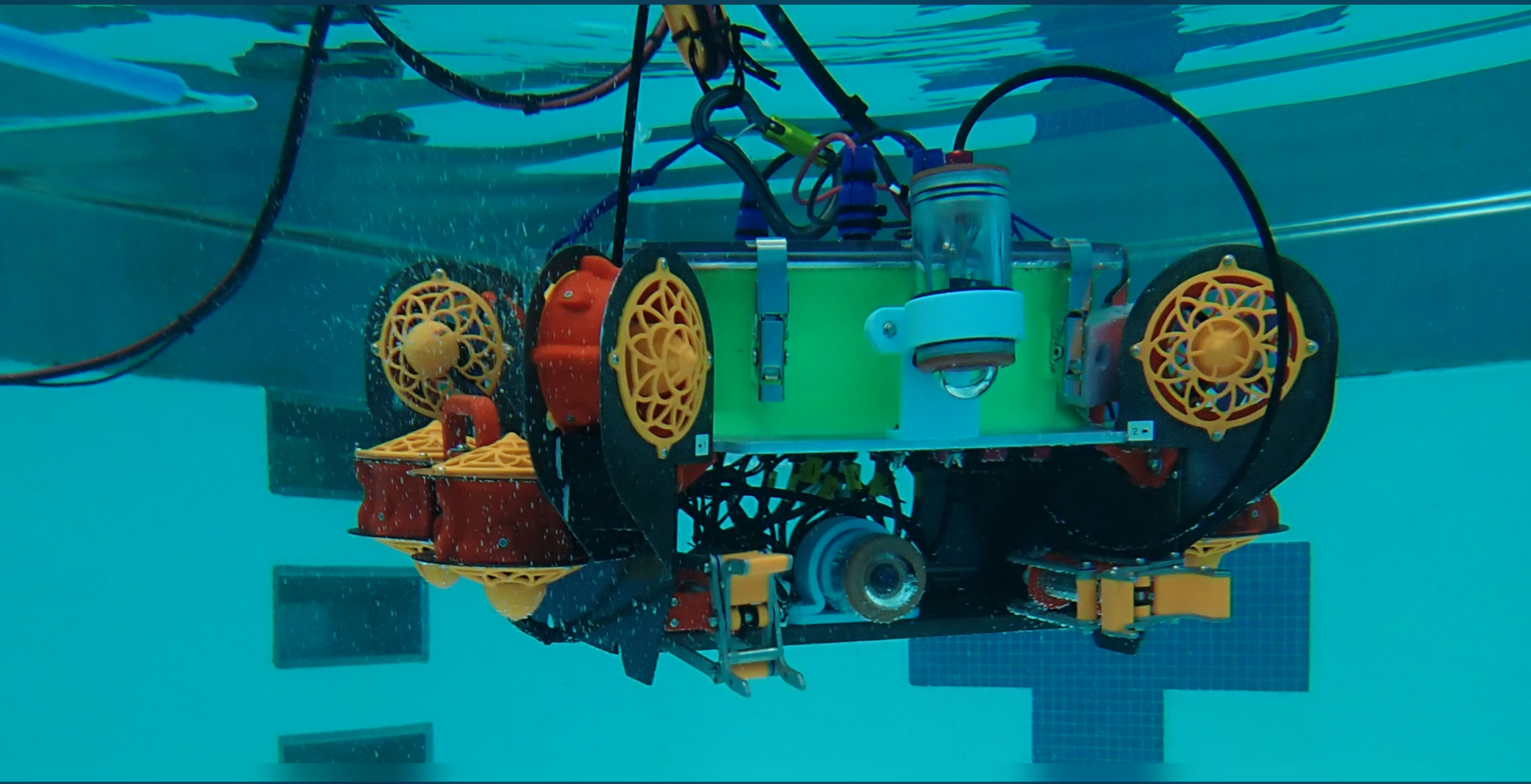
CWRUbotix

2025 Technical Documentation

Monitoring and Mitigating the Impacts of Climate Change on Our Water World

Case Western Reserve University
Cleveland, OH, USA



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Abstract

In response to MATE's Request For Proposals (RFP), the CWRUbotix ROV team presents *Shrimp Fried Rice*, a marine monitoring and repair system comprising the *Fried Rice* remotely operated underwater vehicle, Shrimp vertical profiling float, and Calamari independent photosphere sensor. *Shrimp Fried Rice* was developed over the course of a year by 23 dedicated employees at CWRUbotix. The *Shrimp Fried Rice* system excels at shipwreck exploration, buoy repair, water sample analysis, and pressure measurement.

