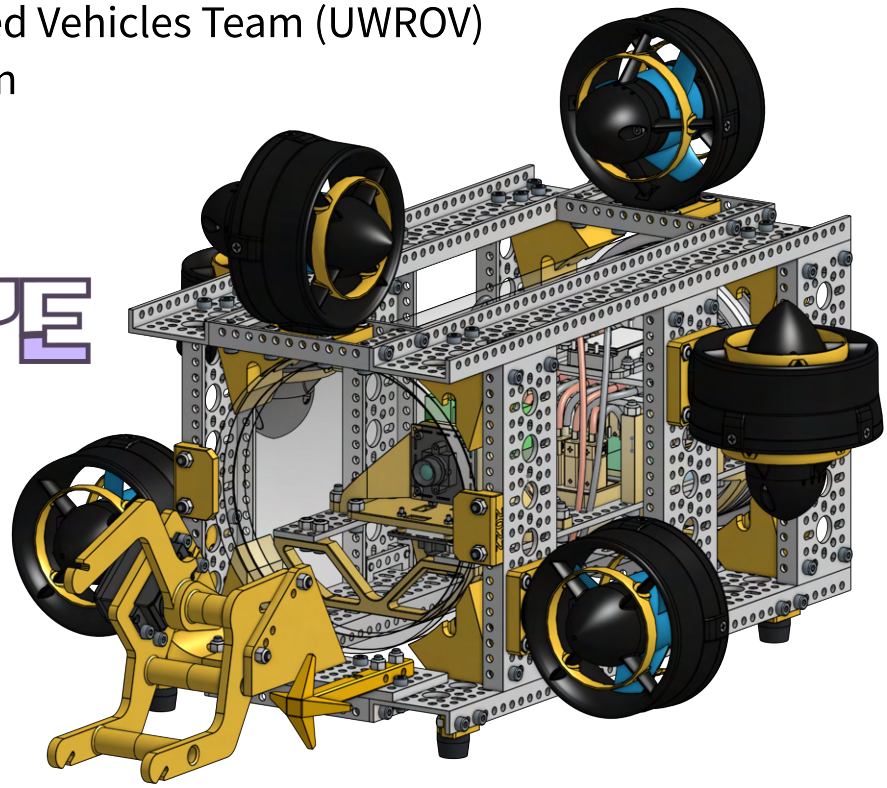
UWROV

2022 Technical Documentation

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

Introducing…

BARRELEYE



Our ROV for the 2022 MATE ROV Competition, Explorer Class

Mentored by Rick Rupan

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Ellie Brosius: *Float Subteam*
Teddy Lautch: *Float Subteam*
Amanda Pitts: *Frame Subteam*
Kenneth Yang: *Simulation Subteam*
Ronan Kau: *Manipulator Subteam*
Anna Shih: *Manipulator Subteam*
Imants Smidchens: *Manufacturing*
Morgan Golden: *MATE VR World Subteam*

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Leah Davis: *Business Lead*
Quang Nguyen: *Team Photographer*
William Le: *Outreach Coordinator*
Catherine Redpath: *Sponsor Relations*

Software subgroup:
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Olivia Wang: *Software Lead, Secretary*
Lauren Krieger: *Autopilot Subteam*
Daniel Berezansky: *Autopilot Subteam*
Marcus Chen: *Autopilot Subteam*
Angela Wei: *Camera Subteam*
Cindy Zhou: *Machine Learning Subteam*
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Jay Lee: *Electrical Lead*
Hongyong (Scott) Li: *Electrical Lead*
Lakshya Sharma: *Pressure Hold Subteam*
Menelik Hailu: *Pressure Hold Subteam*
Austin Martin: *Tether Subteam*
Simon (Hao) Wang: *Pressure Hold Subteam*
Rohan Menon: *Pressure Hold Subteam*

Abstract

We are the Underwater Remotely Operated Vehicles Team (UWROV) at the University of Washington. For the MATE 2022 Explorer Challenge, we are pleased to present *Barreleye*, a Remotely Operated Vehicle (ROV) designed to complete the 2022 MATE mission objectives, including maintaining renewable energy infrastructure, supporting offshore aquaculture operations, and exploring under the ice in the Antarctic. *Barreleye* is named after the real-life deep-sea barreleye fish (*Macropinna microstoma*), having a compact size, transparent "head," and excellent vision. Our ROV emphasizes a small footprint while maximizing functionality to complete MATE objectives. We designed *Barreleye* using the latest digital twin technology, making extensive use of MCAD, ECAD, and simulation tools while developing model-based software control systems.

Our 2022 ROV is the product of relentless work from UWROV employees from September 2021 to June 2022. Throughout these last nine months, our team took lessons learned from our 2021 design and sought to improve on them. Our main objectives were to improve reliability, power density, mechanical packaging, enhance vision and manipulation capabilities, and refine our digital twin pipeline from planning through simulation and execution. The result: *Barreleye* is far more maneuverable, easy to control, and reliably deployable than any previous UWROV iteration.

***Barreleye* is ready to be deployed at the MATE World Championship!**

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Teamwork

Project Management

Company and Personnel Overview:

UWROV is a registered student organization at the University of Washington and is affiliated with the College of the Environment's School of Oceanography and the College of Engineering. We are an undergraduate engineering team that designs, builds, and competes with underwater robots in the International MATE ROV Competition.

Our team is organized into four **subgroups**: Business, Mechanical, Software, and Electrical. This year, we merged our Networking & Interfaces Subgroup with our Software subgroup to better reflect the shared knowledge and close interactions between our ROV operations and control systems.

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

Schedule:

MAY							
	Sun	Mon	Tues	Wed	Thurs	Fri	Sat
Week 6	1	2 Documentation Day	3	4 Submit MATE Application Pilot Practice	5	6	7
Week 7	8	9	10	11 Doc First Draft Pilot Practice	12	13	14 Doc Editing Session
Week 8	15 Video Submission Due Laser, Hydraulics, Release Valve Spec Due	16	17	18 Pilot Practice	19	20	21
Week 9	22	23	24	25 Pilot Practice	26 MATE VR World Assets Due Final Doc Submission	27	28
Week 10	29	30	31				

Props are on loan to MATE/MTS during these days.

Figure 1 (left): An example calendar developed for one month of the 2021-2022 season.

We value early planning as a cornerstone to successful engineering. Subgroup leads decide competition season deadlines in October, and each team is assigned a business representative to ensure accountability for deadlines. Team-wide goals inform subteam schedules, as shown in our chart (Fig. 2). This year, we emphasized earlier deadlines to support iteration. We moved our typical testing target forward from April to February with the goal of delivering a minimum viable product earlier. By treating our initial designs as a prototype, we could identify areas of enhancement while investing less time and resources.

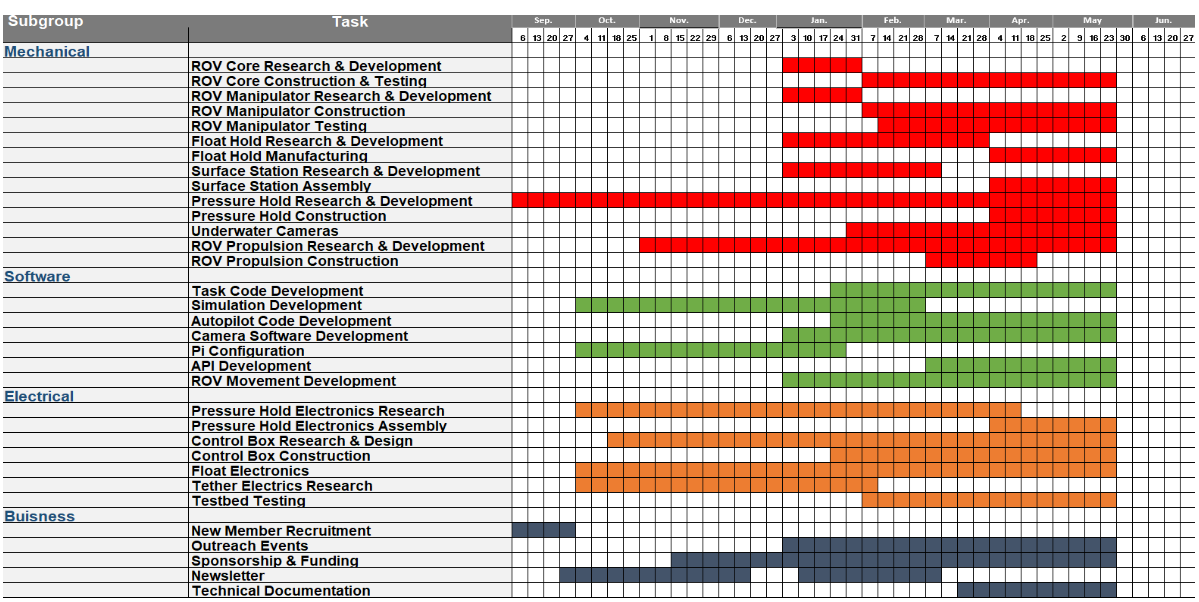


Figure 2 (left): A waterfall chart of subteam project timelines derived from overall team deadlines.

We also emphasized on regular testing in our schedule, ramping up from biweekly to weekly tests between our winter and spring quarter. Testing every two weeks during our build season in winter quarter allowed us to make large-scale adjustments to the ROV, while testing weekly in spring quarter allowed us to make rapid, smaller changes to optimize the performance of our ROV.

Resources, Procedures, and Protocols

UWROV employees work in **project-based subteams**, with representatives from across subgroups working to tackle ROV and MATE mission objectives. For example, Mechanical and Electrical subgroup members work together on our Float subteam to develop the model GO-BGC Float. Each subgroup has a Business representative to assist with communication, deadlines, documentation, and resource procurement (information, supplies, funding, etc.).

We also use various **software resources** to track team progress and manage team communication. This year, we integrated **monday.com** into our workflow to plan and follow the development of our ROV (Fig. 3). It greatly improves our productivity: employees can easily connect with available work, and leads get a bird's-eye view of overall progress.

