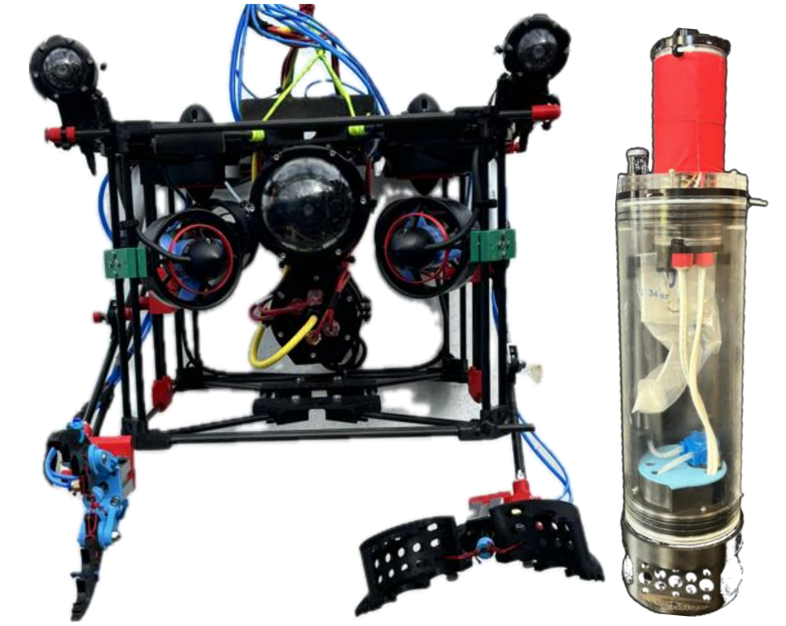
Triton Robotics

Europa ROV and *Enceladus* Float Technical Documentation

2025 MATE World Championships
RANGER Class



Europa ROV and *Enceladus* float. (Not to scale)

(Team Number TBD)

Organization: Triton Robotics (Community Team)
Seattle, Washington, United States

Team:	Thomas Gust	Co-Founder, CEO, Software Lead
	Tenzin Larkin	Co-Founder, Chief Engineer
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	Griffin Fisher	Mission Specialist
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(All team members in 10^{th} grade)

Triton team (left to right): Simon Hajduk, Sterling Howe, Miles Lipson, Griffin Fischer, Thomas Gust, Tenzin Larkin, Theo Lipson.

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ABSTRACT

Triton Robotics is a small, independent company of 10th graders, based in Seattle, Washington. Our mission is to apply marine engineering to address evolving ecological monitoring and restoration challenges. The *Europa* ROV and *Enceladus* float are versatile, robust platforms developed through a year-long, iterative design-build-test-learn process. Both have undergone extensive lab testing, shallow water trials, and deep-water deployments. Throughout development, Triton implemented strict internal protocols to ensure that the systems met or exceeded MATE safety standards.

Our seven-person team collaborates across all aspects of design and production, with members contributing expertise in fabrication, CAD, software, and electronics, while mentoring others to build redundancy in critical skills. This teamwork and our iterative methodology enable us to work through tradeoffs among different solutions to find innovative, unique solutions.

Europa is engineered to interact with both marine infrastructure and underwater life. Its adaptable, reconfigurable systems can be tailored for tasks such as replacing sensors and anodes, patching rust, taking water samples, and collecting fish and jellyfish. Multiple manipulators on vertically adjustable arms allow it to operate effectively on the seafloor and at the surface.

Enceladus uses a precision buoyancy engine to perform depth profiles and station-keeping, with the ability to telemeter data to surface stations. Our use of a bladder and pump allows *Enceladus* to be dependable in various environments. Together, *Europa* and *Enceladus* are ready to meet MATE's request for proposals (*Ref:1*) and contribute to the global initiatives outlined by the United Nations Decade of Ocean Science for Sustainable Development (*Ref:2*).

1. TRITON ROBOTICS TEAM AND PROJECT MANAGEMENT

1.1 Mission Statement

Triton Robotics is dedicated to helping the environment through engineering, using a philosophy of constant iteration and learning to design and deploy robust, nimble, and reliable systems.

1.2 Company Overview

Triton Robotics is a company that evolved through our shared love of robotics and our commitment to working towards an environmentally friendly future. The company was formed in 2022 and currently consists of 10th graders. This is Triton's second year of competing in the Ranger division, and the first year as an independent community team. This year, our original four-member team was joined by three new employees. The small company size necessitates efficiency and collaboration in operating our company. While all our employees work on all aspects of the ROV, we have defined roles and responsibilities for leading, designing, fabrication, software, and operational testing. Our roles are:

- Thomas Gust: Co-Founder, CEO, Software Lead
- Tenzin Larkin: Co-Founder, Chief Engineer
- Theo Lipson: Chief Operations Officer
- Miles Lipson: Chief Safety Officer and Lead Pilot

- Griffin Fisher: Mission Specialist
- Simon Hajduk: Software and Analysis
- Sterling Howe: Outreach and Marketing

Additionally, each team lead (CAD, laser cutting, software development, 3D printing) teaches and mentors at least two other team members to ensure redundancy in each skill.

1.3 Development Schedule

Our development cycle was divided into four phases at the beginning of the year, as detailed in *Table 1*. Each phase had a different focus and schedule, culminating in the PNW Regional MATE Competition in May 2025 (*Ref:3*). Phase 1 (Summer-Oct 2024) focused on brainstorming, idea testing, and goal setting for core ROV systems. Phase 2 (Oct-Dec 2024, 14 weeks) involved regular meetings 3 times a week (Mon/Wed 3:15-5:15, Sat 10-4) and focused on developing core systems. Phase 3 (Jan - Mar 2025, 13 weeks) focused on the MATE RFP, testing mission-specific build-outs and regular pool tests once a week (Sun 4-7). Phase 4 (Apr-May 2025, 6.5 weeks) focused on full system and mission task testing with meetings 5-7 days a week for 2-4 hours during the week and 6-10 hours on the weekends, and included at least 1-2 pool tests per week.

Table 1: *Project Phases, Timing, Goals, and Scheduling*

	Phase 1 Jun-Oct	Phase 2 Nov-Dec	Phase 3 Jan-Mar	Phase 4 Apr-May
Practices / Meetings	1-2x / week	2x / week	4x / week	Daily
Iterative Design Goals	Identify goals Create specifications Test initial ideas Build core systems	Iterative design of core systems	Review RFP Design and test mission specific systems	Final build-out and testing specific
Pool Testing			Weekly pool tests	2x week pool tests

1.4 Project and Resource Management

This year, we became an independent community team due to scheduling conflicts with our school. This necessitated our taking on aspects of project and resource management that we previously took for granted and created challenges that we worked to overcome. At the beginning of the year, we decided to build an all-new ROV and float to challenge ourselves and learn new skills that would lead to a superior product. To accomplish this, we used an engineering process where we: (1) identified a list of desirable features and functions based on our prior experience with the older model ROVs; (2) mapped these lists into design specifications; (3) developed a list of new engineering problems to investigate and solve; (4) prioritized and delegated the above work; and (5) worked through experiments and design processes to create solutions for each problem. These lists and priorities were reviewed at the start of most practices, especially during the more unstructured Phases 1 and 2. We researched the unknowns and estimated lead times before production to determine the value-added of each task. This process allowed for an early and better allocation of time and funds to those tasks with longer lead times and/or focusing on more critical systems. The final steps were system integration and task testing.

2. DESIGN RATIONALE

2.1 <u>Engineering Design Rationale</u>

2.1.1 Overall Design Goals

The *Europa* ROV was designed to be robust, nimble, and versatile. Several key features were identified as being critical: (a) Robustness required extremely reliable capability in basic ROV functions; (b) Nimbleness required better visibility for the driver and lighter weight; (c) Versatility required easy attachment points and the ability to rebalance our thrust-enabling custom mission build-outs. We believe these features are critical to providing *Europa* users the best chance at mission success. These features are the guiding principle of every system described in this report.