The CWRUbotix 2025 design philosophy emphasizes versatility and reliability. To ensure our products follow the CWRUbotix tradition of excellence in design, all mechanical components of the *Shrimp Fried Rice* system are designed, manufactured, and depth tested in-house by CWRUbotix employees. Shrimp and *Fried Rice* use custom motherboards designed by our hardware engineers. To make this year's system more reliable, CWRUbotix equipped *Fried Rice* with more streamlined power supply and navigation solutions, To improve versatility, CWRUbotix emphasizes connectorization and provides a hot-swappable surface manipulation system. Each component of the *Shrimp Fried Rice* system integrates with a central surface computer for easy piloting and data access.

The CWRUbotix Compnay

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Project Management

Company Overview

CWRUbotix is an undergraduate student organization of Case Western Reserve University in Cleveland, Ohio. CWRUbotix's MATE ROV competition team comprises 23 undergraduate students. Students manage every aspect of CWRUbotix, from fundraising and budgeting to recruitment and personnel management. The team is divided into three technical departments: mechanical, electrical, and software. Each department is managed by a subteam lead, an experienced employee responsible for designing systems architecture, reviewing contributions from their team, and onboarding new employees. The three department leads report to the CEO, who is responsible for keeping the schedule and budget and manages systems integration. The CEO of the MATE ROV team reports to the CWRUbotix Executive Board, which is elected by the general body. The Executive Board oversees all of CWRUbotix's competition teams, raises funds, and interfaces with the university. Additionally, the CWRUbotix CFO and Safety Manager are members of the Executive Board. The CFO is responsible for fundraising, accounting, and purchase requests across all competition teams, and the Safety Manager oversees team bay cleanup and ensures all members comply with our rigorous safety policies. CWRUbotix's organizational structure allows the club to field teams for many different competitions and frees up the individual team leaders to focus on systems design rather than administrative responsibilities.

Schedule

CWRUbotix has found in the past that traditional project management strategies like Gannt charts are too restrictive for our development needs. Instead, we use a simple list of milestones, target completion dates, and a list of tasks to be completed for each milestone. This Agile-inspired system allows the team more flexibility to iterate and deal with setbacks, while still ensuring the team is on track to deliver a complete product on time. Each phase culminates with a clear deliverable. The design phases culminate in design reviews, during which team members present their designs to faculty and alumni. Feedback from the design reviews informs the next phase of development. The manufacturing phase culminates in the first full-systems test, which marks the beginning of the testing phase. In the testing phase, the ROV is iteratively tested and improved, eventually resulting in a reliable product ready for demonstration at the MATE ROV World Championship. This year, CWRUbotix focused more on onboarding new members than in previous years to prepare for a high turnover going into the 2025-2026 season. The team also maintained a working version of the previous year's robot as a test and pilot training platform for 2025.

Resources, Procedures, and Protocols

CWRUbotix follows a weekly development cycle. Every Saturday, the full team meets in a classroom to share updates and make a plan for the upcoming week. Most meetings are led by the CEO and subteam leads, but all employees are welcome to attend, present slides and ask questions. These meetings encourage communication between subteams and ensure each employee understands how their contribution fits into the overall system. In addition to full-team meetings, each subteam holds working meetings once a week. At the end of each week, CWRUbotix holds

Project Phase	Task Examples	Outcome	Target Date
Preseason	Onboarding, fundraising	Team ready for season	10/18/24
Conceptual Design	Task analysis, prototyping, electrical SID	Conceptual Design Review	11/23/24
Detailed Design	Integrated CAD model, motherboard routing	Detailed Design Review	3/1/25
Manufacturing	Frame assembly, software completion	Full Systems Test	4/19/25
Testing	Integrated testing, iteration, demo practice	MATE ROV Qualification	5/15/25

Table 1: Project phases for *Shrimp Fried Rice*

an integrated test at a university pool. This weekly test cycle has proven invaluable for quickly identifying problems and evaluating new solutions.

CWRUbotix uses Discord for all online communication. The CWRUbotix Discord server also serves as a repository of information, with quick access to important links, specifications, and files. CWRUbotix employs Google Suite (including Drive, Docs, and Sheets) for documentation and real-time collaboration. In addition, the team uses version control software (Github, SolidWorks PDM, and Altium Workspaces for software, mechanical CAD, and PCB CAD, respectively) to ensure all team members have access to the most recent version of the design and can work in parallel on different files. To ensure code reliability, the software team has implemented a code review process and continuous integration which automatically checks all code for syntax and style errors.