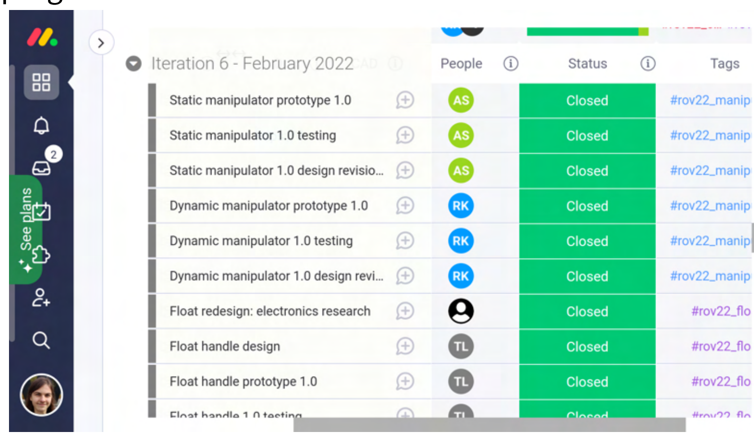


Figure 3 (above): Snapshot of the Mechanical subgroup's work completed in February on monday.com

We use the **Google suite** for file storage (Google Shared Drive), team-wide calendar (Google Calendar), document sharing (Google Docs), and email communication (Gmail). We communicate using **Discord**, with dedicated channels for subgroups and project subteams, and document design plans and post resources on a **MediaWiki** instance. For design work, we use **Onshape CAD** for mechanical design work and **KiCAD EDA** for electrical design work.

UWROV maintains a central **Constitution** with team organization procedures and protocols, including leadership elections, employee recruitment, and meeting frequency. This includes biweekly meetings for all leads to discuss progress and team objectives, followed by posting updates to Discord, laying out tasks, goals, and major design decisions.

Finally, UWROV requires all employees to follow team protocols for ROV construction and operation, including safety rules and ROV operations (see **Appendix A** and **Appendix B**).

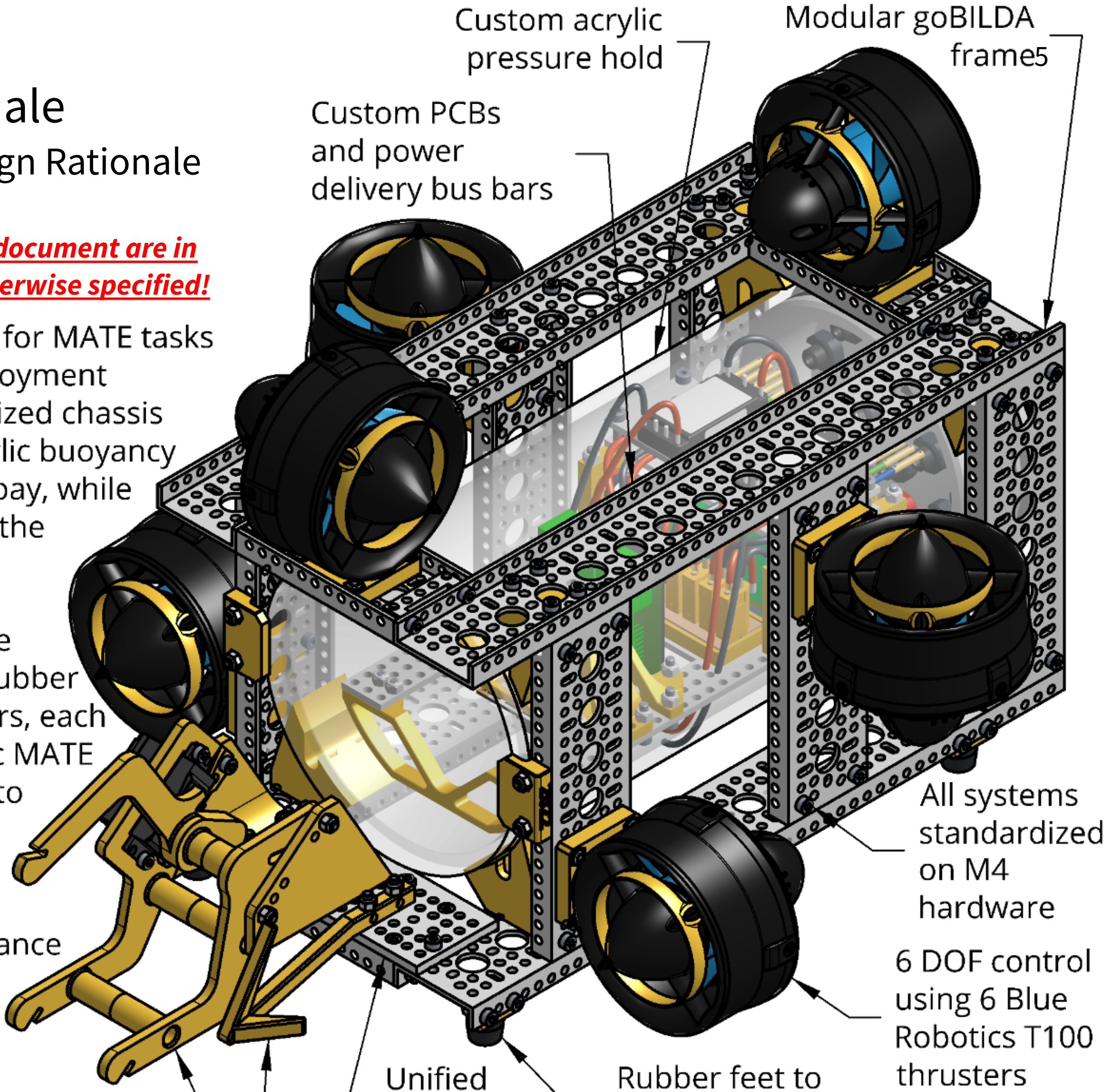
Design Rationale

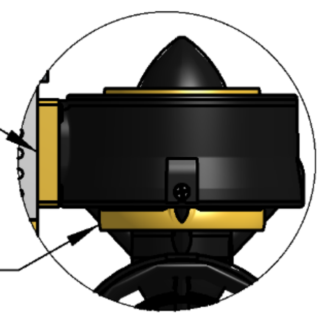
Engineering Design Rationale

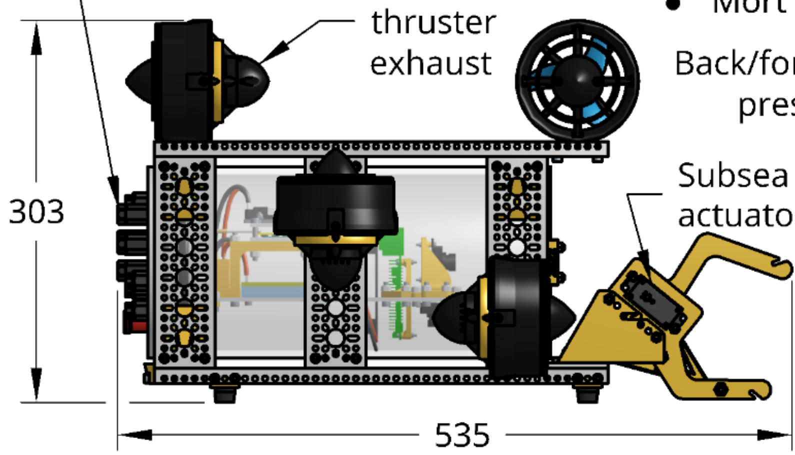
Design Overview

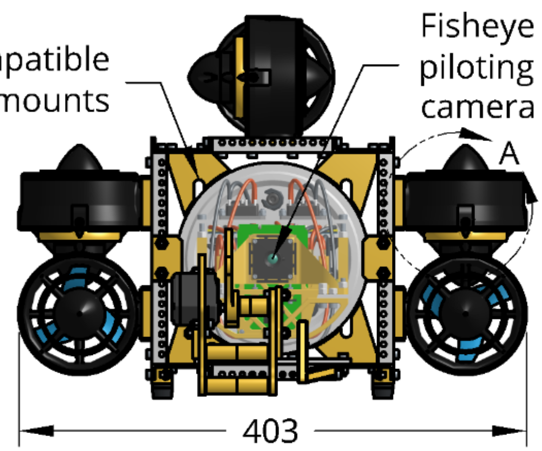
<u>All dimensions in this document are in millimeters unless otherwise specified!</u>

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. Dual manipulators, each specialized for specific MATE tasks, allow *Barreleye* to effectively complete a range of challenging missions, while digital cameras provide guidance to its autopilot and human pilot back on the surface.







