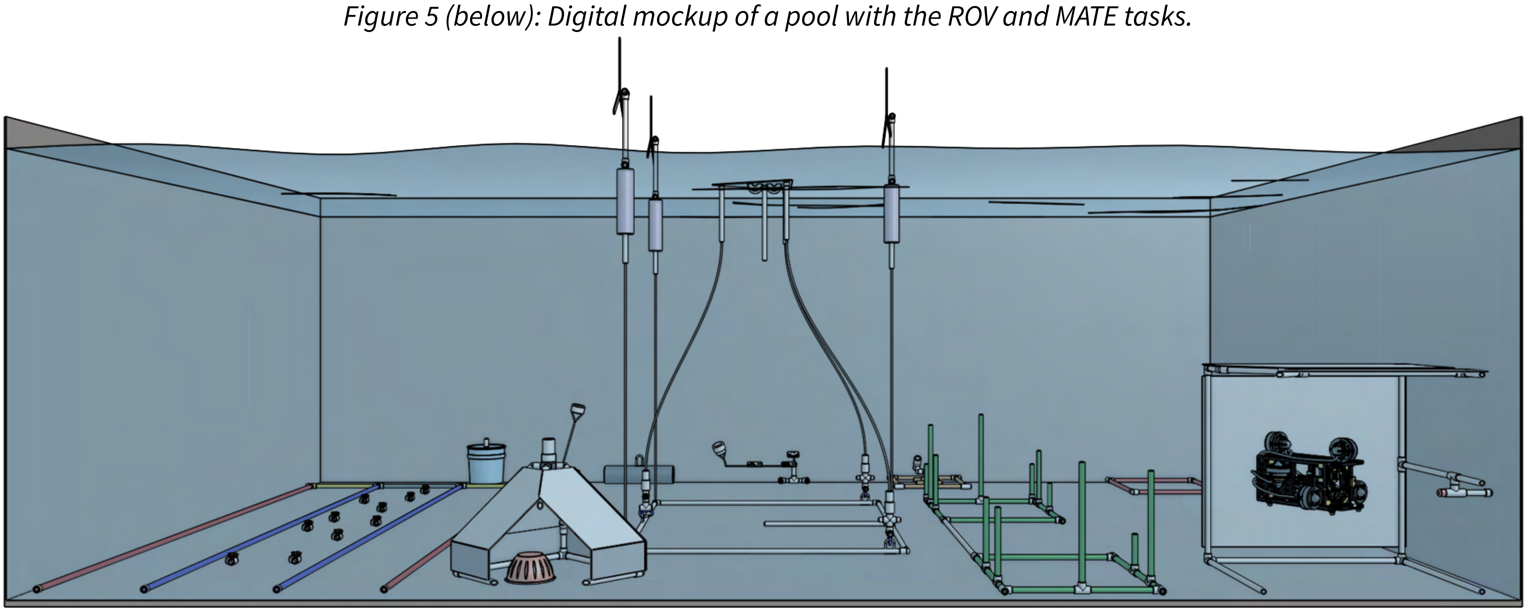
Barreleye is designed with subsystem integration and iteration in mind. The mechanical, electrical, and software components of the ROV are designed in concert, all while making reasonable compromises to maximize total system performance for MATE tasks.

Our **digital twin system** involves electromechanical CAD integration. All physical components of the ROV are modeled together, illustrating their real-life layout. This minimizes design oversights when prototyping new parts, as we can model interactions between new parts and existing components. We are also able to examine details such as wire lengths and camera visibility. While these elements can be tested with the physical ROV, we save time and effort by avoiding unnecessary physical prototypes. Finally, the digital twin is hosted online and can be accessed at any time, accelerating remote prototyping of new parts and promoting collaboration across different subsystems and groups.

The CAD model of the ROV is also utilized to develop the software control system. The motor positions & orientations are used directly to generate control mappings using **Numpy**, a Python library. This significantly streamlines the controls development process, where controls are easy to integrate and update as the design evolves.

By analyzing new components digitally before physically constructing and testing them, we have confidence in how the ROV will function before the components are integrated. This reduces overhead with in-water testing: rather than debugging large issues pool-side, we have the time and ability to make more nuanced refinements.

Figure 5 (below): Digital mockup of a pool with the ROV and MATE tasks.



Vehicle Structure

The structure of *Barreleye* prioritizes a **small form-factor** with the most **customizability**. Having a smaller ROV increases speed and maneuverability, allowing for high performance in tight corridors. The cost of materials is also lower. Additionally, a smaller and lighter ROV can be transported more easily to mission sites. While ease of control and stability are more challenging for smaller vehicles, we have overhauled our software system to support controls development. The modularity of our system also reduces difficulties associated with servicing small parts; replacement parts can be integrated easily.

The frame of the ROV consists of **aluminum goBILDA Low U Channel and Side Block Mounts**, and all mounting and frame construction is standardized to **M4 hardware** to improve serviceability. Although goBILDA is more expensive than other frame options, its material is lightweight, and its multitude of standardized interfacing locations make it adaptable for the mission. For example, our modular manipulator interface is mounted to the goBilda frame via **M4 hardware**. To replace it, or perhaps mount a second interface for simultaneous completion of mission tasks, we can attach and detach it nearly anywhere on the frame with M4 screws, as the goBILDA mounts allow for this.

Our pressure hold consists of a clear **acrylic** cylinder and front plate with an **aluminum** back plate. When factoring in the low cost of machining acrylic and aluminum compared to more traditional options for materials in a corrosive environment like titanium and stainless steel, these materials become very economical. Therefore, we trade off some lifespan for the vehicle in exchange for lower cost, which is acceptable for the MATE task use case. Pressure hold parts were turned on a lathe, with special care paid to smooth finishes (for good sealing) and broken/chamfered edges (for personnel, wiring, and o-ring safety). Our custom pressure hold is designed to be as large as possible while fitting comfortably in the frame and staying dry at MATE task depths, increasing floatation and volume for electronics.

Vehicle Systems

Last season, we chose to use the goBILDA system as it provided the best performance possible. We reevaluated our system this year to see whether goBILDA was still the best option:

System	Performance				Ease of Development			
	Versatility	Strength	Weight	Bulky	Metric	Cost	Already in lab	Design Work
goBILDA	High	Mid	Low	No	Yes	High	Yes	Challenging
Actobotics	Mid	Mid	Low	No	No	Mid	No	Challenging
80/20	Mid	High	High	Yes	Yes	Mid	Some	Moderate
PVC pipe	Low	Low	Mid	Yes	No	Low	Yes	Easy

Table 3 (above): Trade study of alternatives for vehicle frame systems on the ROV.

We found that the **goBILDA system** was still the most favorable, as it has the best performance of the options for completing MATE tasks. In addition, reusing the goBILDA parts purchased last year made goBIDLA's high cost a non-issue in this year's development. Familiarity with these part's from last season's ROV also made design work more approachable and efficient.

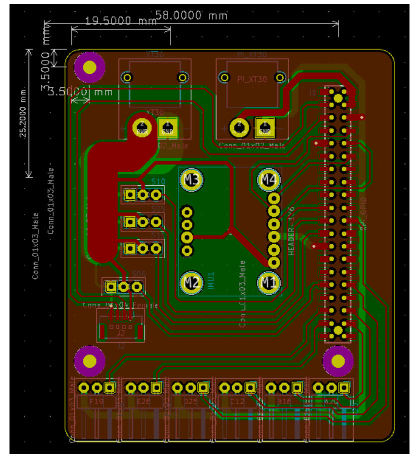
Robustness, Adaptability, and Modularity

Creating a ROV with **robust mechanical, power, and software systems** served as the foundation of the UWROV team's design philosophy. Complementing this robustness, UWROV sought to construct **adaptable systems** that were capable of efficiently completing all MATE tasks. The robust but adaptable vision of *Barreleye* took the form of **modularity** within all systems. Components of the ROV were designed, tested, and if necessary replaced with tangible, **task-oriented goals** in mind. This rationale is best exhibited through the evolution of the manipulator system. We transitioned from using all-in-one manipulators to a modular system where a variety of task-specific manipulators are **hot-swapped** during a mission. Each manipulator is a single, robust, specialized tool that mounts to our modular manipulator interface. The drive towards modularity is also part of the reason why the company chose to use the goBILDA system (see **Vehicle Structure**). This emphasis on modularity allows us to continuously **evolve and adapt** the design as testing data comes in, continuously improving performance for MATE tasks.