2.1.2 Design Philosophy, Process, and Tradeoffs

We created *Europa* and *Enceladus* through a rapid iterative design process. We viewed failure as an opportunity to learn and make the final product better. Initially, we tried to test as many different designs and methods as possible. For example, we built three completely different floats using different buoyancy engines and compared them before settling on our final design. We also tested different materials for our ROV, adjustments to our motor placements, arm designs, gripper designs, and electronics systems. As we discuss throughout the sections below, we balanced tradeoffs among designs with respect to performance, robustness, weight, cost, and other factors. Where feasible, we chose options that led to more custom designs and advanced our team's knowledge of mechanics, fabrication, and software. Examples include designing arms and customized grippers, fusing carbon fiber rods with custom printed components to increase strength, and coding an entirely custom platform to run our float.

2.2 <u>Innovation</u>

Europa features numerous innovations and improvements through extensive testing and iteration, to create a highly mission-capable ROV. Our ROV is fully custom built to maximize adaptability and ensure safety, while paying attention to cost constraints. Our frame and grippers cost substantially less (50%+ savings) than using off-the-shelf components or kits, while enabling innovation and customization. We combine carbon fiber rods with in-house printed parts for our frame to minimize weight and cost while maximizing strength and versatility.

Overall, we designed over 50 custom parts. Each of these has gone through at least three iterations to optimize its design, and many went through well over a dozen. For example, each of our two grippers features a unique manipulator designed to perform a specific set of tasks identified as critical in the MATE RFP. Each of these is on a vertically movable arm allowing for precise manipulation of items at the seafloor, on the surface, or anywhere in the water column. These are actuated by a custom pneumatic system that allows for accurate vertical control of arm position. We have expanded our visibility using multiple custom movable external camera containers to maximize usability for our driver and make image analysis tasks in the RFP easier.

2.3 <u>Problem Solving and Decision Making</u>

Our problem-solving technique typically starts with a discussion about our functional goals. We have learned that revisiting first principles and re-examining decisions through that lens can resolve many issues and lets the team brainstorm new ideas. For example, we rebuilt our float multiple times, testing different methods to achieve our waterproofing and depth hold goals. This included a suite of different buoyancy engine designs, allowing us to compare their performance before completing our final design. This was only possible by maintaining focus on our end-goal and remaining flexible in how to get there. Additionally, we distilled each problem into its core issues and built systems that could test and isolate just one piece of a larger problem. A good example is when we went through multiple arm designs for the ROV using small-scale models and different mechanisms to better visualize the pros of cons of each solution. A key component of our discussions included the cost implications of different solutions. Considering both functionality and cost guided our “Build vs. Buy” and “New vs. Used” decisions (see Section 2.13). Whenever possible, we chose to go with our own designs over purchasing components.

2.4 <u>Systems Approach</u>

In the building of *Europa*, we purposely went back to the beginning to design an all-new ROV. We identified capabilities we wanted and specifications to meet these goals. These were then broken down into systems (e.g. propulsion design, grippers, water sampler), each of which was separated to aid in project management. However, to ensure compatibility and cohesiveness during integration, we identified key principles, including materials and fabrication processes to prioritize (e.g., sizes of screws to preferentially use), power constraints (to maximize power for propulsion and avoid under-voltages for the computers), and weight and drag goals for the designs (to ensure nimbleness), along with cost targets.

2.4.1 Material Decisions

We had to make numerous decisions about what materials to use. Where possible, we prioritized using materials that allowed for custom designs, as a way for us to learn and grow as a team, and reused materials (such as the container for our float) to reduce environmental impact. These decisions were guided by the need to account for strength and durability, including corrosion. For example, we used stainless steel for all bolts, washers, and nuts to avoid oxidation. We also incorporated more advanced materials, including printing in acrylonitrile butadiene styrene (ABS) infused with glass fibers and acrylonitrile styrene acrylate (ASA) infused with carbon fiber. Due to the difficulty in reliably printing with these materials, we used them sparingly. Instead, we used plain ABS extensively for printed parts expected to be in extended contact with water, because of its water-resistant properties and its compatibility with tools like ABS solvent. We tended to use polylactic acid (PLA) where slipperiness is an issue and/or there is no expected water contact (as PLA swells in water) (*Ref:4*). Carbon fiber rods are inserted and incorporated to add strength to the ABS or to span distances. Carbon fiber is both light and strong; it is 5.54 times stronger than steel by weight, and it does not corrode in water (*Ref:5,6*). However, its potential brittleness was a challenge. After extensive testing to find rod diameters that did not break or shatter during overkill tests, we decided on 8mm diameter rods for load-bearing components.

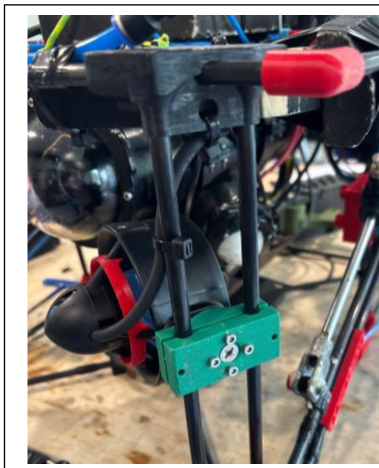
2.4.2 Power Decisions

We use 12VDC electrical power for all of the basic functions of the ROV. The main electrical need is our six thrusters, each of which is rated to safely use 17Amps (A). This means that our limited (25A) electrical supply is immensely overtaxed, and we run our thrusters well below their maximum capacity. This reduces wear and increases their longevity. 12VDC power is also converted to 5VDC (and sometimes 3.3VDC internally) for computers, logic-based systems, sensors, and cameras. Maximum full load amps (FLA) was measured at over 22A even after limitations were placed on the pulse-width-modulation (PWM) signals to our electronic speed controllers. This necessitated the use of a 25A ATO blade fuse per MATE rules (*Ref:1*)

For our grippers and water sampling system, we chose to use pneumatic power. Pneumatic power requires active maintenance (removing liquid, ensuring no leaks), but offers fast action and continuous holding power, without using up our electrical power budget. We began investigating hydraulic power. However, these designs are not sufficiently mature for our ROV at this time, but may become part of future products.

2.5. Vehicle Structure

We required our new frame to be robust, lightweight, nimble, and stable. This created a tradeoff between (a) separating the center of buoyancy and center of mass and maintaining mass (for stability), versus (b) having a smaller, lightweight frame (for nimbleness). We decided to make a moderate-sized frame to enhance stability but to limit its cross-sectional area to reduce drag and its mass to increase speed and nimbleness. These objectives led us to carbon fiber because of its high strength and strain characteristics compared with its size and weight (*Ref:6*). Our design incorporates 8mm diameter carbon fiber rods into custom ABS parts. Strength in the frame is ensured by utilizing two horizontal structures incorporating triangular supports. These are offset using vertical beams. The decision to use only vertical rods is a tradeoff between strength (it would be stronger to angle the rods with respect to each other) and the goal of being able to easily adjust our thruster height in order to create linear motion. Our frame places our thrusters inside the frame and also includes bumpers on the top that extend



Europa ROV frame design showing the vertical rails that allow for adjustment of the horizontal thrust vector. Credit: T. Lipson past the arms in order to protect the mechanisms from underwater hazards, making *Europa* safer and more robust than previous products.

2.6. Vehicle Systems

Vehicle systems were broken down into components for design purposes: frame (Section 2.5), propulsion (Section 2.8), control electronics (Section 2.7), buoyancy and ballast (Section 2.9), analysis software (Section 2.11.4-6), and standard and mission-specific tools and payloads (Sections 2.10-11). Basic components like the frame and propulsion and basic control electronics were integrated first, with more mission-specific components being added later. This created challenges for integration as mission-specific components altered the balancing and drag of the basic ROV. We purposely built in the ability to rapidly adapt to these changes by designing a frame with the ability to move our motors in order to shift the center of mass and also the center of thrust. Overall integration was done through rapid iteration and continuous testing, allowing for even our frame components to be adjusted throughout the integration process.

2.7 Control / Electrical System

2.7.1 Electrical Control System

This year, we approached our electrical and software systems with a clear focus on modularity, reliability, and future expandability. Rather than relying solely on off-the-shelf solutions, we prioritized developing custom-integrated systems that improve both performance and in-field usefulness.