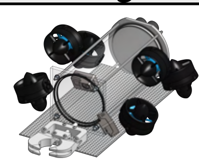
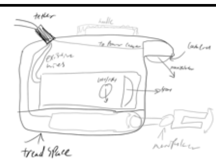
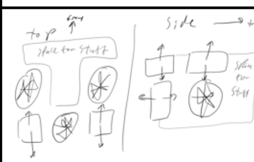
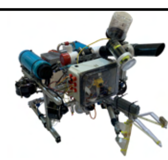


Conceptual Ideation and Selection Process

Before planning the details of our implementation (including Subsystem Design and Digital Mockup), we set the design direction for our ROV. We follow the following four-step process:

1. **Market Research & Concept Identification**
    - *Which designs are commercially successful? Successful at MATE championships?*
    - *What new and unique concepts can we come up with ourselves?*
2. **Competitive Analysis of Concepts**
    - *What works best in each concept?*
    - *What are functionality, implementation, and maintenance pain points?*
3. **“Best Aspect” Extraction**
    - *Which features do we love from each concept?*
    - *How could we blend ideas from all concepts into a greater one?*
4. **Design Guidance Development for key subsystems**
    - *What key decisions do we need to make for our design as a whole?*
    - *What guidance do we want designers to strive towards in their systems?*

Executive summary of **1. Concept Identification** and **2. Competitive Analysis** stages

Concept	Summary	Image	Advantages	Disadvantages
“Big Ol’ Plate”	Thrusters, claw, and pressure bay directly mounted to plate with rectilinear hole grid		+ Easy to mount stuff + Iteration-friendly + Low cost & simple + Easy to design	- Inefficient with mass - Not hydrodynamic - Structural concerns: flexing of plate
“Basically Hercules”	Frame with pressure hold, manipulator under ROV, and external camera bay		+ Commercially validated frame + Very sturdy + Great camera views	- Significant design complexity - Costly fabrication - High part count
“Ariana-I Inspired”	6 DOF control by axis-aligned thrusters recessed in frame; distributed electronics		+ Simple 6 DOF motor layout + Easy fabrication + Protected thrusters	- Hard to mount stuff - Little internal space - Challenging to integrate electronics
“Modular Rails”	Modular aluminum X rails (or other build system) focus on easy assembly & modularity	 *From Jesuit Robotics*	+ Easy to mount stuff + Easy fabrication + Easy assembly + Very easy to iterate	- Lower rigidity - Potential for sliding/ misaligned parts - Not very compact

Summary of **3. “Best Aspects” Extraction** discussion:

- Layout from “Big Ol’ Plate” — central pressure bay, front manipulator, side thrusters
- Structure of “Basically Hercules” — orthogonal frame enclosing pressure hold
- Thruster layout of “Ariana-I Inspired” — 6 DOF control from axis-aligned thrusters
- Construction methodology of “Modular Rails” — modular build system

Key **4. Design Guidance** for our design teams, developed from steps 1–3:

1. Key decisions for design direction:

Question	Consensus
Do we shrink, enlarge, or keep the same pressure hold dimensions?	Use the same size as last year for backwards compatibility.
Do we need 6 degrees of freedom of thruster control/movement?	Nice to have and aim to do this, but it's not necessary for a successful ROV, so it can be sacrificed if necessary.
Do we use a clear or opaque pressure hold?	Use a clear pressure hold to reduce risk if the underwater cameras project runs into challenges.
How many manipulators will we make?	Start with one, and add a secondary manipulator if development progresses rapidly on the first manipulator.

2. Important guidance for system developers based on lessons learned from previous years and materials found during concept research:
    - The ROV **must**: be easy to set down (ideally with rubber feet), have good downward visibility for navigation and imaging, have good visibility of its manipulators for task completion, have easy mounting points for ballasting and balancing, and prevent tether interference with water from thrusters
    - The ROV **should ideally**: have 6 degrees of freedom of control, be easy to take apart for shipping, use a build system where possible for ease of iteration, and use thrusters should be aligned with x, y, and z axes to simplify mounting brackets

Systems Approach

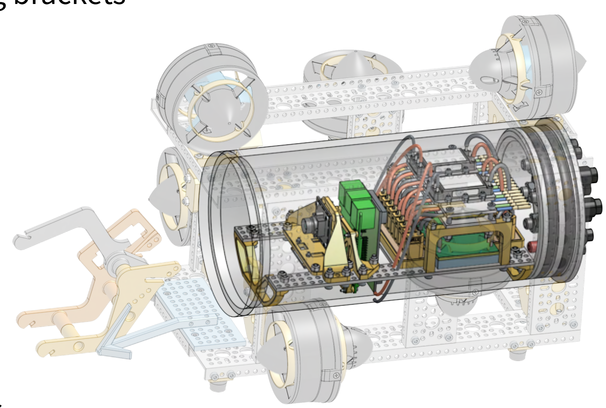


Figure 4 (right): The CAD model of our ROV, which includes a full digital copy of our electrical bay.

Barreleye is designed as a whole: rather than isolating mechanical, electrical, and software development, we make use of a **comprehensive digital twin system** to promote interdisciplinary collaboration across design teams. Electromechanical CAD integration allows us to:

- Perform virtual fit checks to ensure feasibility of designs
- Cut every wire to the right length without manual measurements
- Analyze camera visibility, thermal performance, and ease of assembly

We make extensive use of our CAD model in our software control system too. Our six degrees of freedom propulsion system would be challenging for a human to control manually, but our software lets the pilot "fly" *Barreleye* underwater with standard drone controls. These controls are derived directly from our CAD model's motor positions: if we reposition and/or reorient thrusters in CAD, we run a python script to automatically regenerate our new control mappings using linear algebra in numpy.

Our careful, analysis-based, highly integrated approach means that our systems work when they need to, without surprises. When we put *Barreleye* into the water to record our demo video, we completed all four tasks on our first practice run of the season, immediately followed by a successful 9-minute recorded run for our submission. This is thanks to having extensively tested subsystems individually ahead of time, while designing the ROV as an integrated, cohesive whole.

Vehicle Structure

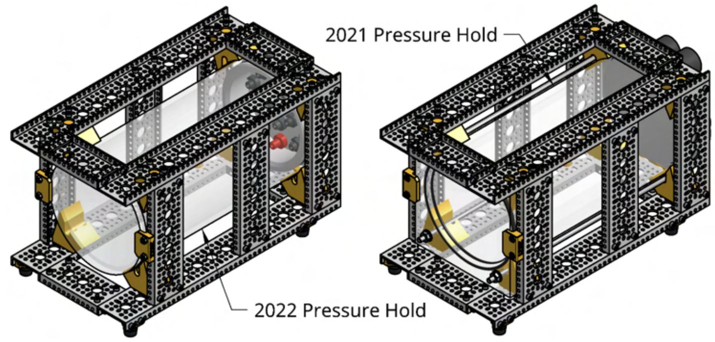


Figure 5 (right): Our 2022 frame can accommodate both our new 2022 pressure hold as well as our old 2021 one.

For *Barreleye*, we optimized the structure to be as minimal as possible to make deployment easier, allow maneuvering through tighter spaces, and to reduce drag. We balanced minimal size with ensuring the structure is forwards and backwards compatible between our new and old pressure holds, is easy to service, and has mount points for thrusters, manipulators, and other attachments (Fig. 5). By minimizing the ROV's dimensions, the components we need are reduced in size and quantity, resulting in lower cost and weight: a win on all fronts! The frame consists of **goBILDA Low U Channel and Side Block Mounts**, and is completely standardized on **M4 hardware** to improve serviceability. Some other quality-of-life improvements we made include:

- Flat bottom & rubberized feet prevents damage to poolside surfaces
- Frame can be **split** into two parts (top and bottom) with 12 easily accessible screws
- Open **mounting surfaces** on all sides for easy payload attachment

We also constructed a new pressure hold made fully out of custom parts. Both end caps were turned from stock material on a manual lathe, and the acrylic cylinder was also turned to break edges and flatten unevenness in sealing surfaces. By making a fully custom new pressure hold, we increased the volume available to electronics while simplifying the structure and reducing the number of seals, resulting in a far more robust and efficient design.

Vehicle Systems

We decided to use a build system based on our Conceptual Ideation and Selection Process. The following table contains an overview of four build systems we evaluated:

System	Performance				Ease of Development			
	Versatility	Strength	Weight	Bulky	Metric	Cost	Already in lab	Design Work
goBILDA	High	Mid	Low	No	Yes	High	No	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

We chose the **goBILDA system** because it offers the best possible performance. While goBILDA mostly scores poorly in ease of development, *Barreleye*'s top priority is good MATE task performance, so raising the development challenge to increase performance is favorable.

The up-front cost is higher with goBILDA than with other build systems but still significantly lower than building a fully custom frame with expensive manufacturing methods (such as SLS metal 3D printing, CNC machining, and composite materials). Additionally, goBILDA is fully reusable, so purchased components can be reused in future iterations.

Painting the ROV

This year, we experimentally tested multiple paint options and application methods to determine the safest option for the environment with the best visual outcome. We evaluated Krylon COLORmaxx "Matte

Sand Dollar" and "Shimmer Metallic Candy Grape" paints on a test goBILDA piece as well as simulated use through six hours of immersion in water. Aesthetics and durability before and after immersion are summarized in the following table:

Paint	Aesthetics	Durability (dry)	Durability (wet)
Sand Dollar - Unsanded	Fair	Fair	Moderate
Candy Grape - Sanded	Excellent	Moderate	Poor
Candy Grape - Unsanded	Excellent	Good	Fair

Because the paint did not stick well in any of the tests, we decided to postpone painting our ROV. In the future, we will evaluate self-etching primers to develop a safe painting strategy with excellent visual results that does not result in pollution from flaking paint.

Control and Electrical Systems

Electronic Design and Cabling

Our electrical system (Fig. 7A) emphasizes modularity, safety, and performance. Last year, our use of screw & spade terminals caused reliability and connection issues. Therefore, this year, we standardized all 48 V and 12 V power systems on XT60 connectors, all 5 V power systems on XT30 connectors, and all motors on 3.5 mm Bullet connectors. 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) designed using KiCAD EDA (Fig. 7B) to save space, improve efficiency, lower part count, improve reliability, and simplify mounting. The Pi Hat PCB (Fig. 7C) connects the Raspberry Pi to the ESC signal wires, BNO055 IMU sensor, 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. 6).