This theme of robustness also extends to electrical systems. To achieve this electrical robustness, creating modular and consistent connectors was a priority. By having **consistency in interfaces** between components, any particular component can be tested in isolation to provide relevant, immediately actionable feedback. Common interfaces also allow us to **iteratively upgrade sections of the electronics** without needing a full redesign or lengthy downtime—we just plug the new module in and test!

Our software systems are similarly modular. Our **software system can be tested end-to-end in a full simulation**, allowing us to develop control algorithms, debug logic, and configure networking without needing the physical ROV. This saves a large amount of development time by giving us an accessible “sandbox” for rapid iteration.

Control and Electrical Systems

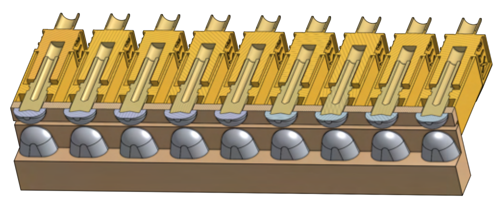


Electronic Design and Cabling

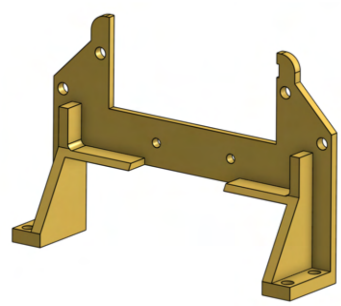
Figure 6 (right, from top to bottom):
6A: KiCAD EDA model of Pi Hat PCB for onboard data & power connections.
6B: CAD render of the 160 A XT60 power buses.
6C: CAD render of the vertical mount for the 48-12V power converters.
6D: CAD render of the vertical mount for the Pi Hat PCB.

Our electrical system emphasizes modularity, safety, and performance. To standardize all electrical connections for easier testing and serviceability, all **48 V to 12 V** and **48 V to 5 V** power systems are equipped with **XT60 and XT30 connectors**, respectively. Standardization allows for easy swapping of spare parts, not to mention the space, weight, and efficiency savings of XT and Bullet series connectors over screw terminals.

We also use **custom-designed Printed Circuit Boards (PCBs)** using KiCAD EDA to save space, improve efficiency, lower part count, improve reliability, and simplify mounting. The **Pi Hat PCB** (Fig. 6A) connects the Raspberry Pi to the Electronic Speed Controller (ESC) signal wires, BNO055 IMU sensor, Raspberry Pi fan, and servo signal wires.

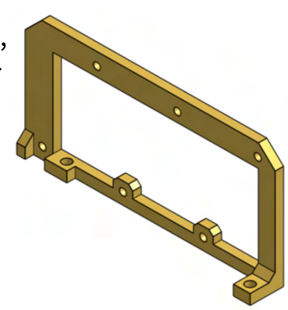


Additionally, since the thrusters can pull a combined 1200 W at 12 V, we must distribute 100 A of current, which no small off-the-shelf solution allows. Therefore, we designed, machined, and assembled our own **in-house XT60 power buses** with copper bus bars capable of 160 A of safe, continuous power delivery (Fig. 6B).



For the electronics bay, we 3D printed a **vertical mount** for the 48-12V power converters. This allowed us to shorten wire lengths by about 50% and mount the 48-5V converters underneath the baseplate. Mounting the electronics in this fashion saved space and opened up opportunities for cooling. A vertical mount gave us easier access to the wires going into the Raspberry Pi. We also revised our Raspberry Pi mount to include “horns” at the top. The horns allow us to support the weight of the electronics chassis while the ROV is upside down. This reduces stress on any wire headers sticking up out of the Pi Hat PCB.

Cooling



Preventing shutdowns due to overheating, the waste heat from three 48-12V power converters, and ambient heat in the competition environment compelled us to add cooling features to our electronics bay. Adding a **5V fan** behind the 48-12V converters, gaps in the vertical mount, and heat sinks attached to the converters’ backsides maximized airflow and surface area for cooling. As a result, our ROV is capable of running 2+ hours at a time.

Power Calculations

For our power calculations, we created a spreadsheet to track the ROV's total power consumption. It contains current, power draw, and efficiency loss estimates linked to automated calculations. The spreadsheet is readily accessible by all employees, and has a user guide to explain how to use, test, and update the calculations.

Table 4 (below): Power calculations for Barreleye operating at maximum power.

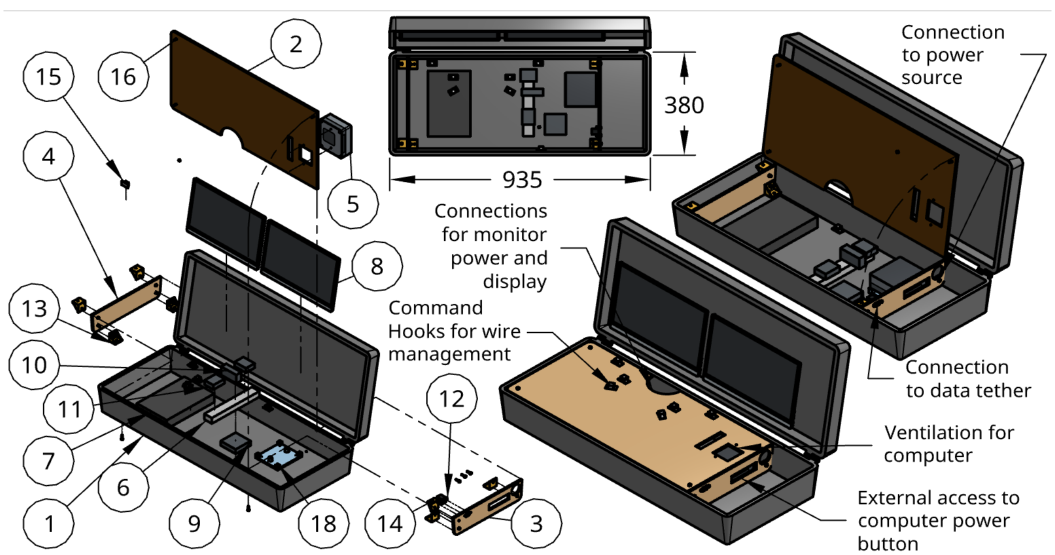
System	Power Draw	
Provided MATE Power Supply	30 A @ 48V =	+1440 W
Tether efficiency losses to environment (voltage drop)	30 A @ 10.142V =	-304.272 W
Branch 1: Sensitive electronics such as Raspberry Pi 4. Isolated from actuators to prevent damage from voltage spikes.	1 Raspberry Pi 4: -6 W 2 USB cameras: -2 W Power Loss due to Converter Inefficiency: -0.72 W	-8.72 W
Branch 2: Low Voltage Actuators	25kg Servo: -9.5 W Power Loss due to Converter Inefficiency: -0.855 W	-10.355 W
Branch 3: Mid Voltage Actuators, T100 Thrusters	6 T100: - 875 W Power Loss due to Converter Inefficiency: -35 W	-910 W
	Remaining margin for efficiency losses and future additions:	206.653 W

Our system consumes **1233 W** at peak load. Three 400 W, 48 V to 12 V power converters are used to power the six ESCs and T100 motors onboard, resulting in **303 W (76%) peak load on each converter**. Furthermore, the design incorporates two 150 W, 48V to 5 V converters, as indicated by Table 4, to provide power to Branches 2 and 3. This measure is implemented to safeguard delicate components against potential harm induced by voltage spikes.

Control Station

The **surface station** is the collection of equipment the pilot uses to operate the ROV. The surface station computer, router, monitors, keyboard, controller, mouse, and all other equipment is enclosed in a single grab-and-go package for rapid deployment and easy setup with minimal clutter. In order to make it suitable for movement, the router and the power strip have been secured to the pelican box using velcro. Command hooks have been used for wire management. The computer has been mounted on a computer mount (Item 18) for easy access to the buttons though the **external computer access hole** and increased ventilation for the computer during heavy workloads. This also makes every non-wire component inside the surface station mounted to the bottom of the case. This is an improvement from the previous year where the router and computer were both mounted to the bottom of the wooden platform. By mounting to the bottom of the case, we were able to get a **flat platform for the controller** to use.