Our main control architecture features a Raspberry Pi 4B paired with a flight controller (Navigator) board, as they are compact, powerful, and thermally efficient. We selected the Pi 4B after carefully evaluating tradeoffs between processing power, form factor, and thermal performance. Compared to alternatives like the Pi 5 or NVIDIA Jetson Nano, the Pi 4B offers sufficient CPU and GPU compute capabilities for our control and vision processing tasks, while maintaining a compact size and manageable heat output, not requiring complex cooling solutions. Its built-in robust Ethernet networking and four USB ports also simplify camera integration and enable rapid debugging during development. Driver vision is accomplished through a USB Sony IMX 322/323 low-light 1080P camera sensor using the H.264 protocol. This is placed on a 90 degree gimbal in the main electronics container mounted forward. The Navigator flight controller board is used to generate the PWM signals that control our thrusters and camera gimbal. This board also integrates a 9-axis IMU, providing real-time orientation and heading data essential for implementing advanced flight-assist features like automated depth and orientation holds. These capabilities are critical for the precise manipulations required during complex MATE RFP tasks, such as tool deployment and component replacement. The Navigator also interfaces directly with our onboard leak sensor and a Blue Robotics Bar 30 depth and temperature sensor, consolidating key environmental and safety monitoring functions.

Supporting the core computer and networking systems, we employ six purpose-built 3-phase ESCs to drive our T200 thrusters (see Section 2.8). These ESCs are connected directly to the primary 12 V rail supplied through the tether and are controlled via 1100–1900 µs PWM signals.

To power our compute and auxiliary systems, we use a dedicated 5 V voltage regulator to step down the 12 V tether power. This power architecture ensures stable, noise-isolated supply lines for both high-draw actuators and sensitive electronics. Many of these components were reused from our previous ROV systems, reducing costs.

This year we re-examined and upgraded our ROV-to-surface communications. Studying the industry standard Fathom-X ethernet compression boards, we were able to learn about the underlying chipsets used by the Fathom-X and find a newer system with more rapid communication, the LX200V50 EVB power line communication (PLC) module from RAKwireless. It offers substantial improvements in both data rate and signal integrity (use of double differential pairs to obtain a nominal 1000 Mbps vs. 200 Mbps and more advanced error correction protocols). This module connects directly to the Pi via Ethernet within the main electronics housing, ensuring clean, high-speed data transfer.

2.7.2 Electronics Enclosures

We have two electronics enclosures on the ROV. Our main electronics enclosure houses all of the main electronics, and was reused from our previous ROV. Because it was acrylic, we found that, with our upgraded systems including additional cameras (Section 2.11.1), our CPU began to overheat and thermally throttle, and occasionally to drop communications. We tried multiple methods to reduce power usage (PWM reduction, eliminating cameras, among others) but, in the end, decided to upgrade our enclosure to an aluminum tube, as aluminum has a thermal conductivity approximately 1000x greater than that of acrylic (237 W/mK vs 0.2 W/mK, *Ref:7)*. This has greatly reduced our overheating problem.

We also have a secondary electronics enclosure. This was added to the design, after our experience with shipping our previous ROV whose design did not allow for tether removal. Our secondary electronics container is located beneath the primary control cylinder and specifically designed to enable rapid tether disconnection and provide a flexible platform for future system expansion. All tether wires terminate in this container using quick-disconnect connectors, allowing for fast, tool-free disassembly and reconfiguration. This greatly improves transportability without disturbing the main electronics assembly, an essential feature for clients who require rapid deployment and easy relocation between field sites. Equally important, this modular architecture positions *Europa* for long-term expandability to meet a wide range of end-user requirements. The secondary electronics container provides a clean, accessible interface for integrating future processing, electronics, additional sensors, or specialized tooling without requiring invasive modifications to the primary control systems. This makes the platform highly adaptable for various mission profiles: academic research, industrial inspection, or environmental monitoring.

2.7.3 Control Software

Europa employs a robust and highly customizable software architecture that provides both low-level, code-based control of every ROV function and a seamless, intuitive high-level piloting experience. At the core of the system, *Europa* runs BlueOS and ArduSub on a Raspberry Pi, leveraging industry-standard tools that expose full control of essential ROV functions via the

MAVLink protocol. This standardized communication framework ensures reliability while allowing for easy integration of new features.

Our primary piloting interface is built directly on top of this stack using Cockpit, an extension that offers extensive interface customization and, critically for our mission requirements, the ability to stream multiple camera feeds simultaneously. This capability directly addresses a major limitation in our previous control infrastructure. The interface is highly configurable to meet the needs of different drivers and customers, and it supports control using a standard Xbox controller. This reduces the learning curve for new operators.

Although not required by the MATE RFP tasks this year, Triton Robotics has continued to develop an autonomous operation mode through our own custom software. We use extensions to integrate computer vision applications directly into the control pipeline at the ROV level to create onboard perception and advanced autonomy. We believe that these future updates will further enhance the capabilities of the *Europa* platform.

Additionally, we have integrated multiple flight modes into *Europa*, allowing the pilot to automatically maintain a desired depth and even hold a specific orientation. Extensive in-field testing has demonstrated that these features significantly improve mission efficiency. Tasks such as sacrificial anode replacement and shipwreck scanning are now completed more quickly and with greater precision, reducing operator workload and increasing overall mission success rates.

2.7.4 Tether Design and Management

Our tether provides communication and power to *Europa*. The goal for our tether this year was to make it more flexible, as previous tethers had limited the mobility of the ROV. Communication is via a tether ethernet cable with an integrated Kevlar line for strength (see Section 2.7.1 for more on ethernet communications). For power, we re-examined our assumptions, and did extensive testing of different wires. After this analysis, we choose to use dual 10 AWG wires for each power direction, rather than the single 8 AWG wire used previously. The dual 10AWG wire was found to have approximately the same net mass (2.62 vs 2.56kg), but with lower resistance (0.032 vs 0.040Ω) and much greater flexibility. This allowed us to exceed our design goal of 85% power reaching the ROV at maximum current (actual value: >89%) while improving flexibility. For fluid power, we wanted to maintain multiple grippers and systems for operational efficiency but needed to improve the flexibility of the lines. We downsized our pneumatic lines, optimizing the tradeoff between enhanced handling and lower cross-section versus the amount of air that can be moved quickly. We chose the smallest lines (2.5mm ID) that were found to still allow for a reasonably rapid activation of our actuators (less than 1.5 seconds). Doing so reduced the cross-section of the pneumatic lines by over 33%, while actually including more lines than in previous ROVs (9 lines vs 6). This tradeoff allows for better ROV motion, but slows down the gripper closing, which incidentally results in a safer gripper. Strain relief protects the tether at all connection points. Note that one of the pneumatic lines serves as the water sampling line / backup pneumatic line should any issues arise in the field. We make the tether neutrally buoyant using pool noodles for smoother ROV motion.

2.8 Propulsion

We have six thrusters (two vertical and four horizontal) in a modified vector thrust orientation, where the horizontal thrusters are angled at 30 degrees from the forward-back direction (as opposed to the standard 45-degree orientation). This applies more thrust in the forward-back direction, allowing faster motion along *Europa*'s longitudinal axis. With this setup, we retain the ability to move in any direction horizontally, including rotation in place (useful for the photosphere) and crabbing (useful when manipulating mechanisms like the Medusa jellyfish release). All thrusters are contained in our frame, helping protect them from damage, as well as having ingress and egress motor shrouds adapted from the UWROV MATE team's design (*Ref:8*). Our frame allows for easy adjustment of the vertical location of our horizontal thrusters, and for the horizontal adjustment of our vertical thrusters. This is instrumental in achieving linear motion and allows us to rapidly re-align thrust, as new modules are required for mission-specific tasks (Section 2.7). For our motors, we chose the Blue Robotics T-200 thrusters for their reliable thrust capacity, low maintenance, and price point. The motors use the surrounding water for lubrication and cooling. The thrusters are above specifications for this ROV, accepting a maximum of 17A each. Since we use the thrusters in pairs, at most we can supply ~12A per motor. This means that our thrust tops out at 3.3 Kg-f = 32.3 N (*Ref:9*), providing ample thrust for our 12.8 kg ROV.