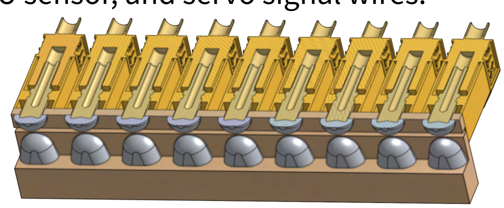


Figure 6: custom XT60 power delivery bus bar

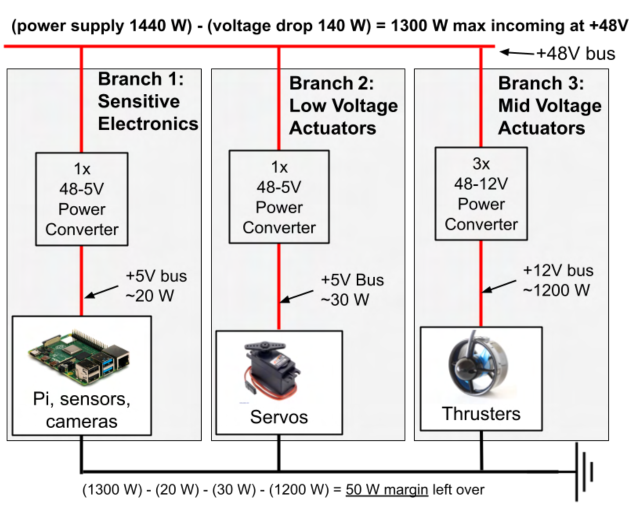


Figure 7A: ROV Power Flow Diagram

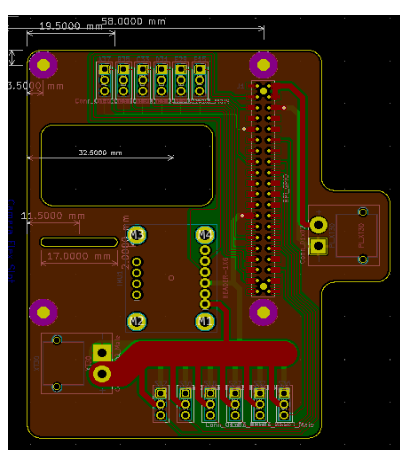


Figure 7B: Pi Hat in KiCAD

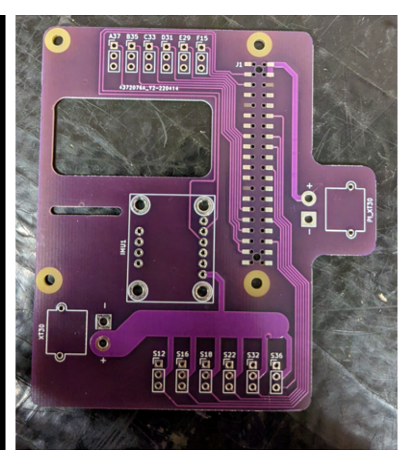


Figure 7C: Pi Hat PCB

Power Calculations:

Because we want to maximize the performance of our ROV, we want to use all of the allowed power we can draw. Our table of power allocations is as follows:

System	Power Draw	
Provided MATE Power Supply	30 A @ 48 V =	+1440 W
Tether efficiency losses to environment (voltage drop)	30 A @ 4.7V =	-140 W
Branch 1: sensitive low-voltage electronics, such as Raspberry Pi 4. Isolated from actuators to prevent damage from voltage spikes.	Pi with 4 cameras: -15 W IMU & future additions: -5 W	-20 W
Branch 2: low-voltage actuators	3x Servo, 2A @ 5 V	-30 W
Branch 3: Blue Robotics T100 thrusters	6x T100, 16.7 A @ 12 V	-1200 W
	Remaining margin for efficiency losses and future additions:	50 W

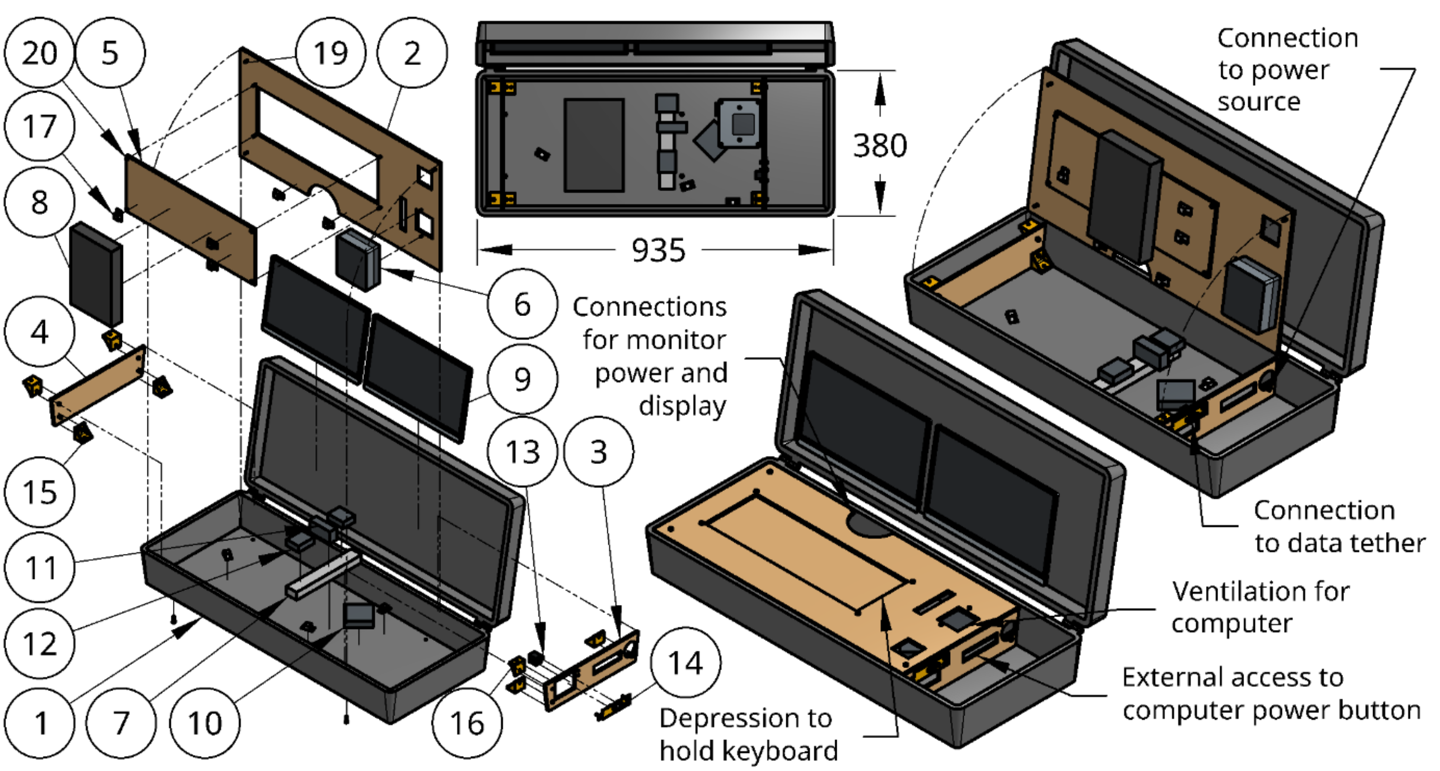
Thus, our ROV consumes 1390 W at peak load (31.99 A at the power supply). For our fuse, we calculated 31.99 A * 1.5 = 47.99 A for overcurrent protection, but are limited to a 30 A fuse for the MATE competition, so we use a **30A Littelfuse**.

Control Station

The surface station is the collection of equipment the pilot uses to operate the ROV. The 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. We meticulously planned our surface station using CAD software to lay out our electronics, design custom panel pieces, and ensure the station will be practical for the pilot to use (Fig. 8).

Figure 8A (right): Bill of Materials (BOM) for surface station.
Figure 8B (below): CAD Model of our surface station.

Item	Name	Quantity
1	Pelican 1700 case	1
2	Top platform	1
3	Right wall	1
4	Left wall	1
5	Keyboard support	1
6	NucBox 2 Mini PC	1
7	Power Strip	1
8	Router	1
9	15.6'' portable monitor	2
10	PC power supply	1
11	Router power brick	1
12	USB-C 15 watt power brick	2
13	Ethernet extension cable connector	1
14	3D printed ethernet extender mount	1
15	3D printed bracket	6
16	3D printed bracket	1
17	Command wire management clip	9
18	M3 screw	2
19	M4 16mm screw	22
20	M4 hex nut	20



Control System Software

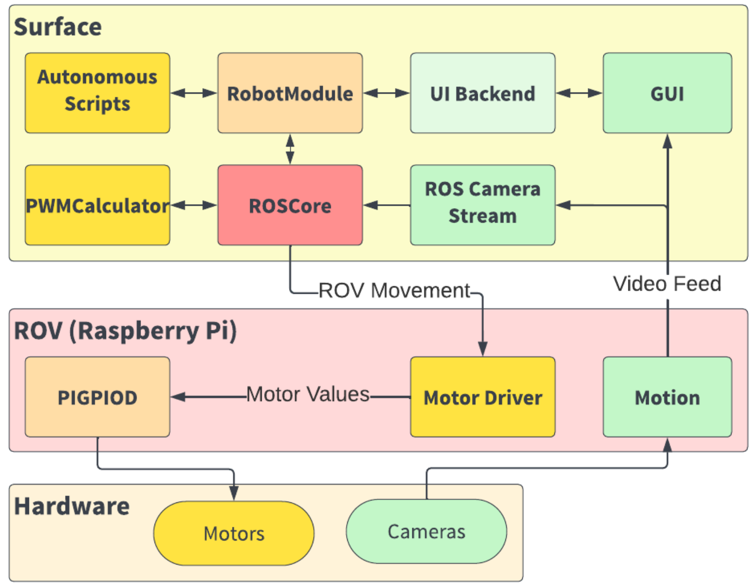


Figure 9 (right): Overview of Barreleye's *control system flow.*

Barreleye uses the industry-standard **Robot Operating System (ROS)** to handle communication between the robot and our surface station. The main control system has been organized into many small scripts that manage individual functionalities, which simplifies development and increases modularity (Fig. 9).

The manual control system consists of an interface (**GUI**) and a server (**UI Backend**) that bridges the interface with our robot's API. The interface displays the camera feeds (provided by **Motion**) and sends commands from a controller to the robot system. The interface is built from React and provides modular components that can be displayed on the window. The server uses the **RobotModule** API to send commands to the robot control system.