Figure 7 (left): Drawing of the surface station and all of its components Refer to Table 5 for the Bill of Materials.
Table 5 (right): The Bill of Materials (BOM) for UWROV's surface station.



Item	Name	Quantity
1	Pelican 1700 case	1
2	Top platform	1
3	Right wall	1
4	Left wall	1
5	NucBox 2 Mini PC	1
6	Power Strip	1
7	Router	1
8	15.6" portable monitor	2
9	PC power supply	1
10	Router power brick	1
11	USB-C 15 watt power brick	2
12	Ethernet extension cable connector	1
13	3D printed bracket	6
14	3D printed bracket	1
15	Command wire management clip	2
16	M4 16mm screw	16
17	M4 hex nut	15
18	Computer Mount	1
19	Command wire management clip	6

Control System Software

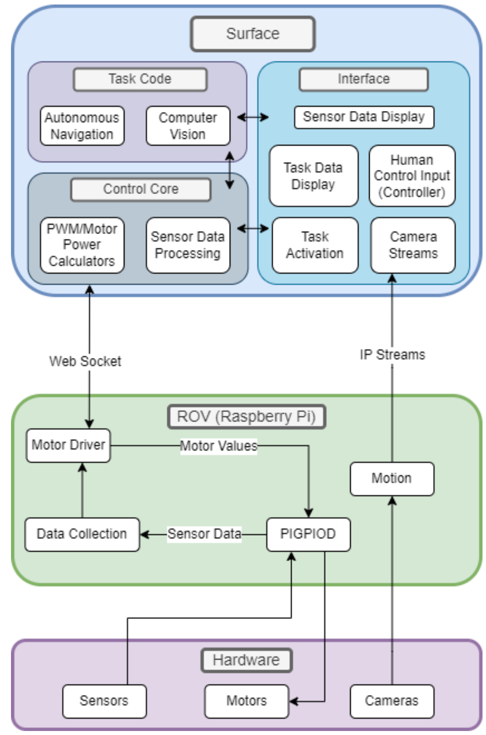


Figure 8 (right): The system integration diagram of all ROV software systems.

The ROV software system consists of a surface station computer and an on-board **Raspberry Pi 4.** The surface station computer contains interface code, task code, and control core code. The Pi is responsible for sending signals to the ROV's motors, as well as transmitting back sensor data. Communication between the surface station computer and Raspberry Pi is through **websockets**. For more information on these design decisions, see **Conceptual Ideation and Selection Process**.

The interface component of the surface station accepts movement commands from a controller. These inputs are sent to the control core which translates them into **pulse-width modulation values** for the motors. The computed values are sent via websocket to the Raspberry Pi, which then relays them to the motor system.

The software components of the ROV are implemented in Godot and Python. Godot's capabilities as a game engine allow it to accept inputs more naturally as well as provide a digital simulation of the robot and its movement. Meanwhile, Python is utilized for the rest of the robot, primarily for movement-related computations as well as task code.

Tether Construction

Flexibility, low weight, durability, and reliability when transporting power and data were the design goals of *Barreleye's* tether. For power, **10 AWG UL 1426 marine-grade wire** was used for its good efficiency-to-weight ratio for our 48-volt system. The two cable power system allows us to use modified WetLink Penetrators to connect to the pressure hold, while its PVC jacket and flexible stranded copper conductors enable safe, dynamic underwater deployment. A **Blue Robotics Fathom ROV Tether** acts as a CAT 5 ethernet cable for data transfer. Its flexibility and resistance to damage provide a stable backbone for the ROV's control system. The three cables are covered with a braided polyester sheath, protecting the cables from abrasion while keeping the tether flexible. It uses a 12 mm (½" nominal) sheathing based on our CAD model of the tether.

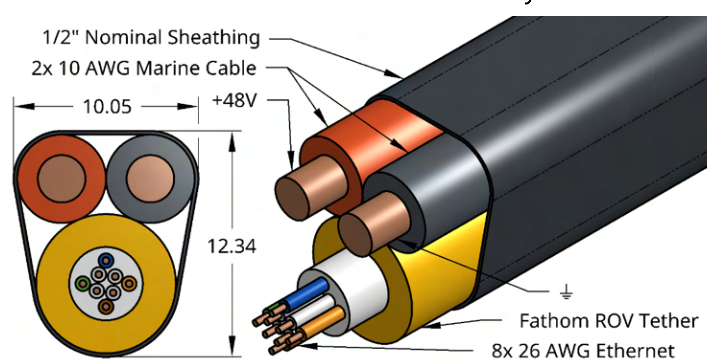


Figure 9 (right): A digital 3D model and cross section of our tether configuration. Dimensions are given in mm unless otherwise noted.

We chose a **20 meter length** for the tether based on a CAD model of the MATE pool specifications, plus ~10% margin. By limiting the length of our tether to what we need, we reduce tripping hazards while mitigating voltage drop. When the ROV pulls its maximum of 30A, the voltage drop is at most 4.7 V, leaving **43.3 V (90% of maximum possible) available** for use. The minimum voltage accepted by our power converters is 36 V, so the ROV will always have sufficient voltage.

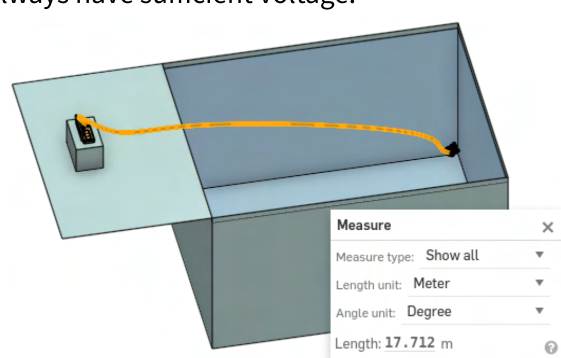


Figure 10 (right): CAD of MATE pool specifications showing min. tether length

The tether's internal wires are protected through **strain relief grips** on each end of the tether and a **braided cable sheath** covering the cable run. When the tether is pulled, the strain relief prevents the wires from experiencing extraneous tension, mitigating damage and improving ROV performance. On the surface, the data cable connects directly to our surface station. The power cables connect to the MATE power supply via a resettable 30A inline breaker that serves as an **emergency shutoff switch**. They are also outfitted with the MATE-specified 30 A inline fuse, and MATE-specified powerpoles. With a working strength of 36 kg and a breaking strength of 159 kg, the tether is strong enough that the ROV can be safely lifted by the tether with the installed strain relief (See Vehicle Safety Features).

Tether Management Protocol

1. Designate someone as tether tender for the duration of operations.
2. Tether tender removes tether from storage bin and uncoils it in a figure eight on the deck. This prevents the tether from kinking or tangling.
3. Tether is connected to the surface station strain relief, then ethernet, then power.
4. Strain relief is checked on both ROV and surface station side.
5. While the ROV is operating, the tether tender must always have contact with the tether.
6. Tether tender must provide enough tether length necessary to allow the ROV to reach its working depth. Too little will inhibit the ROV, too much will cause tangling.
7. ROV pilot must avoid 360 degree rotations & close maneuvers around obstacles when possible to avoid tangling.
8. Do not pull on the tether to clear a snag.
9. Never step on the tether, this could cause bits of dirt to grind into it.
10. Once operations are completed, tether tender is in charge of disconnecting the tether from the surface station and power.
11. After disconnection, the tether tender coils the tether.

Adapted from Christ & Wernli, 2013 and Moore, Bohm, & Jensen, 2010

Propulsion

We used 6 **Blue Robotics T100** thrusters for propulsion on *Barreleye*. We chose to reuse these thrusters due to their moderate cost and good efficiency at lower power levels. At 12 V, the 6 thrusters consume approximately 875 W of power, staying within our total power budget of ~1.3 kW for the ROV's onboard systems. Each thruster provides 25 N in the forward direction and 18 N in reverse, allowing a maximum lift capacity of 50 N when both side thrusters work together to move the ROV upward when neutrally buoyant (*The T100: A Game-Changing Underwater Thruster,* 2015).