Design Rationale

Engineering Design Rationale

Fried Rice was designed to efficiently complete the tasks in MATE's request for proposals. The team's primary design goals for *Fried Rice* were effectiveness on the mission tasks, reliability, and serviceability. The team used a medley of trade studies, data from CAD models and simulations, and improved project management strategies to make informed design decisions for every subsystem.

Systems Approach

The mechanical, electrical, and software systems of *Fried Rice* were developed in parallel, with frequent intercommunication facilitated by design meetings. Systems-wide decisions such as the locations of *Fried Rice*'s cameras were discussed and agreed upon at these full-team meetings, ensuring no design inconsistencies were overlooked. In the conceptual design phase, requirements documents were developed for new subsystems, setting expectations between subteams on how different components will interconnect. For example, the requirements document for the float PCB included the maximum size of the board, the sensors that would be included, and the specific microcontroller that would be used. With this knowledge, the mechanical and software teams were able to develop the other subsystems of the float to be compatible with these requirements in parallel with the design of the float board itself. During the detailed design phase, the electrical team provided the mechanical team with 3D models of their PCBs. The mechanical team then created a complete CAD model of every component of the vehicle, including electronics. This model allowed potential intersections and conflicts between parts to be resolved before manufacturing any physical prototypes, saving material and development time.

Vehicle Structure

The ROV's primary structural components are a sheet metal frame and a watertight electronics bay, described below. This construction was designed to balance buoyancy, weight, and cost. To maximize power efficiency and maneuverability, *Fried Rice* is designed to be neutrally buoyant and hydrostatically stable, meaning that it will naturally remain stationary and upright without requiring input from the pilot. This requires that the mass and volume of the ROV be carefully tracked during the design process and fine-tuned after manufacturing (see Buoyancy and Ballast). As requested in MATE's RFP, *Fried Rice* was designed to weigh less than 18 kg in air. Within this limit, CWRUbotix opted for a relatively large and heavy robot (approximately 16 kg with an envelope of 608 $\times$ 565 $\times$ 257 mm, not including removable tools), as this allows for the inclusion of more electronics, cameras, and manipulators that add functionality. Furthermore, additional mass improves the stability of the ROV when handling larger objects, such as the pCO_2 sensor. The costs of a larger size include reduced acceleration and top speed (due to inertia and drag) as well as reduced access to tight spaces. The former downside is mitigated by a powerful propulsion and electrical power system, while the latter is mitigated by ample pilot practice. The team found in testing that *Fried Rice* is still small enough to easily navigate its environment and complete the required tasks, and that travel speed is of less importance than maneuverability, dexterity, and manipulation capability.

Frame

The ROV's frame is constructed from 1.6 mm (1⁄16 in) 5052 aluminum sheet, which offers good strength-to-weight ratio and high corrosion resistance. The components of the frame are held together using 316 stainless steel machine screws and rivet nuts, which are durable and corrosion resistant. The frame was designed to be sturdy and light, holding all components securely and leaving room in the weight budget for various tools and sensors. It also features ample mounting points for attaching tools, ballast, and buoyancy material as needed.

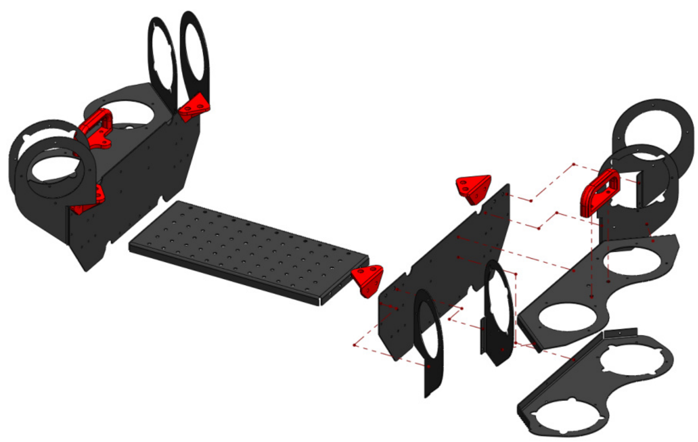

Figure 1: Exploded view of *Fried Rice*'s frame

When choosing the material and construction method for the frame, the initial trade studies considered various metals and polymers as well as a variety of construction methods. A bent sheet metal construction was chosen because it is an effective way to produce strong, lightweight structures with complex geometry. Previous CWRUbotix ROVs have featured frames constructed from flat sheet metal parts held together by 3D printed PETG gussets. *Fried Rice* employs bent features on the sheet metal parts to eliminate the need for gussets, reducing part count and weight. Aluminum was chosen over other alloys such as stainless steel in order to reduce cost and weight, with a 5052 alloy being selected for its good formability. Table 2 shows the weights of several permutations of material and design that were considered [1].