In order to obtain optimal linear motion, we need to align the center of thrust with the centers of mass, buoyancy, and drag. Our frame was purposely designed to allow for adjustment of our horizontal thrust up and down and for adjustment of our vertical thrust front to back. Alignment was done first in shallow water pools and then in deep water in multiple pools.

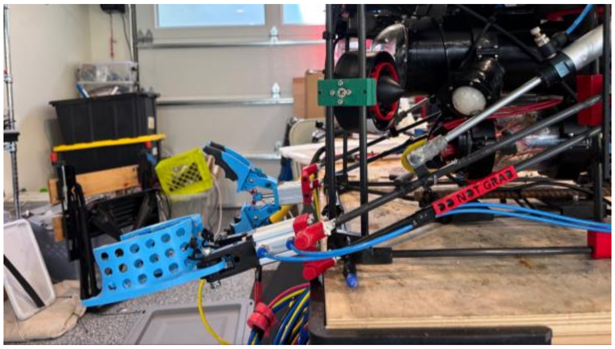
2.9 Buoyancy and Ballast

Overall, the ROV is balanced to provide neutral buoyancy within a tolerance of 2N, with all errors on the negative side as this was found to be operationally preferable to a positive buoyancy. First, the ROV is weight-balanced on land, then tested iteratively in pools. We add additional mass down low and ballast up high to increase the dipole moment of the centers of buoyancy and mass to increase stability. Ballast is provided by custom-fit pieces of polyurethane foam because of its dimensional stability at pressure. Ballast foam is kept thin and placed horizontally (2.5cm) to reduce side-to-side drag, but doing so necessarily adds to vertical drag. This tradeoff is made to ensure nimbleness in horizontal motion. We minimized drag by testing different shapes and locations to reduce the negative impacts.

2.10 Standard Tools

The *Europa* ROV comes standard with two movable arms each mounting a gripper.

2.10.1 Arms



Europa ROV arms and grippers. Credit: T. Lipson

Europa's two arms are made of parallel carbon fiber rods held in a parallelogram configuration that keeps the gripper head level. The arms are mounted to the middle of the vertical motor mounting rods minimizing forward lever arm at the highest and lowest positions. A pneumatic actuator (20mm bore x 100mm stroke) is used to move the arm on each side, and our custom pneumatic topside control system allows for stopping the actuator at any level with precision. The arms allow for increased versatility and the manipulation of objects on the ocean floor and the top of the water column. Additionally, the vertical motion is useful when performing placement tasks (like the pCO2 sensor) that require a vertical insertion process.

2.10.2 Grippers

Europa ROV grippers. Credit: T. Larkin

Europa has two grippers, one on either side attached to an arm, activated by pneumatic actuators (16mm bore x 25mm stroke). The bore size has been picked to reduce the maximum force they can exert below what can cause significant injury (tested with fruit). Their location ensures that each can operate independently and can carry objects simultaneously. At the top of the arms range, the grippers are able to complete various tasks at the top of the ocean, such as collecting jellyfish polyps and fish specimens. At the lower range, grippers are able to get as close as possible to the bottom for objects on or near the ground, such as the anode and the release pin on the hydrophone.

The gripper heads are all iteratively designed to maximize their usefulness across different tasks in the MATE RFP, such as holding large objects, replacing underwater components, and grabbing and carrying small objects such as hooks. Every aspect of the head design is carefully considered and tested for the best result; these different designs increase the versatility of *Europa*. The right head alone allows for the removal and replacement of the anode, collection of jellyfish polyps, opening of sunken cargo, attachment of pCO2 sensors, removal of power connector covers, as well as providing the full functionality of a regular gripper.

2.11 <u>Additional Mission-Specific Payloads, Tools, and Analysis Toolkits</u>

Note that the mission tasks are undertaken using both the standard *Europa* systems and tools described above, as well as customized improvements designed specifically for the MATE RFP such as our customized gripper heads (see Section 2.10.2), as well as the add-on and analysis components described here.

2.11.1 Additional Cameras

To accomplish the tasks in the MATE RFP, specifically the photosphere and need for shipwreck identification through measurements, *Europa* has been equipped with an additional three Sony IMX 322/323 low-light 1080P sensor-based cameras. A wide-angle (180 degree field of vision) camera is added to the main driver's camera gimbal. Two cameras external to the electronics container have an 80 degree field-of-view, resulting in a more natural viewing experience and are easily relocatable even in the field, in order to focus on specific tasks. To ensure a robust signal to the two external USB cameras, we utilize USB signal boosters. Our camera system is flexible and allows for stereo vision capabilities for measurements, as well as specific task monitoring, like the health of the collected Medusa jellyfish. These cameras feed into our topside analysis software described below.

2.11.2 Medusa Stage Jellyfish Collection System

Europa includes a custom laser-cut collection box, mounted to the top of the ROV frame for safe, non-invasive transport. Its open design allows the ROV to maneuver beneath any live specimen and raise it gently in the containment area. The box's design allows water to flow through, reducing drag and guiding the jellyfish gently into the container while maintaining the specimen's natural environment. This system is completely detachable and allows for the collection and transport of live specimens directly from the water to the lab without switching containers.

2.11.3. Water Sampling Mechanism

Europa comes equipped with a detachable water sampling mechanism. Our mechanism utilizes a self-priming water pump topside with a 4mm ID line attached to our tether to transport the water from our onboard sampling mechanism. This mechanism includes a metal straw attached to the line controlled by a pneumatic actuator that allows for the penetration of various membranes. The system is field detachable to reduce drag during other mission tasks.

Water sampler design.
Credit: M. Lipson

2.11.4 Photosphere Software Analysis Toolkit

We provide a complete analysis toolkit to create photospheres and identify critical targets no matter what direction they may be relative to the ROV. We use the wide-angle camera to record a 360 degree video by rotating the ROV in place, using the two auxiliary cameras pointing up and down to fill in the gaps.

The recorded videos are then transferred from the surface control station to an analysis laptop that splits the frames, removes artifacts in the images (typically pieces of the ROV itself) and then stitches these into a photosphere. Fully custom code is used for frame splitting and preprocessing. We then use PTGui to generate control points on each image, and to stitch images together. Photospheres are saved for later viewing and/or explored with PTGui's built-in viewer.

2.11.5 Carp Data Modelling Analysis Toolkit

We use a custom-built, AI-driven mobile app to automatically upload an image of the carp data table to a nearby laptop. Using the OpenCV library, our software detects ArUco markers on a sheet of paper overlaid on top of the table to hide distracting high contrast areas, and mark the edges of the data table. The image is rectified from the points, and a custom-built convolutional neural network (CNN) is used to classify the data inside the thresholded ROIs (identified by OpenCV). The CNN is trained on a custom set of low contrast, skewed, and straight images, and has been found to label regions with an accuracy of 98% in the training and testing data. After labeling, the points are then grouped by row through OpenCV and translated into a list. The list is fed into a converter, which converts the data into a playable video.

2.11.6 Length Measurement Analysis Toolkit

To accurately determine the real-world dimensions of objects such as the shipwreck, we use off-the-shelf structure from motion (SfM) technology, selected for its balance of accuracy, flexibility, and cost-effectiveness. Our workflow begins with recording a video of the target scene using the ROV's primary driver camera. We then apply custom software to decompose the video into individual frames at 30 fps, ensuring sufficient visual overlap for reliable feature matching.

Using Agisoft Metashape, we solve the camera poses and generate a dense point cloud representation of the shipwreck scene, which is subsequently stitched into a complete 3D mesh. To accurately scale this model, we import the mesh into Meshlab and apply known reference lengths provided in the prop-building instructions. This step ensures dimensional accuracy, allowing us to compute real-world measurements of any object or linear feature within the reconstructed scene.