The **autonomous control system** is a set of individual scripts that act as autonomous agents through the robot control system API. These scripts send the same commands as a manual controller, and priority is decided by RobotModule. Using the RobotModule, autonomous scripts can also pull image and sensor data to make decisions based on the task at hand to move the robot, manipulate images, and make decisions regarding autonomous task completion. Example usages include line following, autonomous parking, and mapping of spaces.

We developed an innovative **ROV simulator** to allow for rapid prototyping of new ROV designs, motor configurations, and movement testing, using the Gazebo library. With the simulator, we can upload new CAD files of ROV designs and position motors arbitrarily around the model. This allowed rapid prototyping and testing of frame designs and propulsion configurations.

Tether Construction

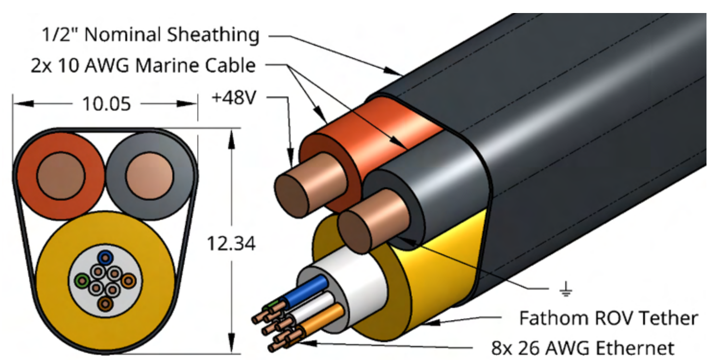


Figure 10 (right): A digital 3D model and cross section of our tether configuration. Dimensions are given in mm.

Barreleye's tether transports power and data while minimizing weight and maintaining flexibility. For data, a **Blue Robotics Fathom ROV Tether** serves as a CAT 5 ethernet cable, chosen for its flexibility, self-healing from damage, 80 lb allowable working load, and neutral buoyancy. For power, **10 AWG UL 1426 marine-grade wire** offers the best efficiency-to-weight ratio for our 48-volt system, with two separate cables used for compatibility with WetLink Penetrators. Its PVC jacket and tinned copper conductors allow subsea immersion. The tether's outside sheathing is made of braided, expandable polyester, chosen for its excellent durability and flexibility. We selected ½" nominal sheathing based on the estimated outside perimeter of the tether, determined by our CAD model (Fig. 10).

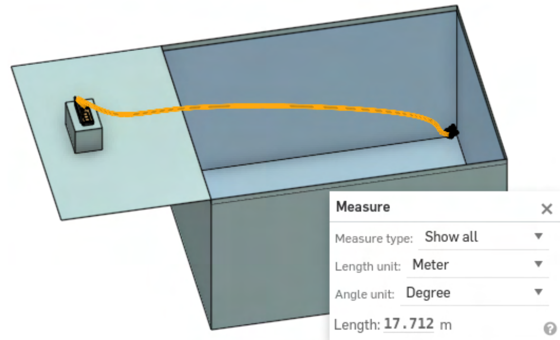


Figure 11 (right): A digital mockup of the MATE-provided pool specifications, showing a minimum tether length of 17 m. This was rounded to a total length of 20m to allow for additional margin.

Our 20m tether allows the ROV to reach the entire MATE-specified competition pool (Fig. 11). Keeping our tether no longer than necessary reduces tripping hazards and increases power transfer efficiency. Voltage drop over the power lines in the tether is at most 4.7V (resulting in 141 W of power loss) when the ROV pulls 30 A. Therefore, at least 43.3 V are always available in the ROV, above the 36 V minimum for our power converters.

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, Fig. 19C).

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, ethernet first, then power.
4. Ensure strain relief is correctly installed on both surface station and ROV.
5. While operating ROV tether tender must always have contact with tether.
6. The 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. While operating the ROV never rotate the tether more than 360 degrees.
8. Avoid weaving around obstacles as this could cause the tether to become entangled.
9. Do not pull on the tether to clear a snag.
10. Never step on the tether, this could cause bits of dirt to grind into it.
11. Once operations are completed, tether tender is in charge of disconnecting the tether from the surface station and power.
12. After disconnection, the tether tender coils the tether.

Sources: (Christ & Wernli, 2013; Moore, Bohm, & Jensen, 2010)

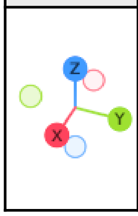
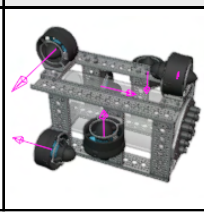
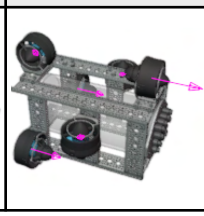
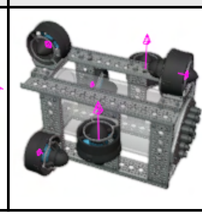
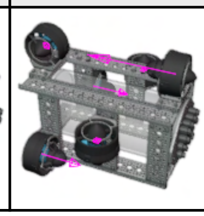
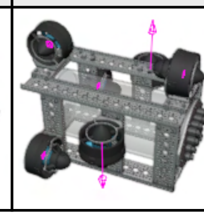
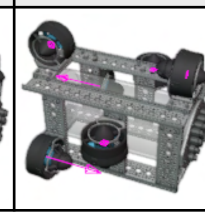
Propulsion

For our thrusters, we selected **Blue Robotics T100** thrusters for their moderate cost, on-hand availability from last year (enabling reuse), and good efficiency at lower power levels. Each consumes no more than 200 W at 12 V, staying within our total power budget of ~1.3 kW for the ROV's onboard systems, but still provides roughly 25 N of peak thrust. With this year's upgraded IP2X motor safety shrouds, thruster efficiency is further improved, so T100s are fully sufficient for *Barreleye*'s mission of completing MATE tasks in a relatively small pool. Also, we designed our thruster mounts to be standardized and interchangeable for faster repairs.

For placement, a goal for *Barreleye* is Six Degrees of Freedom (6 DOF) motion while keeping the ROV structure and thruster mounts simple. We mocked up various options in CAD, inspired by the Ariana-I ROV, to identify mechanically feasible possibilities. To control 6 DOF, at least 6 thrusters are required. We chose to use 6 thrusters to minimize our ROV's size:

- **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 between the surface and pool bottom
- **X axis (left/right)**: 1 thruster used lateral motion only required for slow, precise alignment tasks, such as MATE tasks 1.1 (Cable array inspection) and 2.1 (Aquaculture pen inspection).

We then selected positions on the ROV that allow full control over rotation in addition to translation, as shown in the following table. It was generated from a custom Python script we wrote that calculates thruster powers given some requested motion.

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

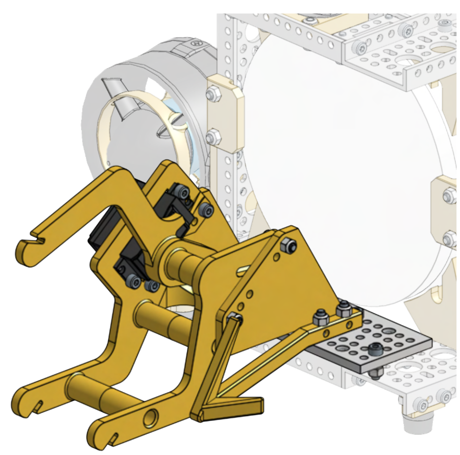
Buoyancy and Ballast

Through our use of a digital twin CAD model, we ensured only minimal buoyancy adjustments would be necessary after construction. The volume of our ROV is estimated by our CAD model to be 8.06 liters (8.06 kg of fresh water displaced), and its mass is estimated to be 7.65 kg. The difference of 0.41 kg is the ballast required to make the ROV neutrally buoyant in freshwater.

The large, air-filled electronics pressure hold also serves as our main buoyancy module. This significantly reduces cost and complexity. For minor buoyancy increases, we use syntactic foam, which better resists pressure than the plastic, closed-cell foam used in our 2021 ROV, enabling more consistent buoyancy across depths. By reducing the weight of our pressure hold from 3.4 kg to 2.2 kg compared to last year, we have almost completely eliminated the necessity of foam to adjust the ROV's balance. For ballast, we attach adjustable bottles of ball bearings to *Barreleye*'s modular frame for quick and precise tuning of our center of mass.

Payload and Tools

Figure 12 (right): CAD Model of the dynamic manipulator.



Barreleye has two manipulators in a combined manipulation package: **a static manipulator** and a **dynamic manipulator** mounted to a custom baseplate. Both were designed from the ground up with specific MATE tasks in mind. The static manipulator is optimized for extraction tasks, such as pulling out ghost net pins and algae loops, while the dynamic manipulator is optimized for precision handling tasks, such as planting seagrass and repairing energy infrastructure.

Dynamic Manipulator

The dynamic manipulator has two **stationary lower prongs** and one **servo-actuated middle prong** (Fig. 12 & Fig. 13). Elastic bands provide friction, distribute loads evenly, and conform to the shape of handled objects. We chose this configuration because it minimizes space usage and manufacturing complexity without sacrificing performance.

Figure 13 (right): Two iterative prototypes of the servo-actuated middle prong. The left notches on the red prong were selected based on tests with MATE mission objects.

We iterated through multiple prototypes with varied prong geometry and placement of elastics, which underwent qualitative assessments of ease of use and tenacity of hold with MATE mission objects (Fig. 13). These included manipulating morts, PVC pipes, and the GO-BGC float handle. We found that having a hard tip protrude in front of the elastic combined with parallel elastic bands allowed the gripper to pull in and retain objects most effectively. We also found in testing that twisted elastic increases tension and grip.