One of the major drawbacks of using aluminum is the risk of galvanic corrosion, which occurs when dissimilar metals are in contact or close proximity in an electrolytic solution. In order to mitigate this, stainless steel rivet nuts are installed in the frame components, which are then powder coated to protect the interface from water.

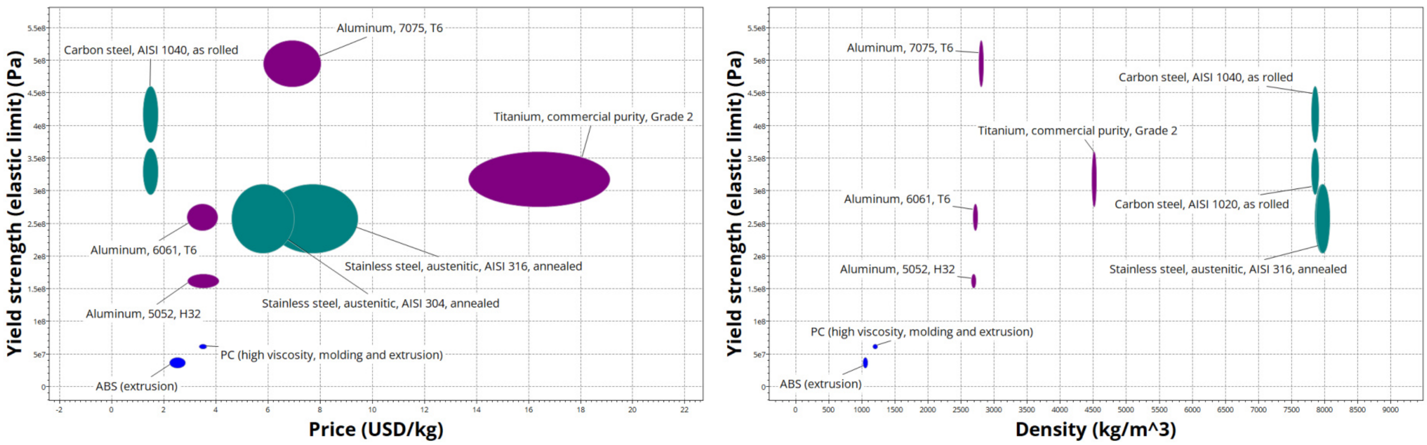

Figure 2: Metal and polymer materials considered for the frame are compared in cost and strength (left) and in strength and density (right) using Granta EduPack

Material	**With PETG Gussets**	**With Bent Tabs**
304 Stainless steel (0.76mm)	2.8 kg	2.2 kg
5052 aluminum (1.6mm)	2.3kg	1.7 kg

Table 2: Weight tradeoffs

Electronics Bay

The walls of the e-bay are 3D printed out of PETG on a Anycubic Kobra 2 Max Fused Deposition Modeling (FDM) printer [2]. The e-bay is an evolution of a design used on previous products, created in order to make it easier to lay out and fit the electronics. The e-bay is designed in the shape of a "squircle," a shape between a square and a circle, to approach a near square layout while still having rounded sides and corners that better withstand water pressure. The e-bay is 3D printed from PETG material to reduce cost and allow for unique geometry, and sits on top of a 6 mm (¼ in) thick aluminum plate to heat sink the electronics within. The final e-bay design measures 328 $\times$ 328 mm at the outermost point of the walls, leaving a 300 $\times$ 300 mm squircle interior for the electronics. The interior has 100 mm of height, large enough to fit large electronics such as the 48V power converter.