We chose this workflow for its adaptability to varied environments and its compatibility with widely available software tools. Compared to more specialized or expensive measurement systems, this approach provides a high degree of measurement precision without requiring dedicated hardware. Additionally, it is robust enough to support future scene reconstruction or photogrammetry tasks beyond the current mission requirements.

2.12 <u>Float Design</u>

Our float, *Enceladus*, in just under half a meter long (0.498m) and features a precision buoyancy engine to enable prolonged holding at specific depths. After extensive testing (including of linear actuators and stepper motors), we settled on a peristaltic pump connected to a 1L bladder design. This was far more reliable than other designs because there were no moving seals requiring waterproofing. Our overall float features the reuse of our old main electronics housing to minimize cost.

The float has several features (see figure) including a smaller electronics section to enable greater height above the water, and an Arduino control system that reads the pressure sensor and controls the pump through a relay. The Feather M0 RFM95 board used contains a built-in 915Mhz LoRa (long-range) radio for communications with our mission station, transmitting float state and mission data and receiving profile commands and parameters. The LoRa system is more power efficient and longer range than other protocols like WiFi or Bluetooth. Power is supplied by a single 12-volt 2000mAh NiMH battery pack with a 2 amp fuse. While the whole float is one chamber that can be vented via the 2.8cm diameter rubber stopper on the bottom plate, the electronics container location and a specially designed snorkel tube connection that makes flooding of the electronics all but impossible.

Enceladus float design.
Credit: M. Lipson

Depth data is sent to our topside custom data analysis system. This system graphs the data over time and can be customized for different mission parameters.

The float uses fully custom software, ranging from the low-level firmware running on our float electronics to the control and visualization tools used at the mission station. *Enceladus* features a rich command interface, and we prioritized making nearly every parameter configurable over the radio link to enhance in-field adaptability and system robustness. We also implemented multiple operational profile modes to suit different user needs. Using high-frequency polling of our depth sensor, we achieve near-instantaneous feedback between pump commands and the float's resulting position and momentum within the water column. To execute depth holds, we employ an improved control algorithm that accounts for position, velocity, acceleration, and control (change in acceleration), reducing overshoot and oscillation.

2.13 <u>Build vs. Buy, New vs. Used</u>

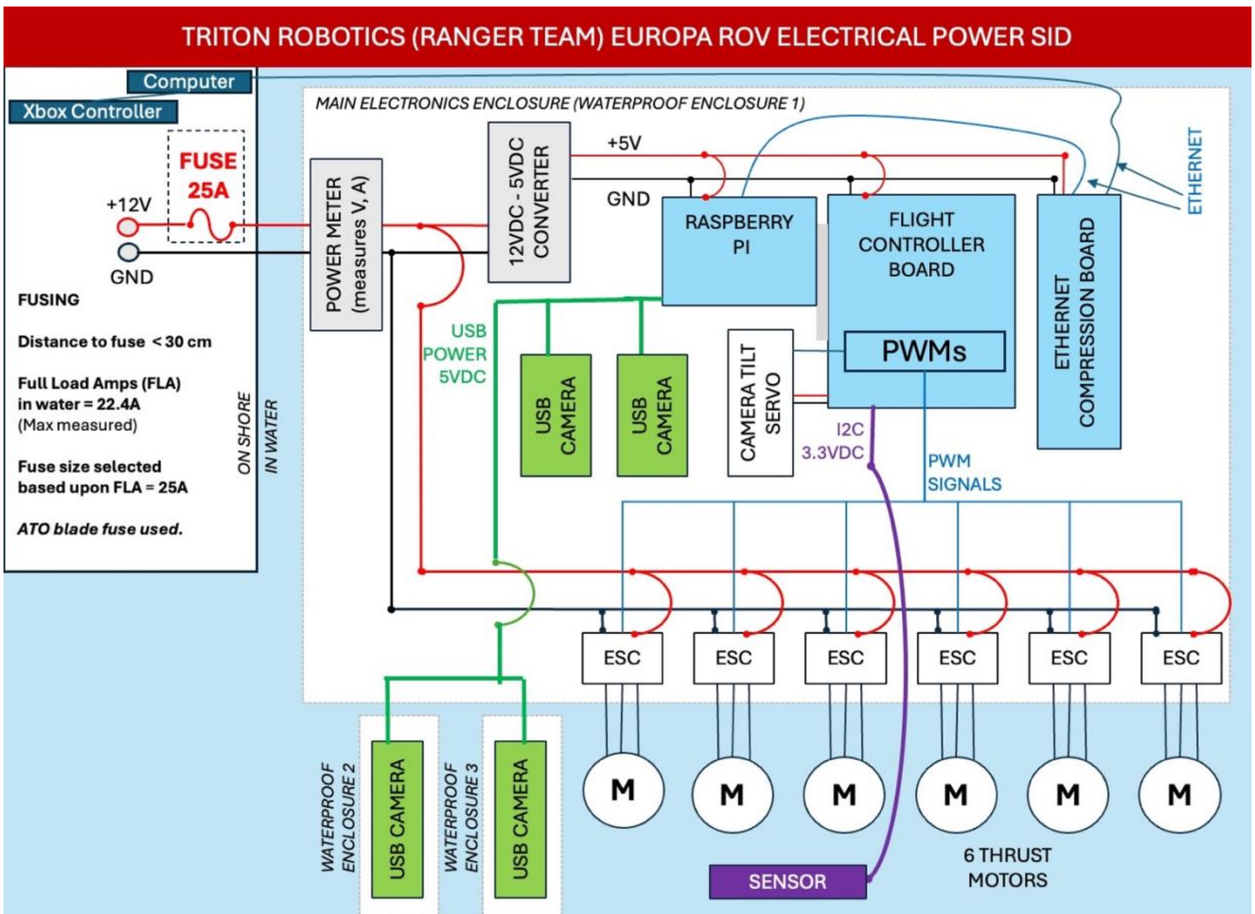
Triton always tries to design and build our own components wherever feasible. For example, we created our own frame, grippers, and water sampling mechanism, to name a few. Overall, *Europa* has over 50 different custom designs. We also relied on learning from household and other items around us and either repurposed these directly—as we did with a metal straw for water sampling—or incorporated their form and function into our custom 3-D parts, as we did when we were inspired by colanders for the design of our gripper heads. We reused elements, where possible, to reduce waste, such as pneumatic switches and, of course, our motors. Our iterative design process placed a high value on the ability to build and test our own parts. Creating unique features is a way to build skills and capabilities in house for the future; this explains why all of our grippers, arms, and other mission-specific features are designed entirely in house. We are proud that *Europa* and *Enceladus* overall have more individual custom-designed and printed parts than purchased ones (excluding screws, nuts, and washers). These parts provide unique, purpose-built, and tested capabilities that enhance our design and the functionality of *Europa* and *Enceladus*.

In general, the things that we did buy were for the reliability of the ROV or because creating some things in house would take up too much time or were unacceptably risky. For example, we ran into problems when trying to build the flanges for the float container and decided to purchase them because the precision-machined seal was far more reliable than anything we could create. Similarly, we bought our electronics boards and containers because these would take up a lot of our time and could potentially lead to expensive losses if these components were to fail, especially our electronics enclosures.