Our team experienced difficulty with pneumatics last year due to the significant complexity introduced in the tether and manipulator and the bulkiness of pneumatic equipment. As a result, we chose to use an **electrical servo** for space savings, simplicity, and design flexibility. We considered multiple powertrain options, including gears, belts, chains, and direct drive. We ultimately opted for a **direct drive** because it eliminated the need for set screws, gears, clamping collars, or other powertrain hardware. For waterproofing the servo, our options were either (1) building a housing around a non-water-resistant servo or (2) upgrading a water-resistant servo for continuous use in subsea conditions. We chose to **waterproof the servos** due to reduced cost and complexity, and validated waterproofing with a 72-hour immersion test.

Static Manipulator

Figure 14 (right): Several iterations of single-pronged static manipulators, precursors of our 4 prong hook design.

The static manipulator is a **four-pronged hook** attached to the front of the ROV, with each prong at roughly 70 degrees. We chose this configuration after multiple iterations of testing (Fig. 14). We first used cardboard prototypes to test different hook shapes, 3D printed the best shapes to test various angles and orientations with MATE mission objective objects. The '7' shaped hooks with the opening to the side worked best for the intended tasks, the smaller one being better at pulling algae and the larger one being better at picking up mission objects with D-rings. We initially went with the larger shape because of the versatility of object interaction, but during underwater testing found that this design had difficulty releasing mission objects like seagrass. As a result, we delegated that task to the dynamic manipulator and specialized the static manipulator for pins. We found that four prongs were most effective for handling varying pin angles.

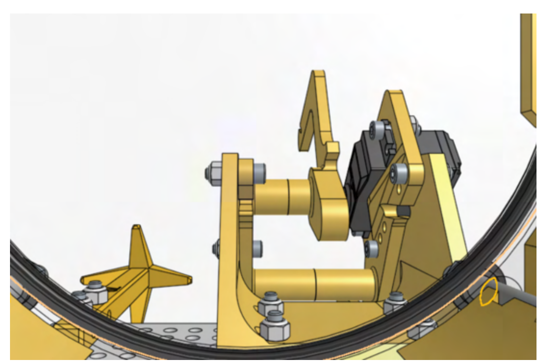


Figure 15 (right): A digital recreation of our front-facing camera feed used to simulate manipulator visibility.

Float Design

Figure 16 (right): A CAD model of our float design.

We developed a **model GO-BGC float** with a pneumatic **buoyancy engine** to complete vertical profiles (Fig. 16). We chose to use pneumatics instead of a linear actuator to reduce float complexity. Two pneumatic pumps move air out of the pressure hold and into an external balloon, allowing the float to change its density and float or sink in the water. These pumps are controlled by an Adafruit Circuit Playground, which enables us to connect to the float via Bluetooth to initiate vertical profiling. We also developed a **custom PCB** to manage power and data signals and to reduce the weight of the float for easier ROV handling. This PCB went through several iterations of testing and refinement.

Cameras

Our goal with the camera system was to increase contextual awareness underwater. We used **four cameras** because having more camera angles enables us to safely navigate sensitive aquatic environments. We initially considered using multiple Raspberry Pi devices to share the camera processing load, but after testing we found that one Pi alone is capable of running four camera streams at a high quality and framerate suitable for competition tasks (640p, 30fps).

We used one **Raspberry Pi camera** and three **Blue Robotics USB fisheye cameras**. The Raspberry Pi camera uses the Pi's Camera Serial Interface (CSI), allowing video data to be directly processed by the Raspberry Pi's GPU and greatly improving performance. Since the Raspberry Pi only has one CSI port, the rest of the cameras use the USB interface. The fisheye cameras allow for a wider field of view to assist ROV operators in preventing damage to environments such as the wreck of the Endurance. To make our camera stream usable for competition tasks, we employ a de-fisheyeing procedure calibrated to our cameras.

Our cameras are placed to face **forward**, **downward**, and to **both lateral sides** of the ROV. The forward-facing camera is essential for piloting and observing the manipulator, and its perspective is utilized in all tasks (Fig. 15). The downward-facing camera helps judge ROV's depth in the water and view the bottom of the pool without pitching down. The side cameras help avoid collisions with delicate surroundings.

Camera Position	Tasks Handled
Front-facing	1.1 Replacing damaged section of inter-array power cable 1.2 Replacing damaged buoyancy module 1.3 Monitoring the environment 1.4 Piloting into ROV docking station 2.1 Inspecting offshore aquaculture fish pen 2.2 Maintaining a healthy environment 2.3 Measure fish size 2.4 Farm seagrass 3.1 *MATE Floats!* 3.2 Endurance22
Downward-facing	2.2 Maintaining a healthy environment 2.4 Farm seagrass 3.2 Endurance22
Side-facing	3.2 Endurance22 (*Collision prevention*)

Sensors

We chose the **Adafruit BNO055 Breakout** to assist in autonomous navigation. It provides absolute orientation, angular/linear acceleration, and angular velocity. While slightly more expensive than the **Ximimark 6 DOF IMU** sensor we used previously, in our tests the Adafruit IMU Breakout gave much more accurate readings without accumulating sensor drift over time. IMU data is used to calculate corrections for autonomous movement which is required for line following, parking, and mapping of the wreck site.

Build vs. Buy, New vs. Used

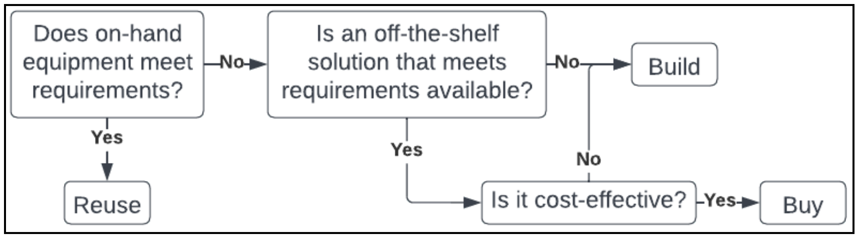


Figure 17 (right): UWROV Build vs. Buy,New vs. Used Decision Process

Table of Reused Purchased Systems

System	Justification
Thrusters	Blue Robotics T100/T200 thrusters exceed propulsion requirements.
Raspberry Pi	Raspberry Pi we have on hand for our control system has sufficient I/O and compute performance to control all ROV systems and stream camera data.
12 V Power	General Electric 12 V power converters we have on hand meet requirements.
Float Housing & End Caps	The float design trade study we conducted led us to determine that last year's structure was close to optimal for this year's task, so it meets requirements.

Table of New Purchased Systems

System	Justification
5V/12V power converters	Replaced non-functional power converters with additional spares.
Cameras	Purchased fisheye cameras for improved visibility and navigation, and for USB-compatibility with the Raspberry Pi 4.
ESC Motor Controllers	Replaced our discontinued ESC Motor Controllers with the Blue Robotics ESC Controllers for greater reliability and replaceability.
WetLink Penetrators	Penetrators took up a smaller footprint on our pressure hold, allowing for more port capacity for the manipulators and servo.
Surface Station Computer, Monitors	Upgraded computer can run computer vision algorithms for associated Product Demonstration Tasks; expected to last 5+ years.

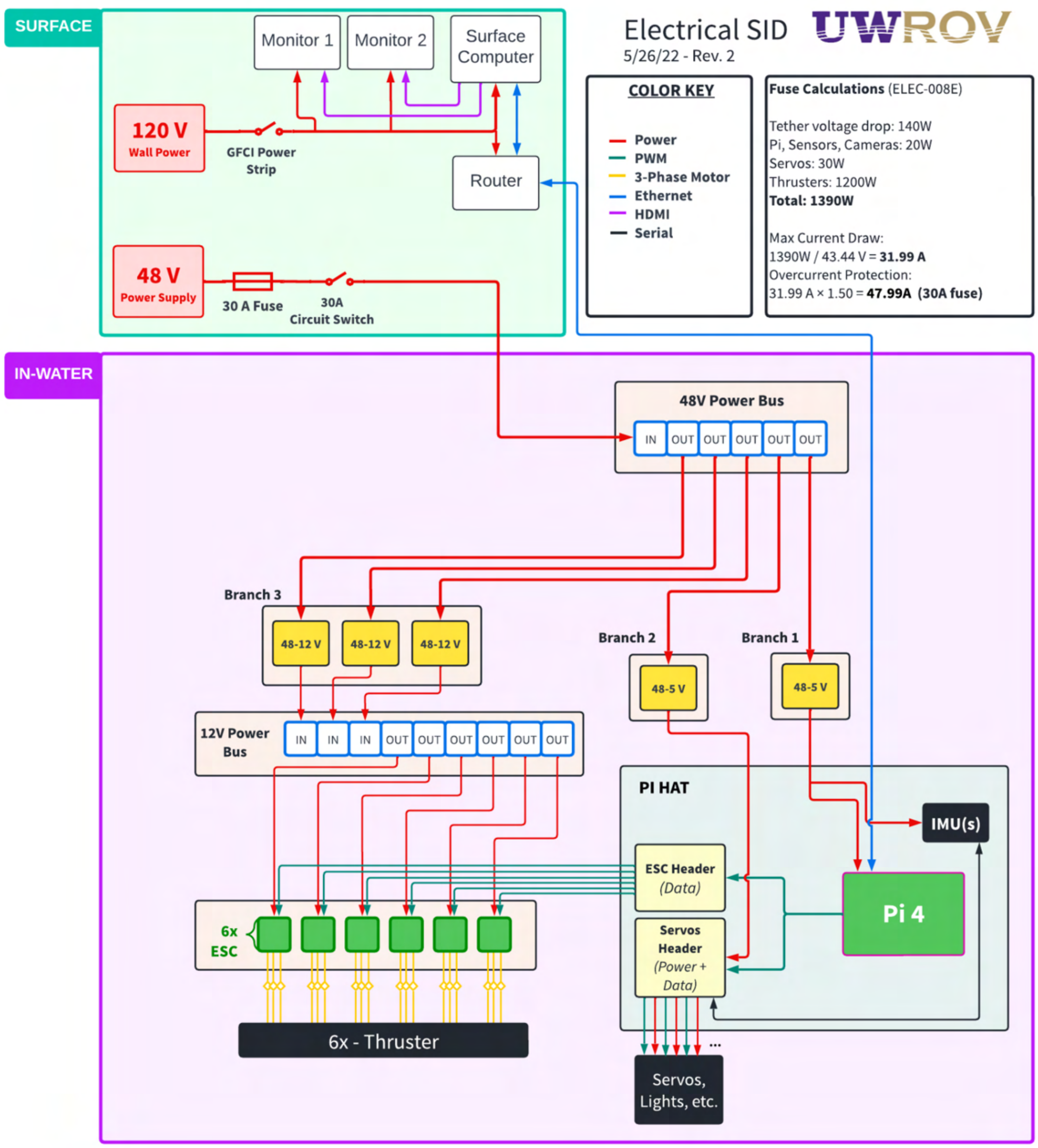
Table of New Custom Built Systems

System	Justification
Manipulators	Off-the-shelf manipulators like the Blue Robotics $590 Newton Subsea Gripper are available, but they are both general purpose (*not* specialized for MATE tasks) and prohibitively expensive. We can build a better option ourselves.
Pressure Hold	We chose to make a new pressure hold this year for improved seal reliability and reduced mass, but made it dimensionally forwards and backwards compatible with last year's design to make electronics development easier.
Power Delivery Bus Bars	No off-the-shelf power delivery bus bars were available that met our specifications (100 A power overall, XT60 connectors), so we made our own.