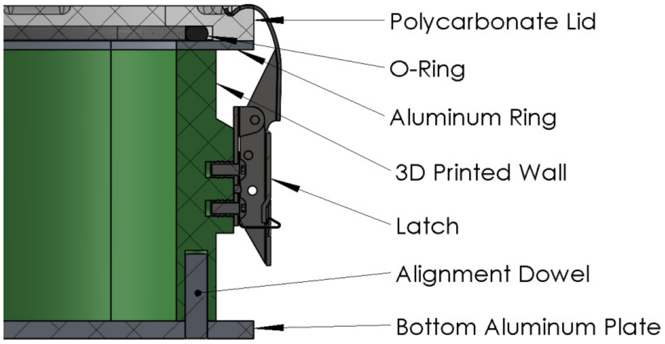

Figure 3: Construction of the e-bay

The e-bay is built on a base plate of aluminum. Aluminum was chosen for its high strength-to-weight ratio and thermal conductivity, since the base plate is both a structural component of the frame and a heat sink for the power converter and electronic speed controllers. The aluminum plate includes tabs to attach the e-bay to the frame, as well as slots for mounting cameras and manipulators, and was manufactured using a waterjet cutter.

The walls of the e-bay are 3D printed out of PETG on a Fused Deposition Modeling (FDM) printer. On previous CWRUbotix ROVs, the e-bay walls have been printed in polycarbonate on a Stratasys Fortus 400mc industrial FDM printer. In order to improve iteration time and reduce costs for Fried Rice, the company switched to printing PETG on a consumer grade machine. While PETG has a lower yield strength and modulus of elasticity than polycarbonate, simulation results indicated that it would still be suitable for this application, and the manufacturing cost is much lower (approximately $.02/g vs $.80/g). To validate the strength of the e-bay and determine the minimum thickness of the walls, finite element analysis (FEA) was performed using SolidWorks' Simulation package [11]. This allowed the team to place a defined pressure over all external faces and simulate how those faces would experience water pressure. Simulations were performed for the maximum depth of 7 m, corresponding to a pressure of approximately 70 kPa. The results of these simulations are shown in Figure 4. The maximum stress on the model in the simulation was 8.2 MPa. With a yield strength of 47 MPa for PETG [10], this corresponds to a factor of safety of 5.7.

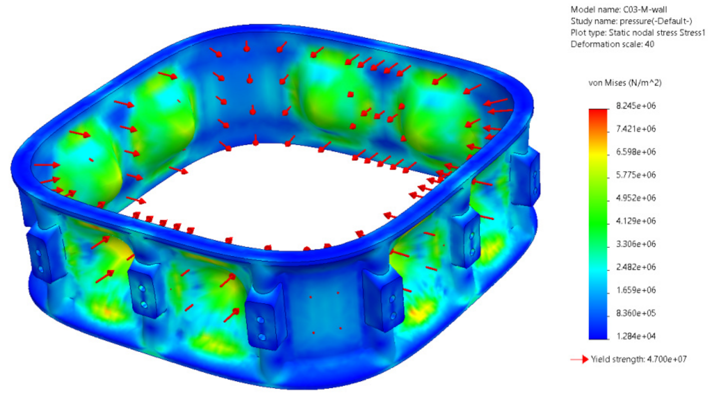

Figure 4: FEA simulation of the e-bay wall

The top lid of the e-bay is constructed of a clear polycarbonate sheet, allowing operators to see into the e-bay and diagnose any problems quickly without removing the lid. The polycarbonate lid was machined by the team on a Laguna CNC router table. The lid seals against the e-bay with a large o-ring and is held on with 12 latches, allowing quick tool-free access to the electronics.

The e-bay includes eighteen Blue Robotics wetlink and potted cable penetrators through the bottom aluminum plate and three similar penetrators through the polycarbonate lid. These lid penetrators are for the tether, containing the two power lines and Ethernet. The cable penetrators in the bottom plate lead to the thrusters, cameras, solenoids, and other devices spread across the robot.

Control and Electrical Systems

Fried Rice's electrical and control architecture is composed of two primary elements: the surface based control station and the onboard electronics housed within the ROV. These elements are connected via a tether. The onboard system is split into two subsystems: the power system, which handles the conversion and distribution of electrical power received from the surface, and the control system, which manages communication with the surface station and governs operation of all onboard components. See Figure 9 for an SID of the electrical system.