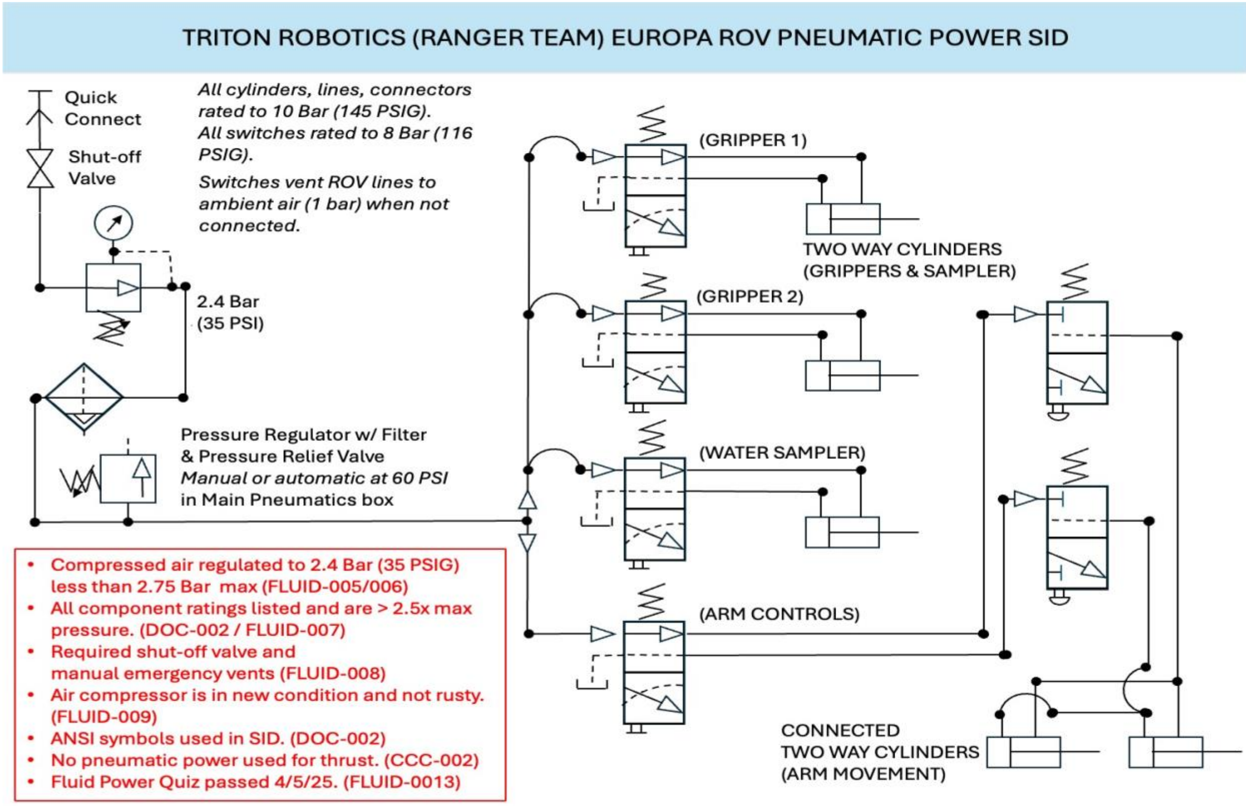
All of our custom parts, except for motor guards (adapted from UWROV) were designed from the ground up, making *Europa* and *Enceladus* unique, versatile, and highly capable.

3. SYSTEM INTEGRATION DIAGRAMS (SIDs)

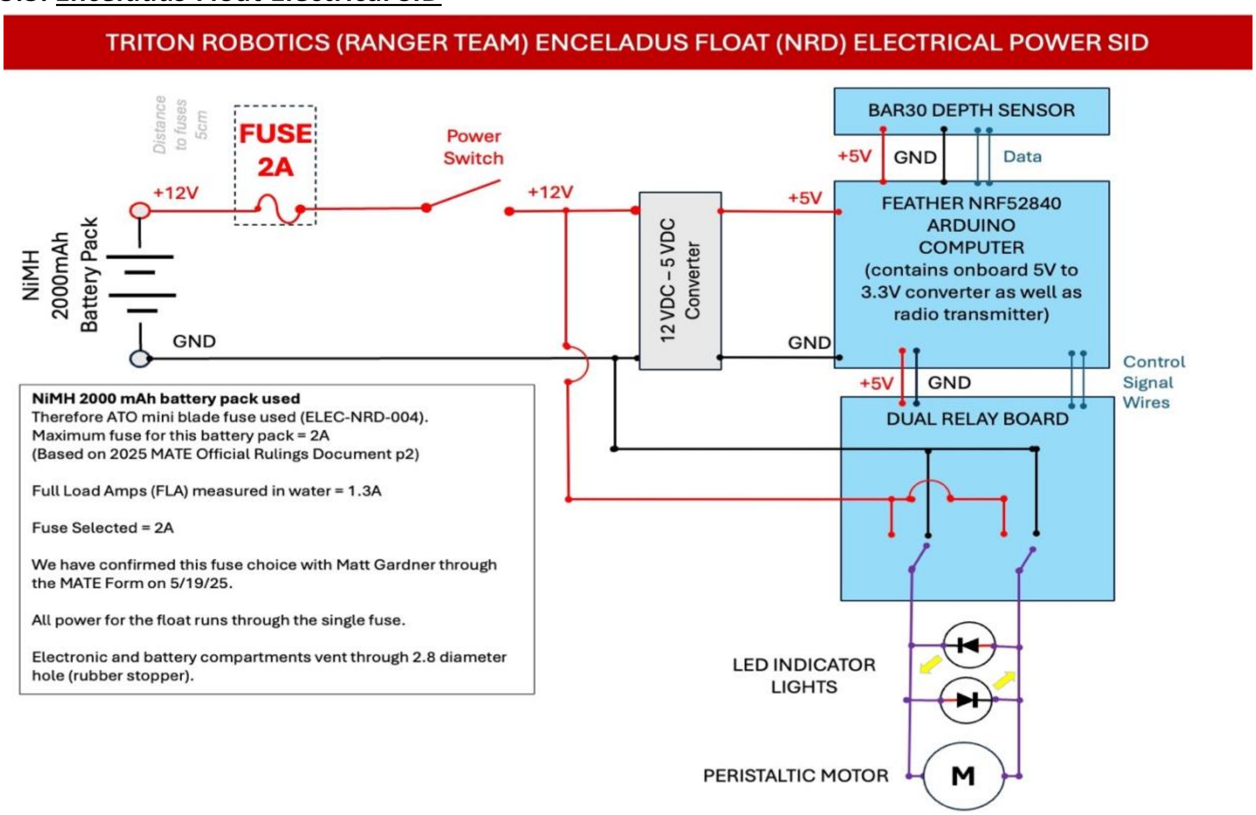
3.1 *Europa* ROV Electrical SID



3.2. *Europa* ROV Fluid Power SID



3.3. *Enceladus* Float Electrical SID



4. SAFETY

Red motor shrouds. Credit: M. Lipson

At Triton, safety is our core principle. We address safety through the use of personal protective equipment (PPE), checklists, call-and-response communication, job safety and environmental analyses (JSEAs), materials and engineering research, and intentional design decisions. These practices ensure that we meet or exceed all MATE safety requirements.

We incorporate safety considerations into every design discussion, fabrication session, and operational test. By making safety a habit, we were able to focus on the process of building advanced functionality into our systems and learning through the iterative design process.

We considered safety across three main areas: personnel, equipment, and operations. *(For Safety Checklists and Job Safety Environmental Analyses, see Appendices A.2-A.3.)*

4.1 Personnel and Equipment Safety

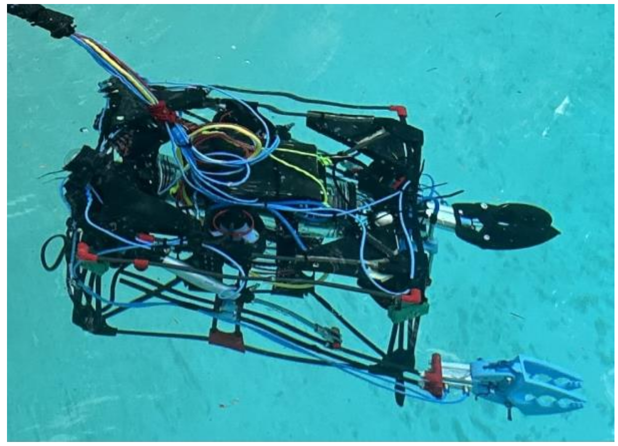
Testing gripper safety with a tomato. (The tomato was only slightly bruised and was eaten after.) Credit: T. Larkin

The most significant personnel hazards are related to pneumatics, motors, and electrical systems. We mitigated the risks of the pneumatic actuators by using shielding to prevent placement of hands in areas that might get caught; (b) reducing the bore size of the pneumatics to the lowest acceptable level where the forces are below those that can cause significant injury (tested with fruit, see photo); (c) properly securing all lines; (d) building a topside box to contain the pneumatic valves and switches; (e) reducing our pressure level to 2.41 bar (35PSI); and (f) having easy-to-reach emergency venting. We mitigate the risks of electrical power by using shielding (no exposed connections), enclosures, and fusing. We mitigate the risks of the motors using IP20 motor guards adapted from the UWROV design (*Ref:8*). We also have added red color coding to call out areas of concern and put warning labels on the ROV. We also have protocols for all handling and lifting of the ROV. These precautions allow us to safely test more advanced features and systems. Clear communication ensures everyone understands the risks and how to reduce them.