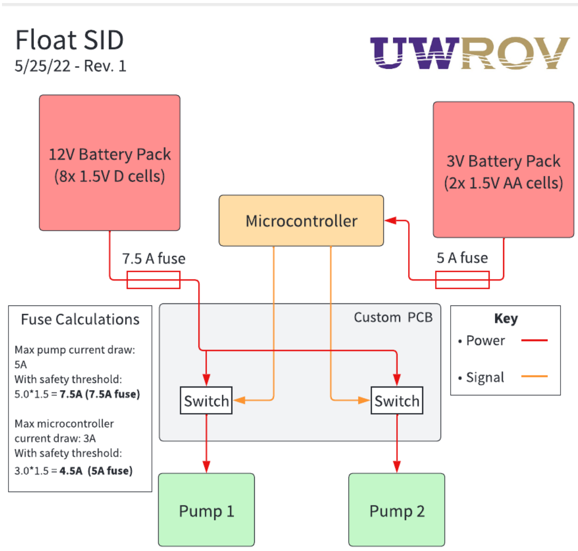
Custom PCBs (Float and Pi Hat)	We decided to use custom PCBs to save space and weight. By their nature, they must be custom-designed for this year. Fabrication was outsourced to JLCPCB.
Thruster Shielding	No *efficient* existing IP2X shields for our thrusters available to buy or download.
Thruster Mounts	Blue Robotics thruster mounts for goBILDA are not commercially available.
Electronics Bay	Our electronics system and its support structure were custom-designed for this year's competition, so no off-the-shelf solutions are applicable.
ROV Structure*	Off-the-shelf ROV structures are far too large for our size minimization goal.

**We designed and built the frame ourselves, but by the nature of COTS modular build systems, they contain significant quantities of purchased components that are not made in-house.*

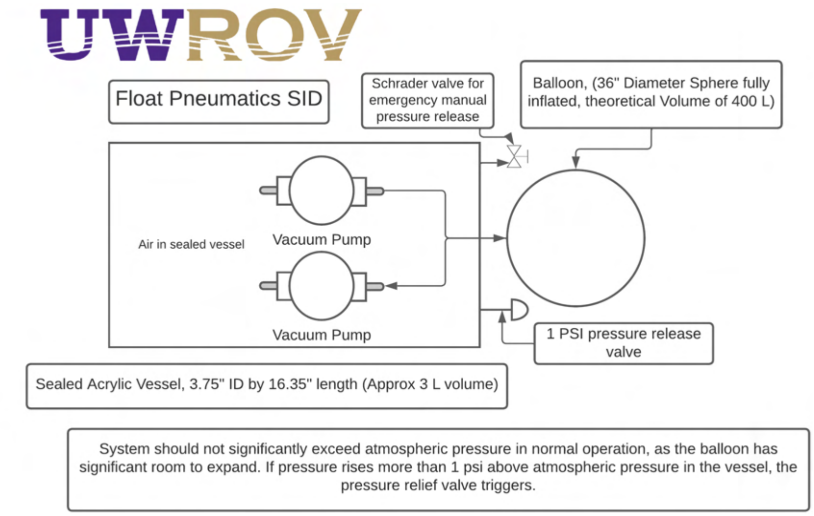
System Integration Diagrams (SIDs)



ROV Electrical SID



Float Electrical SID



Float Pneumatics SID

Safety

Personnel and Equipment Safety

For the majority of the design development portion of the creative process, we were able to meet in person. However, in January 2022 when COVID-19 cases were surging, we experienced a month of socially distanced virtual learning. We prioritized COVID-19 Omicron safety with virtual team meetings and small-group construction meetings on the ROV when absolutely necessary. Any meeting that did not require physical work was kept online for the safety of employees. Furthermore, even when the mask mandate was lifted in the spring, UWROV continued to remain masked to ensure employee safety.

We require all employees to go through a **mandatory lab safety training** before they are permitted to work in the lab, which covers the following topics:

- Locations of first aid, fire extinguishers, and eye showers
- Contact information for lab supervisors and accident procedures
- Required PPE (safety glasses) and lab attire (close-toed shoes)
- Storage locations for chemicals
- Tool usage rules for the hacksaws and other hand tools

Additional **one-on-one training sessions** were held for power tools like soldering irons, drills, and drill presses so employees could practice safe equipment use in a hands-on environment. A complete list of the UWROV lab rules is included in this document (see **Appendix B**).

Drop-in inspections by our Safety Officer are performed several times per week to ensure employee compliance. Additionally, employees were also required to complete a follow-up reading quiz, which covered MATE safety policies and the Explorer competition specification.

Operational Safety

We performed a **Job Safety Analysis (JSA)** to identify potential hazards during ROV operation and implemented operational procedures to control for these risks (Oceaneering, 2013). Pre-launch rules include clearing loose debris to reduce falling hazards, tying back loose hair or clothing to prevent pinching or catching, and verbal calls before ROV power is turned on to prevent injuries from the thrusters. These hazard controls were codified into **operational checklists** used during all launch and recovery operations (see **Appendix A**, *ROV Operation*) (Fig. 18).

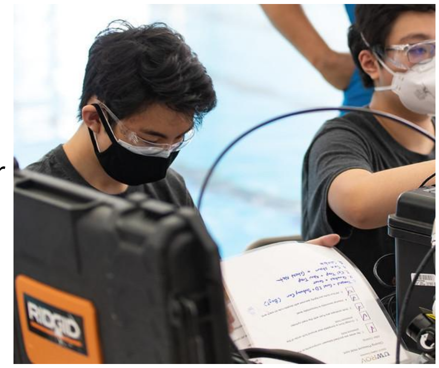


Figure 18: Operational safety checklists in use by a UWROV employee.

Vehicle Safety Features

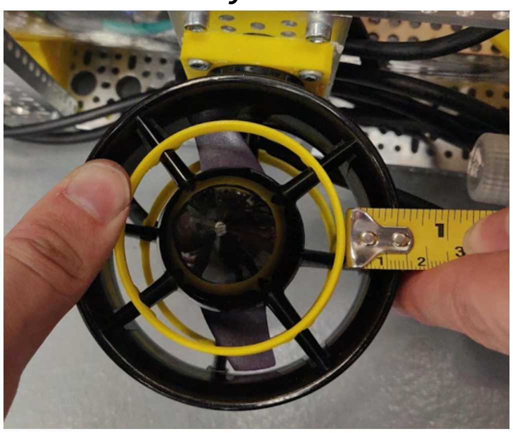


Figure 19A (above): Our 3D-printed thruster shielding leaves no openings >12.5 mm, complying with IP2X.

Figure 19B (above): Warning labels on thrusters follow ANSI Z535.3-2011 for safety symbols (ANSI, 2011).

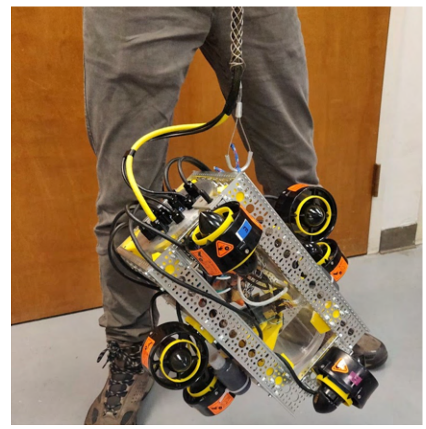


Figure 19C (above): The ROV can be safely lifted by the tether via the strain relief system

Barreleye's outer structure is designed with a number of safety features. We designed and 3D-printed our own **thruster intake shields**, which conform with the IP2X standard (max opening size of 12.5 mm) and prevent finger injury from the thrusters (Fig. 19A). **Safety warning labels** compliant with ANSI Z535.3-2011 are placed on all ROV hazards, most notably the thrusters (Fig. 19B). All sharp edges on the frame are filed, and *Barreleye* features **soft rubber feet** to prevent damage to poolside surfaces when not in use.

Barreleye's wiring complies with the NASA Workmanship Standards (NASA, 2002). All electrical connections are done via enclosed connectors or with a lineman splice that is flooded with solder and protected with heat shrink. This minimizes exposed electrical connections within our pressure hold. **Tether strain relief** on both our surface station and ROV prevents connections from coming undone due to force (Fig. 19C). A **braided cable sleeve** prevents tether abrasion and reduces tripping hazards from loose cables.