Power Electronics

Fried Rice is powered by a power supply box on the surface, which sends power to the ROV at 48 volts. However, *Fried Rice*'s thrusters run at 12 V, so the power from the tether must be stepped down before use. To solve this challenge, CWRUbotix developed a custom in-house 1200 watt power conversion solution: ScuPSU-Mini. Using two onboard buck converters, ScuPSU-Mini efficiently converts the 48 V DC supply from the tether to 12 V DC to power the ROV's thrusters. In addition, the board includes integrated voltage regulators to supply stable 5 V and auxiliary 12 V outputs for control electronics and other components. ScuPSU-Mini is significantly smaller and less expensive than the CWRUbotix's previous solution, which was purchased from a local electronics company.

In addition to converting the voltage, ScuPSU-Mini distributes power to the ROVs eight electronics speed controllers (ESCs). Each ESC connects to a high-current XT60 connector and a DuPont header for PWM signals. Though PWM signals originate from the flight computer and not ScuPSU-Mini, routing these signals through the power board greatly simplifies ESC wiring, allowing each ESC to connect directly to a single board. All eight PWM signals are carried from the flight computer to ScuPSU-Mini via a single ribbon cable. To reduce expenses associated with international manufacturing tariffs, the board was entirely assembled in-house.

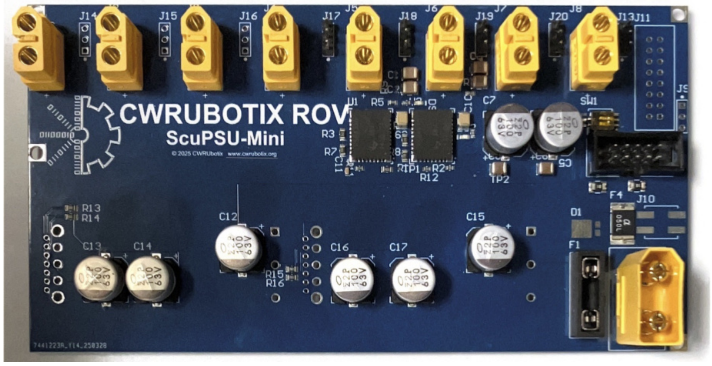

Figure 5: ScuPSU-Mini

Motherboard

The motherboard serves as the central hub for *Fried Rice*'s control system, connecting the surface computer to the onboard Raspberry Pi Compute Module 5. The Pi was selected for its high-speed performance, robust support for ROS 2, and integrated I/O, including Gigabit Ethernet, USB 2.0 and a PCIe x1 lane. The PCIe lane is used to interface with a USB 3.0 controller card, enabling four high-speed USB connections for onboard peripherals.

The board includes a 5 V to 3.3 V regulator to support the PCIe specifications and power auxiliary components. It also features UART, GPIO, and expansion slots that connect to various daughterboards, minimizing wiring complexity and improving serviceability. USB 2.0 connects the Pi to the ROV's flight controller, while Ethernet is used for communication with the surface system.