4.2 Operational Safety

Operational safety relies heavily on having a plan, being aware of dangers, testing the plan, strong communication during the test, and after-action reviews to improve safety over time, as well as specific modifications to the ROV as mentioned above. We have safety protocols that involve designation of a Safety Czar overseeing the test as well as designated duties for team members (see Appendices A.2-A.3). Our Chief Safety Officer has also undergone advanced water safety courses and certificates and serves as our rescue swimmer. We have adopted setup and takedown protocols that create a safe working environment, call-and-response protocols that coordinate team actions, and before and after inspections of the equipment. Extensive testing (numerous shallow water tests and over a dozen deep water tests) creates a safer environment as we learn, diagnose, and modify any identified hazards and issues. These protocols, checklists, JSEAs, and modifications are what make *Europa* and *Enceladus* both reliable and safe to operate.

5. TESTING AND TROUBLESHOOTING


Europa during mission testing. Credit: M. Lipson

We actively look for flaws in all of our products through repeated testing so we can improve functioning and reliability. This is done through a sequence of tests leading to mission-specific task testing. Testing begins in the lab with individual component tests, ensuring basic function and reliability. Successful parts are tested in shallow water for underwater compatibility before being mounted onto the ROV. Finally, components undergo deep pool testing (3.5m+) to verify waterproofing and mission performance under pressure. A part may be redesigned or discarded if it fails to meet these standards. Every system on *Europa* was tested at least five times in deep water before final integration. This process ensures all systems function reliably and cohesively to accomplish the mission.

Troubleshooting is done continuously as the rapid iterative process highlights issues (see Section 2.3 and examples throughout Section 2). Resolving these issues often involves going back to first principles and re-examining our goals. We have had to troubleshoot numerous issues this year from float electronics that would not work (multiple issues including a floating ground), leaking chambers (leading to multiple redesigns), overheating (resulting in changing materials), and software issues. As a younger team, we prioritize learning new skills; thus, we embrace these challenges as ways to expand our capabilities.

6. BUDGET DISCUSSION

For budget tables and accounting, please see Appendix A.1. Triton estimated a budget of $4000 at the beginning of the year based on our previous year's experience. This budget was estimated on the basis of creating an all-new ROV and float after looking at existing parts we might reuse (e.g., thrusters), as well as MATE-related costs of building a set of props and regional competition registration fees. We did not include costs of the World Championships. The costs were split into categories: $1000 for electronic components, $750 for structural components, $500 for mission specific components, and $250 for additional tools. We also recognized that there were a lot of unknowns and budgeted $1500 for miscellaneous costs. As a first-year independent team, we took this budget to our families as a group and obtained the funding, with the understanding that additional funds would be required if we progressed beyond regionals.

We tried to budget as a group within these categories with our Chief Engineer and CEO being the decision makers regarding what parts to purchase. Overall, the budget worked well as we came in a bit below ($3602) our estimate. Our category totals differed from what we expected, in particular the need for an aluminum housing for thermal purposes exceeded our structural budget. Purchases were made directly by the team against the budget in many cases, with mentors being asked to purchase from certain sites due the need to establish accounts.

The World Championship costs (particularly travel) far exceed this budget and we have had to go back to our families including extended families to obtain additional support. As such, we would like to thank our families for their continued and extended support. See Appendix A.1 for a full list of funding and tool donation sources.

7. ACKNOWLEDGEMENTS

We at Triton Robotics know that we could not have done this alone and would like to thank everyone who helped us along the way. A special thanks to our families for their encouragement and our parent mentors, Sim Larkin and Charles Gust, for their support and guidance. A grateful thanks to our families and specially George and Ann Fisher for their sponsorship of the team; to Chris Suver, Jennifer Cast and Liffy Franklin, and the Overlake Club, for allowing us use of their pools for testing; and to Blue Robotics, Fishery Supply Company, and City Peoples' Market for discounted supplies. We thank our school, Seattle Academy, and our teachers for giving us the confidence to go out on our own. We are deeply grateful to the MATE Competition, especially the World Championship and PNW Regional Competition organizers and volunteers, for their support, advice, and the opportunity to present *Europa* and *Enceladus*.

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APPENDICES:

A.1 BUDGET TABLES

ROV and Float Expenses (*All prices in US Dollars, USD$). Start of year budget estimates totaling $4000 are included in table under each category.*

Category	Items	Donated	Reused	Purchased
Electronics (est. $1000)	Raspberry Pi and Arduino		139.99	34.95
	Navigator Board		320.00	
	USB Cameras		110.00	282.00
	Pressure sensor		85.00	85.00
	12VDC-5/3.4VDC converters		70.00	35.00
	Anderson Powerpole Connectors		9.00	
	Ethernet Tether (20m)		245.00	
	Ethernet compression boards			198.00
	T200 Thrusters and ESCs		1776.00	296.00
	Subtotal Electronics (est $1000)		**2754.99**	**930.00**
Structure and Waterproofing (est. $750)	Waterproof Enclosures		584.00	726.00
	3-D Filament Rolls & Acrylic		29.95	115.00
	Heat Shrink and Hot Glue			37.85
	Wetlink Penetrators		210.00	60.00
	Carbon Fiber			197.78
	Epoxy			35.00
	Subtotal Structure (est $750)		**823.95**	**1171.63**
Mission (est. $500)	Pneumatic lines, fittings, actuators			278.00
	Props		120.00	227.00
	Subtotal Mission (est $500)		**120.00**	**505.00**
Tools (est. $250)	Air Compressor		189.00	
	Borrowed Tools	5000.00		
	Borrowed 3-D Printers	1500.00		
	Borrowed Glowforge	3000.00		
	Subtotal Tools (est $250)	**9,500.00**	**189.00**	
Misc. (est. $1500)	Miscellaneous supplies		300.00	412.74
	Stainless Steel Bolts and Nuts			132.00
	MATE PNW Regionals Registration			450.00
	Subtotal Misc (est $1500)		**300.00**	**994.74**
ROV AND FLOAT ITEM TOTAL		9,500.00	4,187.94	3,602.32

World Championship Expenses (*All prices in US Dollars, USD$).*

Travel	Quantity	Per Item	Estimated Expenses
Registration	1	450.00	450.00
Airfare: 6 team members, 2 mentors	8	555.00	4,440.00
House (all team members)	1	4,770.90	4,770.90
Rental Cars	3	545.00	1,635.00
Shipping (Checked Baggage)	5	80.00	400.00
Subtotal Worlds			**11,695.90**

Total Costs and Total Funding from Sources (*All prices in US Dollars, USD$).*

Expense Category	Estimated Budget	Actual Expenditures
ROV and Float Materials - Purchases	4,000.00	3602.42
Reused Materials / Donated Tools	n/a	13,687.94
World Championship Costs	n/a	11,695.90
TOTAL		28,986.16
Funding Raised (from Families)		15,298.22
Reused Materials		4,187.94
Donated Tools and Parts		9,500.00

Full list of funding and donation sources:

- **Funding was received from:** George and Ann Fisher, the Larkin-Spoonemore family, the Gust family, the Fisher family, the Hajduk family, the Howe family, and the Lipson-Seelig-Kavalam family.
- **Donated/borrowed tools and equipment were provided by**: the Larkin-Spoonemore, Gust, and O'Donnell-Gracz families. Estimated fair market value of the tools and equipment provided on a replacement basis.

A.2 SAFETY CHECKLISTS

These are our checklists we will be using at the MATE competition, including construction after shipping and operations in and around the pool-deck.