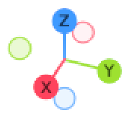
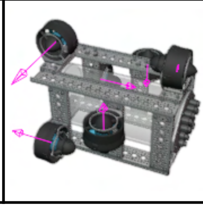
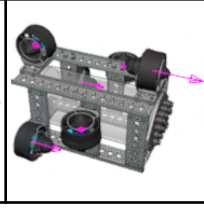
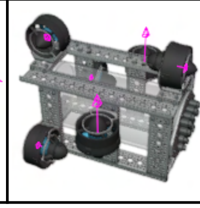
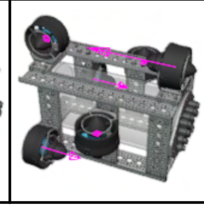
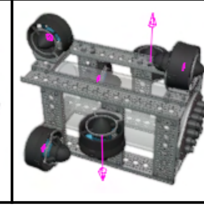
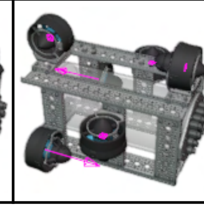
To improve *Barreleye's* precision of motion, motor **thrust is variable** based on inputs from the control system. Thrust from the T100s operate on an input scale of -1 to 1, with all values in between being possible amounts of thrust for forwards or backwards force. Additionally, custom **IP2X motor safety shrouds** provide improved thruster efficiency compared to more traditional protective gratings often seen on ROVs. These capabilities allow the ROV pilot to accurately maneuver in smaller spaces and rapidly accelerate in more open waters. Through these improvements, the T100s meet requirements for *Barreleye*'s mission of completing a wide variety of MATE tasks.

Barreleye's six thrusters were arranged to enable **Six Degrees of Freedom (6 DOF) motion** while keeping the overall structure of the ROV simple. We decided to maintain our previous layout, inspired by the Ariana-I ROV, to focus on fine tuning propulsion rather than creating a new system from the ground up. While 6 DOF increases the complexity of the control system compared to more traditional layouts, it raises our performance ceiling, making the tradeoff worthwhile. We allocated motors for different axes of movement based on MATE task requirements:

- **Y axis (forward/backward)**: 3 thrusters, prioritizing speed over long distances to move efficiently between MATE tasks in different areas of the pool
- **Z axis (up/down)**: 2 thrusters used for moderate vertical speed when delivering payloads to/from seafloor
- **X axis (left/right)**: 1 thruster used for slow, precise alignment during manipulation tasks

We then selected positions on the ROV that optimize serviceability and control authority, while maintaining our directional movement allocations. When running the ROV, a Python script uses the desired force and torque on the ROV combined with thruster orientations and locations in our CAD model to solve for the necessary motor powers.

Table 6 (below): Table of thrust directions (pink) for each axis of movement and rotation (red, green, blue)

Axes	Translate +X	Translate +Y	Translate +Z	Rotate +X	Rotate +Y	Rotate +Z
						

Buoyancy and Ballast

The main buoyancy module on the ROV is the **air-filled electronics pressure hold**. Combined with the low overall weight of the ROV, our product is **positively buoyant before ballasting**. Ballast is added, in the form of waterproof **bottles of steel balls** to make our ROV balanced and neutrally buoyant, increasing the ease of precision movement and control. Our tether, being naturally negatively buoyant, has foam added to bring it to neutral buoyancy.

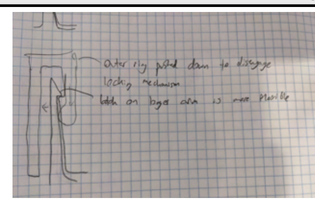
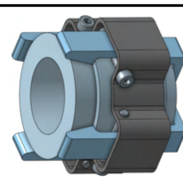
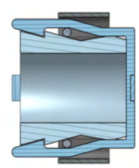
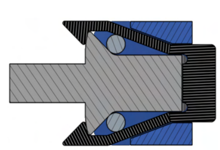
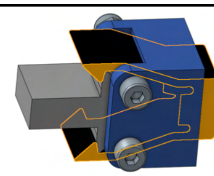
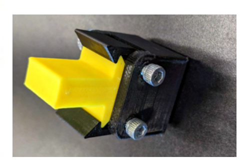
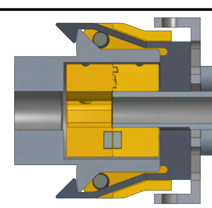
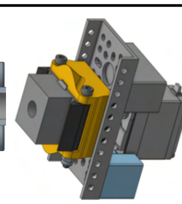
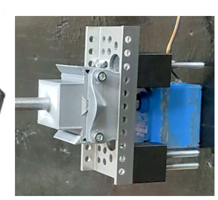
We used our digital twin CAD model to predict ballasting needs before making actual adjustments to the ROV. Our CAD model estimates that our ROV has a mass of 7.70kg while displacing 8.06 liters (8.06kg of freshwater), so the difference of 0.36kg gave us a starting point of how much mass to add. After adding our initial estimate of ballast, we iteratively test drive and redistribute ballast to optimize its amount and distribution.

Payload and Tools

Modular Manipulator Interface

To tackle the wide variety of tasks for this year's challenge, we designed a manipulator interface that would let us quickly hot-swap both static and dynamic manipulators many times during a single match. This allows us to rapidly adapt and specialize the ROV's capabilities to maximize performance for MATE tasks.

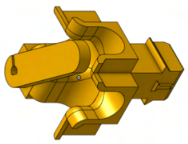
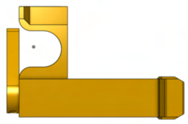
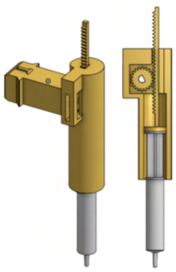
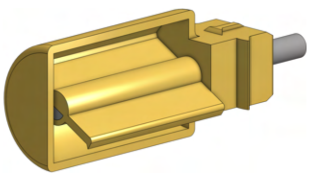
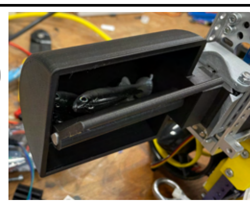
Table 7 (below): Concepts and prototypes of the ROV's modular manipulator interface.

Design Idea	Concept Models and Prototypes
Preliminary ideation for quick-release mechanism allowing manipulators to be swapped quickly during a match. Allows for the design of specialized, more reliable manipulators for handling different objects.	
Version 1: Rotational symmetry for easy alignment, functional, but not particularly strong or stable.	  
Version 2: Miniaturized and simplified quick-connect mechanism as much as possible while retaining stability.	  
Version 3: sized up to house a hybrid splined & magnetic coupler to transmit torque to dynamic manipulators. Retaining arms went through multiple iterations to find ideal resistance & latch force.	  

Dynamic Manipulators

Dynamic manipulators achieve **independent motion** through a rotating shaft that connects to the external servo via a hybrid magnetic & splined coupler. The alternating poles of the **miniature neodymium magnets** in the couplers help automatically align them during installation to engage positive splined drive.

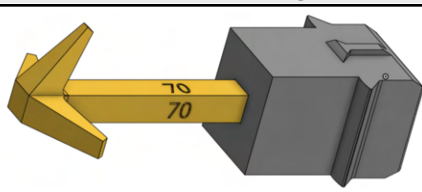
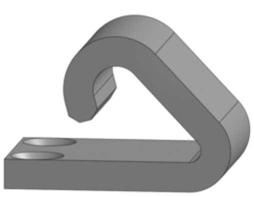
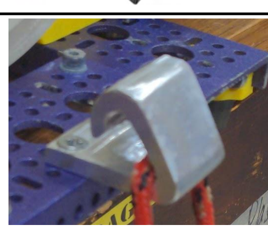
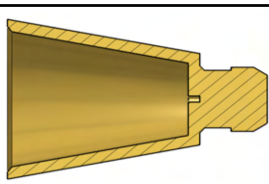
Table 8 (below): Interchangeable dynamic (moving) manipulators designed for specific MATE tasks

Models and Images	Description
 	Has a coped cross section with a securing latch for holding onto components of the mooring, syringe, and camera implements. *Used for Task 1.1 (moor solar array)*
 	This syringe manipulator is designed to retrieve or inject a sample of fluids. The syringe is attached on the end of a rack and pinion that extends and retracts when gathering or injecting fluids. *Used for Task 2.3 (administer Rx to corals), Task 2.2 (collect water sample)*
 	The manipulator stores the fry in the half-cylinder compartment, with the cover initially being flush with the half-cylinder. When the fish are to be deposited, the cover rotates, dropping the fish. *Used for Task 2.5 (reintroduce endangered native fry)*

Static Manipulators

Static manipulators do not move relative to the ROV, and instead take advantage of our **high overall agility** to maneuver props. Modular static and dynamic manipulators can be installed interchangeably in the quick-connect interface, allowing for rapid tooling changes in the field.