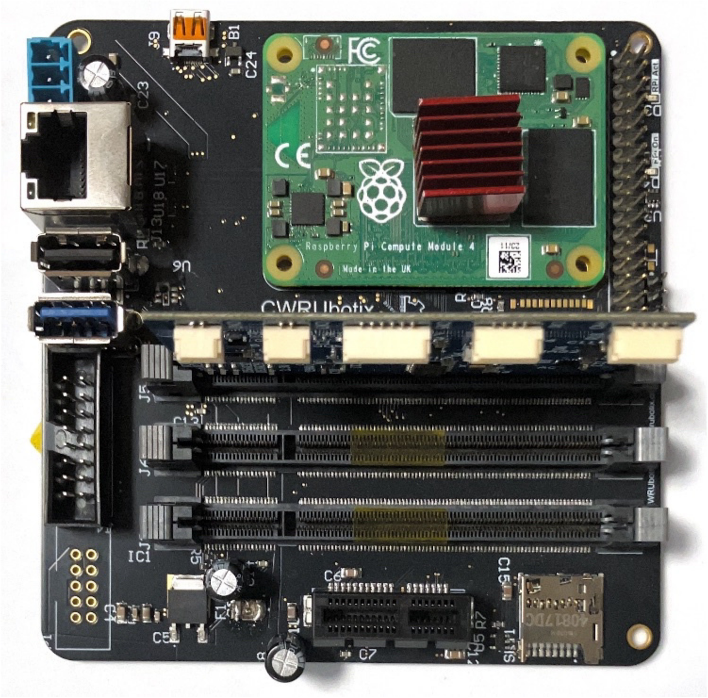

Figure 6: The Motherboard

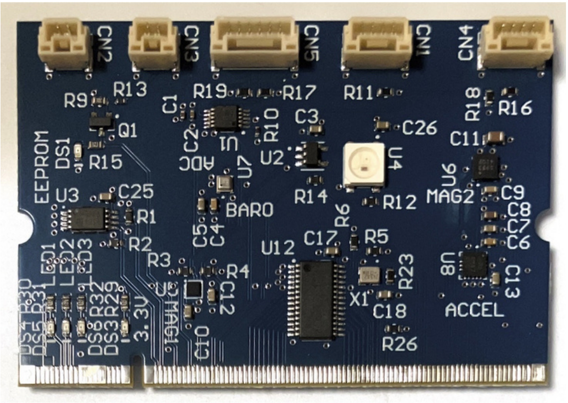

Figure 7: Custom Navigator

Navigator

The Navigator serves as the flight computer for *Fried Rice*, handling all real time control and motion related tasks critical to stable underwater operations. Designed in house, the Navigator connects to the motherboard via a dedicated daughterboard slot, allowing for streamlined integration and minimal wiring. It features onboard sensors including a magnetometer and compass for navigation and a leak detector for safety. The Navigator outputs PWM signals to control the ROV's thrusters, translating high level movement commands into precise motor instructions. By processing sensor data and managing the ROV's response to its environment, the Navigator ensures stable, responsive maneuvering across all six degrees of freedom. This board plays a crucial role in determining how the robot moves, responds to pilot input, and maintains its position, enabling both manual and autonomous operation with high reliability.

Control Box

To improve on operational efficiency, the Shrimp Fried Rice surface control box replaces previous CWRUbotix ROVs' cable sprawl with a single, easily transportable unit. The control box accepts AC power through an IEC C14 socket, which is directed by a consumer power strip to the surface laptop power supply and (using a built-in converter) over USB to the surface router. We chose to purchase a power strip for our high voltage wiring to ensure robustness in this critical system. The laptop power supply powers a central laptop dock, which provides port expansion over a single thunderbolt cable for the router, a built-in monitor, and the profiling float surface transceiver. The control box also includes pass-throughs for 48 VDC and pneumatics, with an inline emergency stop button for DC power and a pressure regulator and readout for the pneumatics.

Figure 8: The control box

Tether/Tether Management

Fried Rice's tether is designed for reliability; prioritizing flexibility and durability. It contains two power cables, a CAT6A Ethernet cable, and a 6 mm (1/4 inch) polyurethane pneumatic line. The power cables are 10 AWG UL Standard 1426 marine grade wires designed to be lightweight and flexible, with the positive wire connected to a 25 A fuse between the ROV and control box. The Ethernet cable is outdoor rated for improved durability. Strain relief anchor points are located on both sides of the tether, attaching to the frame of the ROV and the control box. In addition, flexible strain relief cones (3D printed in TPU) are fit around the penetrators in the lid of the e-bay to protect the cables from bending. To keep the tether out of the way of the ROV's path, several blocks of buoyancy foam are attached to the tether. The tether is designed to be approximately 10 meters long. This is long enough to reach all of the tasks in the pool but short enough that there is only a small voltage drop of approximately 1.9 V across the power wires when the maximum current of 25 A is drawn.

During operation of the ROV, a tether manager is designated to follow CWRUbotix's tether management protocol. While transporting the ROV outside of the pool, the tether manager carries the tether and ensures that it does not become a tripping hazard. Before deployment, the tether manager coils the tether on the pool deck. During operation, the tether manager pays out and reels in the tether as the ROV moves, ensuring that there is no tension in the tether but that there is no excess slack in which the ROV could become entangled.

Software

Fried Rice's control system is split into four subsystems:

1. the surface system, which is hosted by a laptop on the surface,
2. the ROV system, hosted on the Pi CM5 module onboard the ROV,
3. the independent photosphere sensor,
4. and the float system, a custom RP2040 float board and an Adafruit Feather transceiver board.

We connect our surface, ROV, and photosphere systems over an Ethernet network managed by the surface-side router. Using Ethernet for communication over both tethers minimizes camera feed latency (versus USB) and tether size (versus many analog connections).