CONSTRUCTION AND OPERATIONS CHECKLISTS

CONSTRUCTION CHECKLIST

If constructing ROV after shipping:

- ☐ Check for damage
- ☐ Separate top and bottom from shipping struts
- ☐ Attach vertical struts to top and bottom
- ☐ Attach tether to secondary electronics container (attach power and ethernet inside container)
- ☐ Attach pneumatic lines to ROV
- ☐ Attach pneumatic lines to pneumatics box
- ☐ Seal secondary and main electronics container
- ☐ Double-check ethernet connections
- ☐ Go through power-up to test system before pool

POOL DECK / OPERATIONS CHECKLISTS

Unloading:

- ☐ Check-in with entire team/JSEAs covered
- ☐ Communicate with others in area
- ☐ Area is dry and clear
- ☐ Walkways and areas for staging designated
- ☐ Safety czar overseeing designated
- ☐ Safety glasses / PPE on

Setup (pre power-up):

- ☐ Unbox ROV and float
- ☐ Setup up computers (Xbox, ethernet, USB)
- ☐ Turn on computers
- ☐ Place compressor and pneumatics box
- ☐ Secure strain relief (surface control station, tether, pneumatics)
- ☐ Connect computers to surface control box
- ☐ Unroll tether (double-check strain relief)
- ☐ Check ROV and float for damage
- ☐ Check water seals on ROV and float
- ☐ Connect power and pneumatics

Power-up:

- ☐ Verify power and pneumatics properly connected
- ☐ “Ready for compressor”; “Clear” before compressor on; “Compressor on”
- ☐ Double-check compressor at 40PSI
- ☐ “Ready for pneumatics”; “Clear” before pneumatics on; “Pneumatics on”
- ☐ Double check pneumatics box at 35PSI
- ☐ Confirm pneumatics work (arms / grippers)
- ☐ “Ready for power on”; “Clear” before power on “Power on”
- ☐ Confirm surface – ROV connection; cameras
- ☐ “Ready to arm”; “Clear” before arming; “Armed”
- ☐ Confirm motor control

ROV Launch:

- ☐ “Ready to deploy”
- ☐ All items in grippers
- ☐ Lift ROV from designated spot (use spotter)
- ☐ ROV out over water, down gently
- ☐ “Deployed”
- ☐ Look for unusual bubbles

Operating ROV:

- ☐ Tether Manager is silent except for collisions that would damage pool, people, or ROV
- ☐ Only Navigator instructs Pilot
- ☐ Others discuss with Mission Specialist, who then confers with Navigator

ROV Retrieval:

- ☐ Ensure disarmed (“Disarming”; “Disarmed”)
- ☐ Ensure pneumatics shut-off set
- ☐ “Bring on deck”
- ☐ Tether manager finds designated handholds; spotter arrives
- ☐ Lift with straight back
- ☐ Place ROV on deck so that arms are not hitting deck
- ☐ “Deployed”
- ☐ Check for water

Power-off:

- ☐ “Powering down”; “Agreed” then power off
- ☐ Ensure pneumatics shut-off valve closed
- ☐ “Depressurizing”; “Clear” then compressor relief valve

Working with ROV on deck:

- ☐ Confirm disarmed
- ☐ Confirm pneumatics shut-off
- ☐ If working around motors, confirm power-off
- ☐ Tether manager has control
- ☐ Ensure tools and equipment not left on ROV
- ☐ Ensure all wires, tape, zip ties secured
- ☐ Double check for water
- ☐ Double check water seals on ROV

A.3 JOB SAFETY AND ENVIRONMENTAL ANALYSES (JSEAs)

Pool Deck / Operations JSEAs. Review before each session. Initial and sign.

No	Job Step / Task	Potential Hazard/ Cause	Potential Consequences	Risk Reducing Measures	Responsible Person
1	Arrival at pool deck / operations area	Dehydration, low blood sugar	Loss of judgment, potentially falling	Ensure everyone is ready to be there by asking; ensure water and food are available as needed	Safety Officer (Miles L) COO (Theo L)
		Getting caught in equipment	Crushed fingers, hair pull, entanglement with equipment	Ensure everyone is dressed appropriately: closed-toed, high traction shoes, no loose or hanging ends on clothes, no hair not tied up that could get tangled in	
		Wet pool deck / floor	Slipping, falling, injury/trauma	Identify wet areas; notify team; avoid the area or clean up with towels	
2	Identifying area to set up the test	Items in way	Tripping, falling, injury/trauma	Do a visual check of the area to identify hazards before moving items into the pool/deck area	Safety Officer (Miles L) COO (Theo L)
				Identify walkways to create	
		People	Bumping, conflicts over space	Introduce team to anyone there; ask about space; identify areas for team to work; point out walkways through these areas	Outreach (Sterling H)
3	Moving in ROV and float and other necessary equipment	Heavy objects	Back injuries, falling objects on hands/feet; strained muscles; falling	Always lift ROV with two sturdy legs. Set feet and straighten back; avoid lifting from non-designated places on ROV; get help with heavier toolboxes; do not stack boxes up high; Safety Officer to watch over process and ensure above.	Safety Officer (Miles L)
		Delicate objects	Broken equipment	Make sure team knows which items are fragile (ensure labeling in place as needed)	COO (Theo L)
		Tripping	Falling	Be aware of tether and items on ground; clear path; call out items not movable to partners before starting; no running; Safety Officer to watch over process.	Safety Officer (Miles L)
4	Topside setup and power up	Toppling equipment	Broken equipment; Injuries from equipment falling on people	Place each piece separately; ensure cords are not tangled or intertwined; attach strain relief immediately (surface control box, pneumatics box, tether)	Flight Crew (Griffin F) (Tenzin L) (Thomas G) (Miles L)
		Pneumatics malfunction	Flying debris; Damage to eyes, skin, even bones	Ensure safety glasses on for everyone; visual check of all systems; check pneumatics on compressor is zero; get acknowledgment from all for compressor on and for pneumatics on	COO (Theo L)
		Power malfunction	Electrical shock; fire; burns	Check wires; check for water; ensure GFCI (use portable GFCI if unsure); ensure all wearing safety glasses; ensure power supply safety situated and surface control box is attached; use call-response protocols before turning on	Engineer (Tenzin L)

No	Job Step / Task	Potential Hazard/ Cause	Potential Consequences	Risk Reducing Measures	Responsible Person
5	ROV operations	Lifting ROV into/out of water	Back injuries	Lift with straight back; ensure good footing; ensure proper holding of ROV	Tether (Theo L)
			Falling into pool	Watch side of pool; ensure proper footing; do not step on not bearing surfaces	Tether (Theo L)
		Tangled tether	Damage to ROV; potential entanglement	Watch tether movement	Tether (Theo L)
		Tripping	Falling; injuries/trauma; broken equipment	Communicate with tether manager when approaching; Follow designated walkways; No running; Tether manager oversees	Tether (Theo L)
		Pinching	Cuts, crushing, strains/sprains	Do not approach ROV until power and pneumatics are inactive; notify everyone of activity around ROV; no hands in motors; no hands in between arm components	
6	Closing down / packing out	Heavy objects	Back injuries, falling objects on hands/feet; strained muscles; falling	Stack boxes in proper order; Set feet and straighten back; Avoid lifting from non-designated places; Get help with heavier toolboxes; do not stack boxes up high; Safety Officer to watch over process and ensure above.	Safety Officer (Miles L)
		Delicate objects	Broken equipment	Put items back in their place; ensure packaging	Engineer (Tenzin L)
		Tripping	Falling	Be aware of tether and items on ground; Clear path; Call out items not movable to partners before starting; No running; Safety Officer to watch over process.	Tether (Theo L)
7	Throughout	Slipping, tripping	Falling down; injuries / trauma	Use designated walkways; Always approach ROV and tether only after getting Tether managers attention. Analysis station to watch over	Analysis (Simon H)
		Falling into pool	Drowning	Designated rescue swimmer for pool session.	Safety Officer (Miles L)

Initial JSEAs for each section after reviewing.

Date of Pool Session ________________________ Chief Safety Officer ________________________