Table 9 (below): Interchangeable static (non-moving) manipulators designed for specific MATE tasks

Models and Images	Description
	Static 3-pronged hook designed to easily snag loose elements such as rope or algae in the water. *Used for Task 1.2 (biofouling removal)*
 	Permanent aluminum hook machined from 6061 Aluminum for high-load tasks, mounted close to the center of thrust on the ROV to make moving large/heavy objects easier. *Used for Task 2.6 (heavy lifting)*
 	Housing for UV irradiation tasks. Can be repositioned on the ROV side when not in direct use without needing to change wiring. *Used for Task 2.3 (administer Rx to corals)*

Float Design

This year our float design mostly focused on integrating radio communications between the float and the surface station as well as upgrading mechanical components. We chose to use a pump and solenoid buoyancy engine due to its success in last year's competition. For establishing communications with the float, we explored three main options: Bluetooth, wifi, and radio. Radio communications using an **Adafruit RFM96W LoRa Radio Transceiver Breakout** board was found to be the best option for several reasons. Our main reasons for choosing radio over Bluetooth and wifi were range and reliability.

Figure 11 (right): The CAD render of our GO-BGC Float Replica.

Cameras

The primary objectives of our camera system are to enable the pilot to successfully navigate the sensitive aquatic environment, and to enable our computer vision systems to map terrain. We selected two cameras since this allowed us to fully meet the requirements without unnecessary complexity risks. Our cameras are mounted inside the pressure hold, facing **forward and downward** of the ROV. The forward-facing camera is essential for piloting and observing the manipulator, which is important to every mission task. This camera uses a fisheye lens to provide the pilot with a wider view for situational awareness. The downward-facing camera contributes visual guidance for how deep the ROV is in the water as well as how close it is to objects without requiring the ROV to be pointed downwards. This camera uses a rectilinear lens to help simplify computer vision processing.

Table 10 (below): ROV camera applicability to MATE tasks.

Camera Position	Tasks Handled
Front-facing	1.1 Install a floating solar panel array 1.2 Remove biofouling from the foundation and mooring lines of floating wind turbines 1.3 Pilot into ‘resident ROV’ docking station 2.1 Create a 3D model of a diseased coral head 2.3 Administer Rx to diseased corals 2.5 Reintroduce endangered native Northern Redbelly Dace fry 2.6 Ensure the health and safety of Dillon Reservoir 2.7 Monitor endangered Lake Titicaca giant frogs
Downward-facing	2.2 Identify reef organisms using eDNA 2.4 Monitor and protect seagrass habitat

Sensors

For autonomous movement, we utilize the **Adafruit BNO055 IMU**, which is capable of providing absolute orientation, angular velocity & acceleration, and linear acceleration. Its accurate & reliable measurements enable advanced autonomy and pilot assists, enhancing the ROV’s capabilities for MATE tasks. Observation tasks (e.g. flying the transect) and precision manipulation (e.g. administering Rx to diseased corals) benefit from the stability it provides.

Build vs. Buy, New vs. Used

UWROV **reuses** components of the ROV when they meet requirements and are not performance bottlenecks. Reuse allows us to reduce costs (by avoiding the purchase of new hardware), increase reliability (by using previously qualified systems), and lets us focus our development energy on the components that are our current performance bottlenecks. Last year, we invested significant development resources into revamping our propulsion, structure, and control systems. This year, we are **focusing on less visible**—but mission critical—upgrades to our manipulator, power distribution, and software, as those were our MATE mission capability bottlenecks in prior years.

Table 11 (below): Reused Purchased Systems on Barreleye

System	Justification
B.R. T100 Thrusters	Meet requirements: power draw, thrust, and efficiency. Thruster power is sufficient to carry task payloads such as the tent over coral (Task 2.3).
Raspberry Pi	Meets requirements: compute, power draw, ROV systems control, camera & data streaming.
G.E. Power Converters	Meet requirements: amount of power, efficiency, thermal performance.
Cameras	Meets requirements: sufficient visibility for pilot & autonomous systems for MATE tasks requiring underwater visibility (ex. Task 2.4).

Table 12 (below): Reused Custom-built Systems on Barreleye

System	Justification
Float Hull & End Caps	Trade study found current shape, size, and strategy are near-optimal for the mission (Task 3).
Tether	Meets requirements: efficiency, safety, strength, abrasion resistance, and strain relief.
Pressure Hold	Meets requirements: space, mass, visibility, serviceability, and electrical connectivity.

Table 13 (below): Newly Purchased Systems on Barreleye

System	Justification
Manipulator Servo	Current company capabilities do not extend to ground-up servo development yet. Adding this component improves the task-based capabilities of dynamic manipulators.

Table 14 (below): Newly Manufactured Custom-built Systems on Barreleye

System	Justification
Static Manipulators	Multiple static manipulators were manufactured for the new modular system, where static manipulators can be quickly and safely swapped depending on the task at hand.
Magnetic Coupling System for Manipulators	The magnetic coupling system allows static manipulators to remain fastened to the servo whilst in operation, but can be removed and swapped out without tools.
Power Distribution PCBs	Unique power architecture requires distribution PCBs unlike what is available commercially.
Data Connection PCBs	Tight space constraints and specialized layout necessitates custom data interconnect PCBs.

System Integration Diagrams (SIDs)

Figure 12 (below): The System Integration Diagram (SID) for all electrical systems on the GO-BGC float replica.

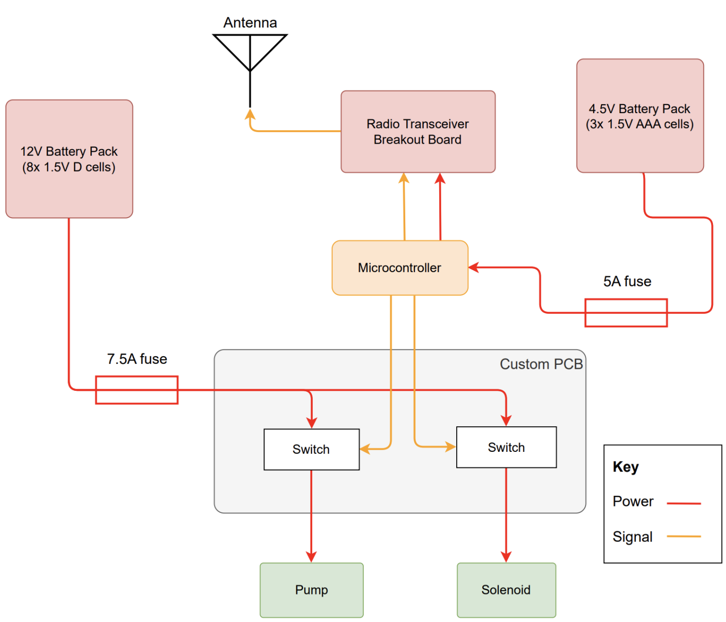
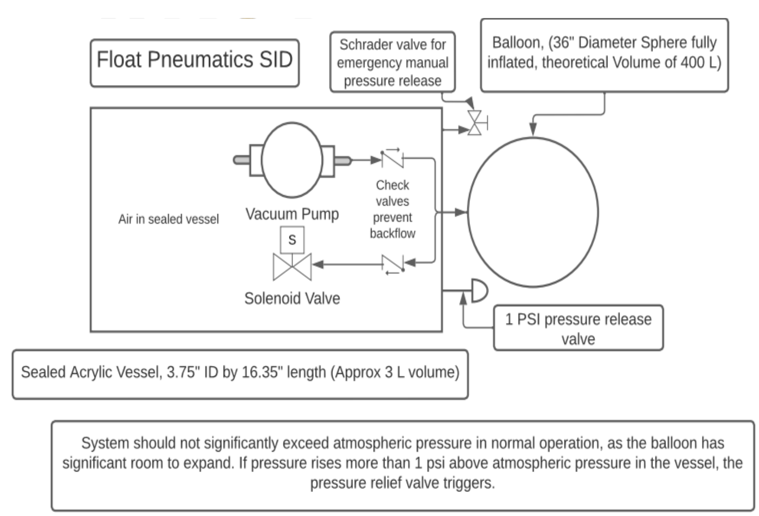


Figure 13 (below): The System Integration Diagram (SID) for all pneumatic systems on the GO-BGC float replica.