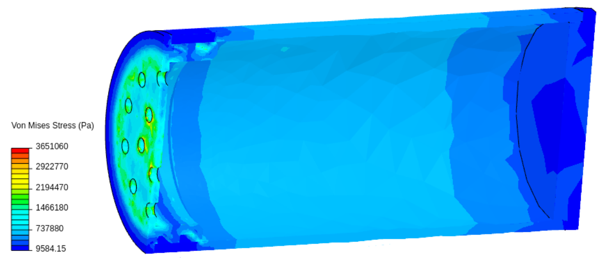
Our task-related payloads are also designed with safety features in mind. Our static and dynamic manipulators feature rounded corners to prevent scratch injuries to personnel or pool equipment, and use soft materials like rubber O-rings. This prevents damage to deployment environments like the aquaculture pens in Task 2 (Aquaculture). Additionally, the model GO-BGC float (developed for Task 3.1) comes equipped with a 1 psi **pressure release valve** to safely release gasses in the event of a battery malfunction.

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**).

Critical Analysis: Testing & Troubleshooting

Figure 20 (right): Finite Element Analysis (FEA) conducted on Barreleye's *pressure hold design.*



We tested *Barreleye*'s systems extensively both before and after integration. Our main strategy is **"first isolation, then digital evaluation."**

For example, in component (isolated) testing, we found high resistance on one contact of our custom bus bar using a multimeter (digital evaluation), allowing us to preemptively repair a potential safety and performance issue. Also, before building our new, radically redesigned pressure hold, we ran a **Finite Element Analysis (FEA)** study to ensure structural integrity (Fig. 20). We found that by spacing the inner holes further apart than the outer ones, we could increase strength and reduce the thickness and mass of the part with zero additional manufacturing complexity. For our autopilot software, we use **Docker** to allow us to run and test our on-ROV code on any Linux system (isolation), not just on Raspberry Pis. We then use **Gazebo** to simulate and validate our software before testing on the physical ROV (digital evaluation).

We also use prototypes across all three engineering subgroups. Before ordering a custom in-house designed PCB, Electrical projects are physically prototyped with breadboards and protoboards, as well as digitally with **KiCAD EDA**. Mechanical team creates parametric CAD models using **Onshape Configurations**, then 3D prints many prototypes with a parameter sweep and runs a battery of physical strength and performance tests to identify the best option. Software team mocks up control and vision systems such as our autopilot using **Godot Game Engine**, allowing for easy, low-code concept development and testing.

Accounting

Budget

We began the 2022 season with roughly 1.5 times the number of employees we had in 2021, so we scaled up our **Team Operations** costs to match. Additionally, we created budget categories for **Lab Safety** to improve safety conditions in our manufacturing lab space, with a major focus on electronics safety and ventilation. Our **Tooling & Equipment** budget was more than doubled this year in anticipation of a greater number of employees using our lab spaces simultaneously (roughly 2.5x due to the lifting of COVID gathering restrictions), and was also used to replace and augment aging equipment. Our **travel** estimate likewise increased for multiple reasons. This included accommodating increases in the number of traveling employees(up to 11 from 7 our previous year), lodging costs in the World Championships area, and airfare.

We also reorganized categories of our budget to reflect the changing needs of our team, which has shifted towards interdisciplinary project-based subteams (Float, ROV Structure, etc.) rather than subgroups. This can be seen in the separate **ROV Surface Station**, **ROV Structure**, **ROV Electronics**, and **Float** budgets.

Travel Estimate				
Category	Description	Cost	Qt.	Subtotal
Airfare	Reimbursement per employee	$400.00	12	$4,800.00
Lodging	Lodging rental, per night (AirB&B)	$569.28	7	$3,984.99
Van Rental	Rental for a 7-seater van (Enterprise)	$626.47	1	$626.47
Car Rental	Rental for a 5-seater car (Enterprise)	$423.84	1	$423.84
			Total:	**$9,835.30**

Budget Allocation			
Category	Description	2021 Allocation	2022 Allocation
Lab Safety	Safety glasses, labels, ventilation, gloves, etc.	N/A	$800
Tooling & Equipment	Multimeters, wire crimpers, drills, etc.	$1000	$2500
Electronics R&D	Research and development for subteams	$300	$900
ROV Surface Station	Case, computer, router, controller, etc.	$1700 *(Merged Manuf. Budget)*	$800
ROV Structure	ROV tether, frame and pressure hold		$1,000
ROV Electronics	Onboard computer, power converters, cameras, etc.		$500
Float	Pneumatic pumps, onboard computer, etc.		$200
Team Operations	Team branding (shirts/polos), domain hosting, etc.	$400	$600
Business Outreach	Costs associated with outreach events, including transportation, power, and activities.	$70	$300
Competition Logistics	Shipping costs for the ROV and printing costs for competition materials.	$200	$250
Competition Fees	Registration fees for the MATE ROV Competition	$425	$425
Competition Travel	Transportation	$3,000	$10,000
	Total:	**$7,095**	**$18,275**

Cost Accounting: See Appendix C

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Acknowledgements

We are incredibly grateful for the help and support we have received this year, and would like to thank the following organizations and people for their contributions:

- **The University of Washington School of Oceanography** for its continual support of our team and for providing laboratory space for UWROV,
- **Rick Rupan** for supervision and guidance throughout our club's development,
- **The MATE Center** for their dedication to enriching student learning & outreach in ocean technology,
- And our sponsors, who have provided generous in-kind and financial support:

Student Technology Fee

Mary Stewart

King-Hwa & Eleanor Lee

Appendix A: Safety Checklists

ROV Construction:

Disassembly:

- ☐ Power supply is off (announce "POWER OFF").
- ☐ Outside of pressure hold is completely dry.
- ☐ Work surface is free from tools or (metal) debris.
- ☐ Static electricity discharged by touching a metal surface.

Assembly

- ☐ Assembly is powered off and no power cables are connected.
- ☐ 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 scratches, 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.
- ☐ 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.
- ☐ All four bolts are tightly secured with wrenches.

ROV Operation:

Pre-Deployment:

- ☐ All ROV connections are screwed securely.
- ☐ No pressure hold ports are exposed.
- ☐ There is no damage in the ROV frame or pressure hold.
- ☐ All ROV attachments (motor shrouds, floats, weights, motors) are secure.
- ☐ There are no loose connections in the pressure hold.
- ☐ All connectors are screwed on tightly.
- ☐ Color-coding on the motor connectors match.
- ☐ The tether is laid out neatly without knots or tangles.
- ☐ Battery/power supply is completely dry and away from the side of the pool.
- ☐ Control box connectors are screwed in tightly.
- ☐ Control box is stable and on a level surface.
- ☐ Control box computer and router are plugged in and powered on.
- ☐ Control box monitor is securely in place and connected.
- ☐ All pool operators have close-toed shoes, safety glasses, no loose clothing, and long hair tied back.
- ☐ Recovery equipment (pole, net, etc.) handy.
- ☐ Poolside is 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
Community Funding	Sound Water Stewards of Island County	$500.00
Community Funding	King-Hwa and Eleanor Lee	$250.00
Community Funding	Mary Stewart	$100.00
Community Funding	Anonymous Donors	$100.00
Grant	Student Technology Fee Grant	$7,920.00
Sponsorship	foundry10	$7,225.00
Sponsorship	Applied Physics Laboratory	$3,000.00
Sponsorship	Washington Sea Grant	$1,000.00
Sponsorship	Marine Technology Society (MTS)	$424.00
	Total:	**$22,783.85**

Donated, Discounted, and Waived Items:

Budget Category	Donor	Item	Est. Value
Tools and Supplies	MODE Studios	LulzBot Mini 2 3D Printer	$1,495.00
Tools and Supplies	Digilent	Logic Analyzer Student Discount	$69.92
ROV Surface Station	UW Oceanography	Pelican Case	$319.95
ROV Structure	goBilda	goBilda Student Discount	$45.60
Float	UW Oceanography	Pneumatic Pump	$49.90
Team Operations	UW Oceanography	Team Freebies	$40.00
MATE Registration Fees	MATE	Explorer Registration Fee	$400.00
		Total:	$2,420.37

Reused Items:

Budget Category	Item	Est. Value
Electronics R&D	Raspberry Pi 3B Kit	$54.95
Surface Station	Xbox Controller	$30.00
Float	Float Housing and Endcaps	$150.00
ROV Frame	Syntactic Foam	$40.00
ROV Power Electronics	Thrusters	$600.00
ROV Power Electronics	Power Converters	$115.00
	Total:	**$989.95**

Expenses:

Budget Category	Example Items	Budgeted	Total Value*	Spent
PPE/Safety Equipment	Safety glasses, Gloves, Label Maker, Fume Extractor and Filters	$800.00	$727.57	$727.57
Tools and Supplies	ex: Multimeters, Logic analyzer, Solder station, Cordless drills	$2500.00	$3,672.32	$2,107.40
Electronics R&D	ex: Power supply, Cameras, Sensors, Raspberry Pi 4B Kits	$900.00	$1,270.41	$1,215.46
ROV Surface Station	Monitors, Router, PC, Keyboard, Mouse	$800.00	$1,391.44	$1,041.54
ROV Structure	Frame, Tether, Pressure Hold: Acrylic, O-rings, Aluminum Stock, Filament	$1,000.00	$1,275.85	$1,190.25
ROV Power Electronics	ESC Motor Controllers, Connectors, Power Converters, Cameras, PCB	$500.00	$1,838.30	$1,009.67
Float	Custom Float PCB, Circuit Playground, Battery, Pneumatic Tubing	$200.00	$309.29	$109.29
Team Operations	Team Gear, Snacks, Website Hosting	$600.00	$833.85	$793.85
Business Outreach	Transportation, Printing	$300.00	$43.00	$43.00
Competition Logistics	Shipping, Printing Costs.	$250.00	N/A	N/A
Competition Fees	Explorer Registration, Fluid Power Quiz	$425.00	$425.00	$25.00
Competition Travel	Airfare, Lodging, Car Rental	$10,000.00	$9,821.29	$9,821.29
	Total:	**$18,275.00**	$21,608.27	**$18,084.32**

**Total Value includes the value of reused, donated, and waived items.*