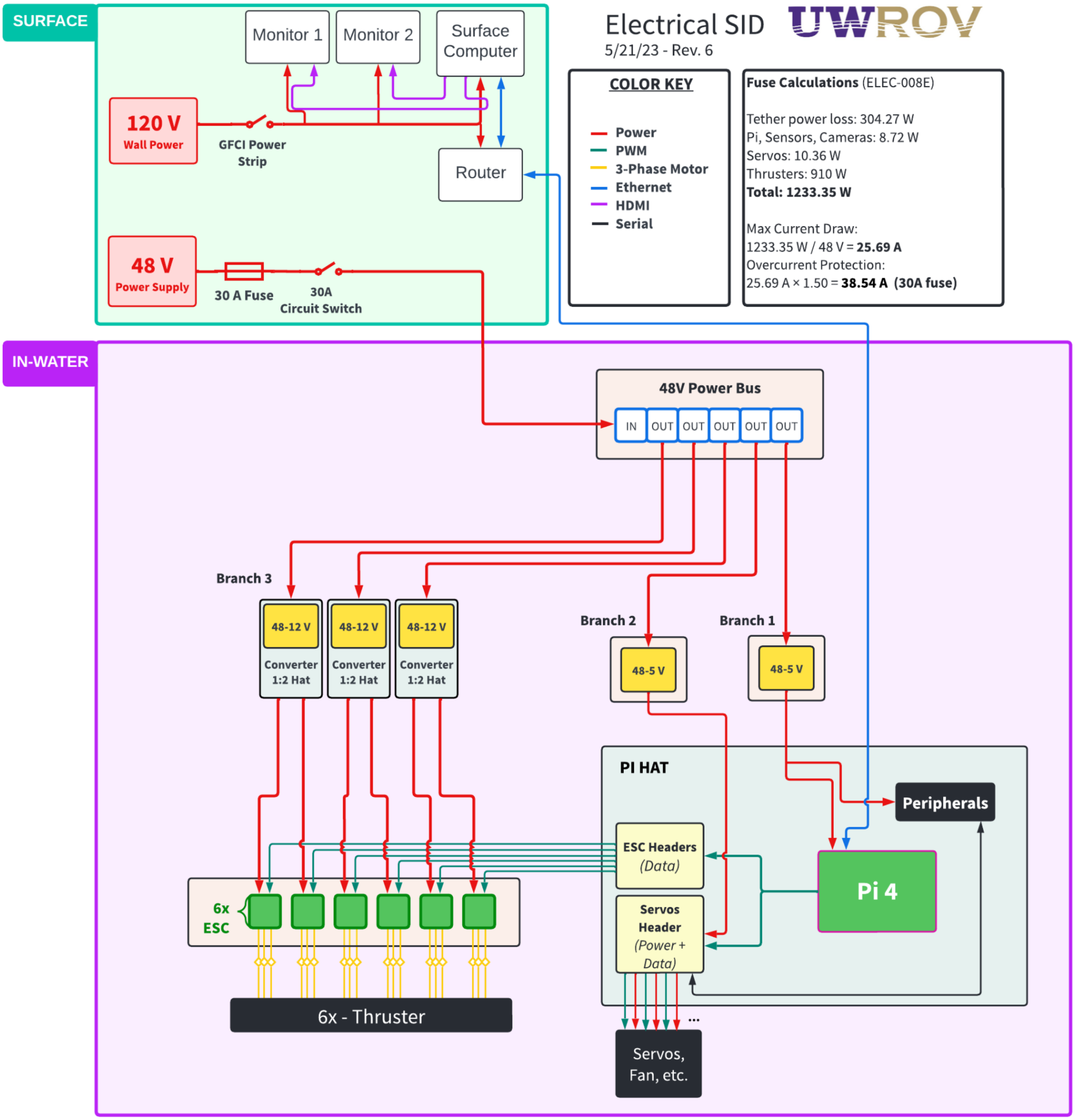


Figure 14 (above): The system integration diagram for all electrical systems in the ROV and surface station

Safety

The core of safety at UWROV is to mitigate risks long before unsafe situations occur. Due to an influx of new employees with little to no experience with engineering equipment, **personnel and equipment safety** was a high priority this season. We have a dedicated **safety officer** who ensures that employees learn and comply with safety standards set forth by the team and local regulations.

Personnel and Equipment Safety

At the start of the season, all incoming and returning employees have to go through **a mandatory lab safety training** before being permitted to use the space. The safety information covered include locations of safety equipment, accident procedures, required PPE, hazardous materials storage, and emergency contacts in case of accidents.

This season, UWROV also assigned a dedicated **shop lead** who supervises the acquisition and usage of all equipment within the UWROV lab. In order to use lab equipment, especially power tools, employees must complete a training course created by the shop lead. Employees must display their proficiency, awareness of hazards, and understanding of safety procedures to the shop lead before they can use the equipment independently. The goal is to create an environment where employees are confident in their ability to contribute to the engineering process whilst remaining cognizant of safety hazards. Another safety change made this season was the **reorganization of the lab space**. Unused pieces of equipment were moved out of the lab into storage, freeing up space. This additional space allowed for more work stations and reduced the danger of employees getting in the way of each other. As part of the reorganization, UWROV employees tallied hazardous materials, storing them separately from other materials.

While COVID-19 has not inhibited the team's ability to meet in-person this season, we maintained a **hybrid** work environment for all meetings. Employees can choose to work remotely over **Zoom** should personal health and safety concerns arise.

Operational Safety

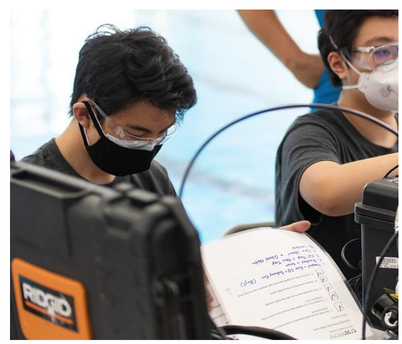


Figure 15 (right): Operational safety checklists in use by a UWROV employee.

In order to determine potential hazards during ROV operation, we performed a **Jobsite Safety Analysis (JSA)** and implemented operational checklists to mitigate potential risks. Examples of pre-launch rules include tying back long hair, removing loose debris, and verbally stating the power status of the ROV. For a full list, see **Appendix B**, *ROV Operation* for our checklists. (Fig. 18).

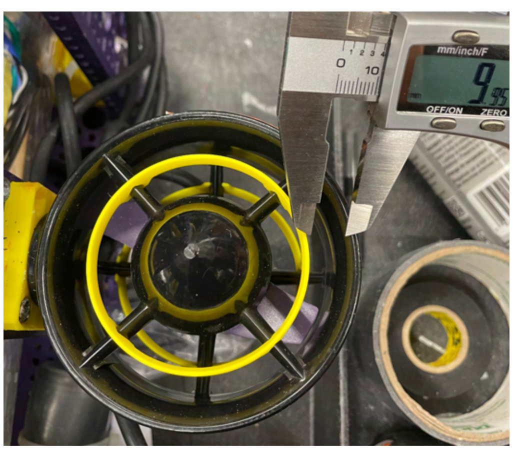


Figure 16A (above): Our 3D-printed thruster shielding leaves no openings >12.5 mm, complying with IP2X.

Figure 16B (above): Warning labels on thrusters follow ANSI Z535.3-2011 for safety symbols (ANSI, 2011).

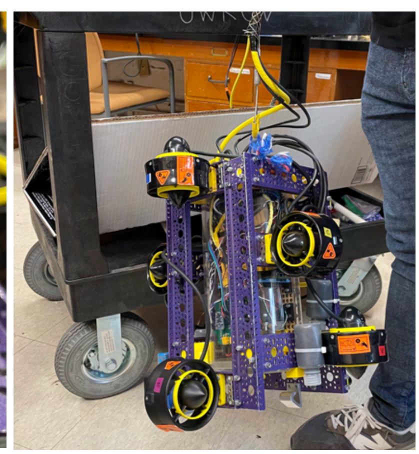


Figure 16C (above): The ROV can be safely lifted by the tether via the strain relief system

Preventing injury through safety features was one of the main design priorities that the UWROV team maintained throughout the season. This involved eliminating potential dangers on the ROV and making hazards clearly visible to employees. We used our custom 3D-printed, **IP2X compliant thruster intake shields** on our T100 thrusters to prevent injury whilst handling the ROV (Fig. 16A). As visual aids, ANSI Z535.3-2011 compliant **warning labels** are placed on ROV thrusters to warn against potential injury (Fig. 16B). In addition, many of the mission tasks involve navigating near ropes or cords; the intake shields prevent them from becoming tangled in thrusters. For carrying and setting down the ROV, **soft rubber feet** cover sharp edges that could hurt employees or damage poolside surfaces. All sharp edges on the ROV frame are broken, typically by filing. This also prevents harm to sensitive marine environments.

Barreleye's wiring complies with the NASA Workmanship Standards (NASA, 2002). To ensure all electrical safety, all electrical connections are done via enclosed connectors or with a lineman splice that is flooded with solder and protected with a heat sink. We ensured there were no exposed electrical connections within the pressure hold To further prevent overheating within the pressure hold, an **internal fan** was installed to circulate air, preventing hotspots from forming. A **braided cable sleeve** on the tether, in conjunction with, **tether strain relief** on the ROV and surface station prevents damage to the tether from tension (Fig. 16C).

To ensure that no harm comes to UWROV employees, task-related payloads, pool surfaces, and the marine environment, all static manipulators are designed and manufactured with broken edges. Precise manipulation is necessary when handling delicate cargo like the fry seen in Task 2 (Inland Lakes and Waterways). The model GO-BGC float also has a **pressure release valve** with a cracking pressure of 1 psi in the event of emergency or battery failure.

Safety Procedures

We use a series of safety checklists when assembling and deploying the ROV to reduce the risk of harm to employees or the ROV (see **Appendix A** and **Appendix B**).

Critical Analysis: Testing & Troubleshooting

Our methodology for testing our ROV involves designing based on the **digital twin** and iterating based on physical feedback. Designing with the digital twin allows us to catch any oversights before spending resources building physical prototypes. After refining a prototype digitally, the component is then constructed or machined so that it can undergo physical testing. The component is integrated into the ROV and tested for any design flaws. If any are found, then the design will undergo a new iteration digitally, before repeating the process.

Manipulator components were tested using **finite element analysis (FEA)** using Onshape simulation software. A static PLA hook implement was tested against a 5 lbf load applied through the hook, as pictured below in figure 17. All manipulators were subjected to similar testing against anticipated load conditions with a minimum safety factor target of 2.5, with all manipulators exceeding this threshold.

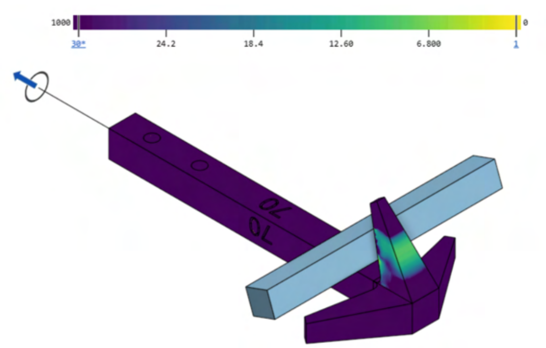


Figure 17 (right): FEA test of three-pronged hook for tasks 1.2 & 1.3.

For the heavy lifting test event in task 2.6, an aluminum hook was implemented directly affixed to the frame of the ROV. To test this manipulator, a load of 45 lbf was applied in line with the fixed face of the hook, while a stainless steel 300 series bolt was used to fix the hook against the load. The results indicate that the hook is more than strong enough to lift the heavy implement without failing.

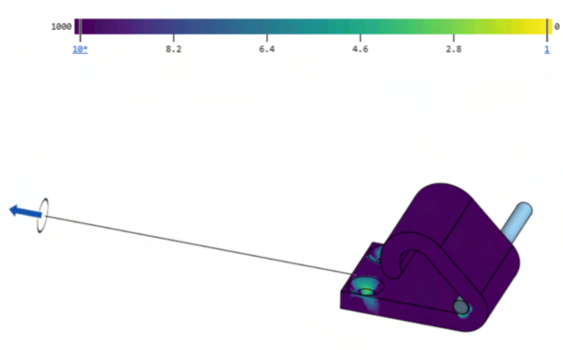


Figure 18 (right): FEA test of heavy-lift aluminum hook for tasks 2.3 & 2.6.

When we experience a challenging issue, we make extensive use of test equipment to **gather quantitative data** to inform our troubleshooting strategies. For example, we utilized an oscilloscope and a multimeter to debug crashes in the power delivery system. Using the scope, we were able to measure voltage changes in very small time increments which helped us find the root cause of the problems we were experiencing—rapid shifts in demand from the ESC causing the power converter's output voltage to go out of its rated range, resulting in an overvoltage shutdown. This aided us in developing software and electrical mitigations to prevent loss of control due to the propulsion power system rebooting

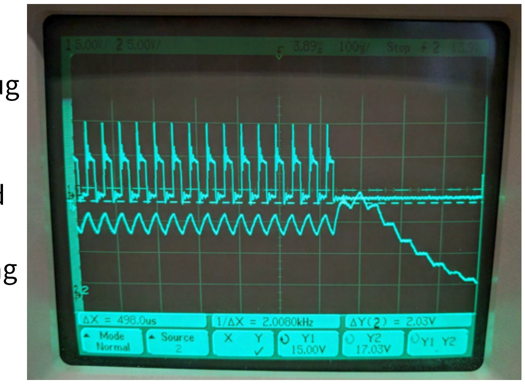


Figure 19 (above): scope trace of the 1 millisecond surrounding the crash of a power converter, showing overvoltage.

Another way we collect quantitative data is through the pilot-facing interface: for example, **displaying input and output values** during the ROV's operation, allowing for quick problem isolation. One use case is if the motors are not spinning correctly, we can easily detect whether it is a control input issue or translation issue depending on whether the input or output values are suspicious.

Digital testing, physical testing, and data-based troubleshooting provide ample opportunities for UWROV employees to make informed design changes and innovate. Providing multiple stages of development where oversights can be identified, iterated on, and resolved is the core of UWROV's critical analysis process.

Accounting

Budget

This season, our competition team is substantially smaller than it was during the year prior. As a result, some portions of our budget have been reduced in order to compensate. For example, **travel costs** were reduced due to a smaller team size attending the world's competition (7, down from 12 in 2022). Reflecting on power issues that plagued last season's ROV, we combined **electronics R&D** into **ROV electronics** and increased funding. The goal was to increase our electronic testing capabilities and improve on previous design flaws. Another emphasis of this year's budget was continuing to improve our lab space with new **tools and equipment**. A large influx of new UWROV employees necessitated the acquisition of new, safe equipment to help them learn engineering skills and contribute to ROV development. Large amounts of spending on **safety equipment** and **structural ROV components** during the previous season lead to the reuse of many parts and pieces of equipment. Expensive items previously purchased or manufactured were reused due to their success in our previous design, and to eliminate excess costs.

Table 15: A financial travel estimate for UWROV to attend the MATE World Championships

Travel Estimate				
Category	Description	Cost	Qt.	Subtotal
Airfare	Reimbursement per employee	$200	6	$1200
Lodging	Lodging rental, total (Airbnb)	$3517	1	$3517
Car Rental	Rental for a SUV (Hertz)	$1333	1	$1333
			Total:	**$6050**

Table 16: A financial breakdown of budget allocation for the 2023 season, contrasted by allocation during 2022.

Budget Allocation (*note: spans page break*)			
Category	Description	2022 Allocation	2023 Allocation
Lab Safety	Safety glasses, labels, ventilation, gloves, etc.	$800	$300

Budget Allocation (*note: spans page break*)			
Category	Description	2022 Allocation	2023 Allocation
Tooling & Equipment	Multimeters, wire crimpers, drills, etc.	$2,500	$3,500
ROV Surface Station	Case, computer, router, controller, etc.	$800	$400
ROV Structure	ROV tether, frame and pressure hold	$1,000	$400
ROV Electronics	Onboard computer, power converters, cameras, etc.	$500	$1,500
Float	Pneumatic pumps, onboard computer, etc.	$200	$150
Team Operations	Team branding (shirts/polos), domain hosting, etc.	$600	$700
Competition Logistics	Shipping costs for checking in luggage with the ROV	$250	$180
Competition Fees	Registration fees for the MATE ROV Competition	$425	$450
Competition Travel	Transportation and lodging for the MATE Competition	$10,000	$6,050
	Total:	**$18,275**	**$13,530**

Cost Accounting: See **Appendix C**

Acknowledgements

Our operations would not be possible without support from our sponsors. We are incredibly grateful for the help and support we have received this year, and thank the following organizations and people for their contributions:

- **The University of Washington School of Oceanography** for continual support of our team and for providing laboratory space for UWROV,
- **Rick Rupan, our mentor,** for his supervision and guidance throughout our club's development,
- **Foundry10** for continued financial support,
- **The Applied Physics Laboratory at the University of Washington** for guidance & continued financial support
- **The University of Washington Student Technology Fee** for continued financial support,
- and **The MATE Center** for their dedication to enriching student learning & outreach in ocean technology.

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Appendix A: Safety Checklists

ROV Construction:

Disassembly:

- ☐ Power supply is off (announce “POWER OFF”).
- ☐ Outside of pressure hold in back region of ROV is completely dry.
- ☐ Work surface is free from debris, including metal shavings, hair strands, and dirt.
- ☐ Static electricity discharged by touching a metal surface.

Assembly

- ☐ ROV is powered off at the surface-side tether switch.
- ☐ The control board is clean, with no residue or metal debris.
- ☐ No wires are disconnected, loose, or exposed.
- ☐ The inside of the pressure hold is completely dry.
- ☐ The pressure hold has no clouding or cracking.
- ☐ All ports on the pressure hold are sealed tightly.
- ☐ O-rings are undamaged and lubricated.
- ☐ O-ring grooves are clean and undamaged, especially watching out for hairs, dirt, and metal shavings.
- ☐ No wires are pinched between components or the walls of the pressure hold.
- ☐ Both O-rings form a complete seal.
- ☐ Both endcaps are flush with the main cylinder.
- ☐ Internal assembly is horizontally level.
- ☐ Pressure hold retaining arm is lowered.

ROV Operation:

Pre-Deployment:

- ☐ All ROV connections are secured.
- ☐ There is no damage in the ROV frame or pressure hold (watch out for clouding & cracks).
- ☐ All ROV attachments (motor shrouds, floats, weights, motors) are secure.
- ☐ There are no loose connections in the pressure hold.
- ☐ The tether is laid out neatly without knots or tangles.
- ☐ Battery/power supply is completely dry and away from the side of the water.
- ☐ Surface station tether strain relief is connected, and tether ethernet and power are connected.
- ☐ Surface station is stable and on a level surface.
- ☐ Surface station computer, router, and monitors are plugged in, powered on, and connected.
- ☐ All personnel have close-toed shoes, safety glasses, no loose clothing, and long hair tied back.
- ☐ Recovery equipment (pole, net, etc.) handy.
- ☐ Control center and tether staging area are clear of clutter and tripping hazards.

Pre-Initialization:

- ☐ No water is flooding the pressure hold.
- ☐ No parts have come loose from the ROV.
- ☐ All connections are secure.
- ☐ ROV is placed in the water.
- ☐ No employees are directly touching the ROV.

Announce “POWER ON” before turning on the ROV!

Appendix B: Lab Safety Policy

1. NEVER WORK ALONE IN THE LAB.
2. Wear lab-appropriate clothing at all times in the lab: safety glasses or side-shields; close-toed, no-slip shoes; gloves (never when working with rotating/moving machinery); no loose clothing; no rings, watches, or bracelets; long hair must be tied back.
3. All injuries or accidents must be reported **immediately** to the Lab Supervisor.
4. If you are in doubt as to a proper or safe procedure, **stop work** and ask for guidance.
5. Report unsafe or hazardous conditions wherever noted. Correct them if possible.
6. Eating or drinking is prohibited in lab spaces.
7. Be thoroughly knowledgeable concerning the equipment you are using.
8. Use tools for their intended purpose only.
9. Do not use fingers or hands to remove chips from moving or stationary machines.
10. Never adjust a moving or rotating machine unless motion is necessary to make adjustment. Always allow the machine to come to a standstill before making adjustments or repairs.
11. Never leave a machine running while unattended, unless machinery is intended to do so.
12. Do not attempt to slow down or stop rotating or moving equipment with hands or tools.
13. File all machined parts or stock with sharp edges.
14. Always clamp or secure the workpiece properly.
15. Use appropriate respiratory protection when working with dusts, mists, fumes or vapors.
16. Read the SDS for all lubricants, resins, adhesives, or other chemicals you are working with.
17. Concentrate on what you are doing. Do not talk or be distracted while operating equipment.
18. Use proper techniques and obtain assistance when lifting, moving, or carrying loads.
19. Watch for tripping hazards. Do not place material or objects in thoroughfares or passageways.
20. Know the location of fire extinguishers, fire exits, and first aid kits.

Adapted from the UW Mechanical Engineering Machine Shop Rules (College of Engineering, 2021).

Appendix C: Cost Accounting

Fundraising:

Category	Name	Amount
Sponsorship	Foundry10	$5000.00
Sponsorship	Applied Physics Laboratory	$3000.00
Grant	Student Technology Fee Grant	$4202.00
	Total:	**$12202.00**

Reused Items:

Budget Category	Item(s)	Est. Value
ROV Surface Station	Pelican Case	$320
Float	Pneumatic Pump	$50
ROV Power Electronics	Tether Components	$400
ROV Power Electronics	6 Blue Robotics T100 Thrusters	$650
ROV Power Electronics	Blue Robotics Speed Controllers	$150
ROV Power Electronics	Raspberry Pi 4 B 4 GB	$182
ROV Structure	Acrylic Pressure Hold	$60
ROV Structure	goBilda Low U Channel and Side Block Mounts	$180
Safety Equipment/PPE	Safety Glasses	$44
Safety Equipment/PPE	Hakko FA400-04 Fume Extractor	$160
	Total:	**$2146**

Expenses (September 2022 to June 2023):

Budget Category	Example Items	Budgeted	Total Value*	Spent
PPE/Safety Equipment	Safety glasses, Emergency Medical Supplies, Hearing Protection, Face Shields	$300	$266.58	$62.58
Tools/Supplies	Ex: Benchtop lathe, Hacksaws, Center Punch, Calipers, Deadblow Hammer	$3500	$3177.16	$3177.16
ROV Surface Station	Joystick, Router, PC, Keyboard, Mouse	$400	$341.92	$21.92
ROV Structure	Frame, Tether, Pressure Hold: Acrylic, O-rings, Aluminum Stock, Filament	$400	$368.68	$128.68
ROV Power Electronics	Servos, Connectors, Power Converters, Cameras, PCB, Raspberry Pi	$1500	$2411.21	$1079.21
Float	Float PCB, Tubing, Check Valves	$150	$128.84	$78.84
Team Operations	Projector, USBC Adaptors, Printer	$700	$640.98	$640.98
Competition Fees	Explorer Registration Fees, Fluid Power Quiz Registration	$500	$475	$475
Travel Fees	Airfare, Car Rental, Lodging	$6685	$6685	$6685
	Total:	**$14135**	$14495.17	**$12349.37**

**Total Value includes the value of reused items.*