SID

ROV Full Load Amps (FLA) in water = 21 A

Fuse size selected based upon FLA = 25 A

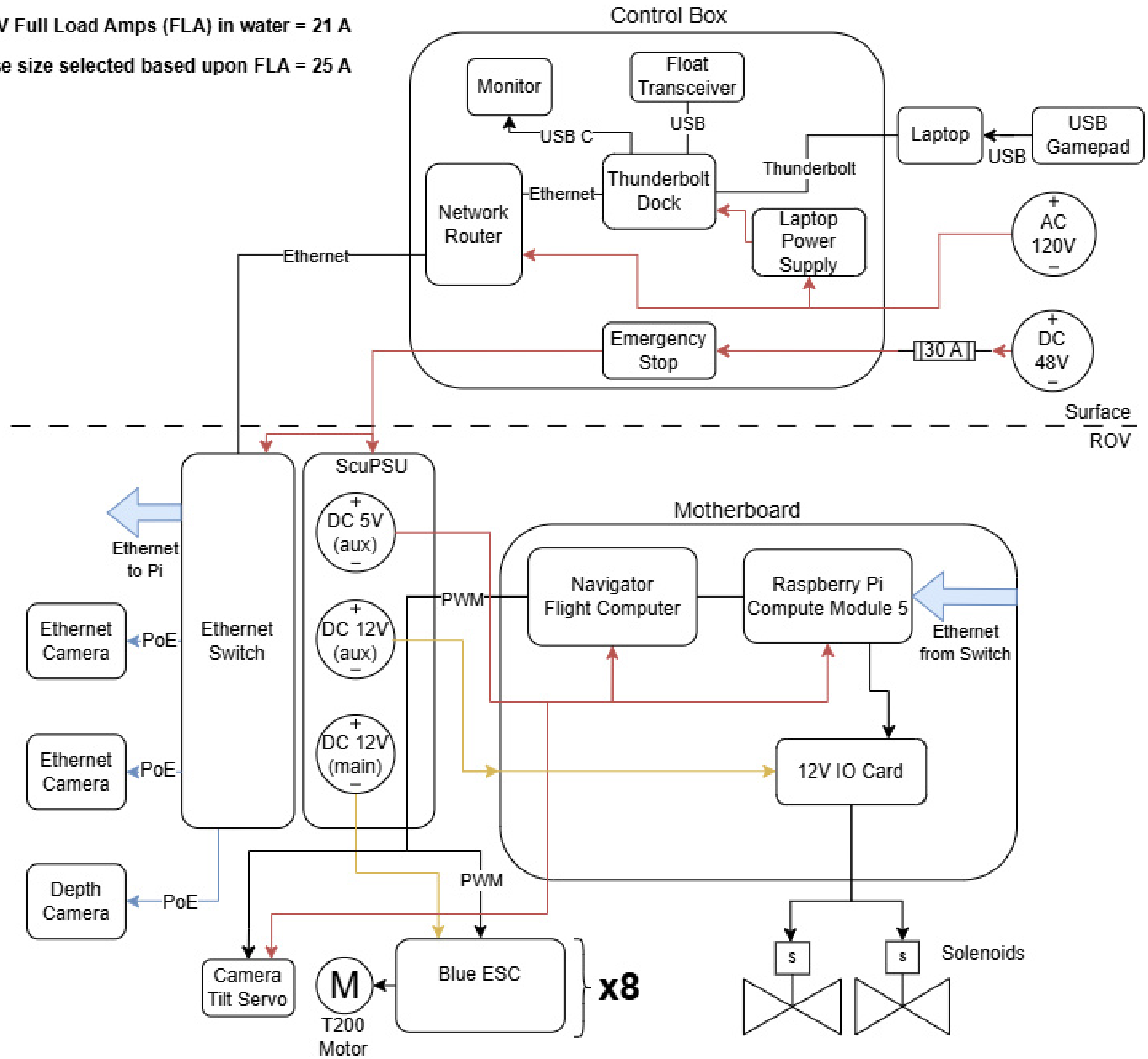

Figure 9: Electrical system SID

BlueOS

The Raspberry Pi compute module on the ROV runs BlueOS, a software ecosystem developed by Blue Robotics [5]. BlueOS manages the ROV's thrusters, sensors, and the Ethernet connection to the surface control box, and provides a simple web interface to manage the vehicle. BlueOS also runs an instance of ArduSub, an open-source autopilot system, which listens for commands from the pilot and controls each of Fried Rice's thrusters to achieve the desired forces and torques on the vehicle [3]. Using BlueOS rather than a custom-built vehicle management system increases system reliability and frees up our developers to focus on mission-specific tasks like photosphere creation and shipwreck measurement.

To interface BlueOS with our custom relay board, CWRUbotix developed a custom BlueOS extension, which receives commands from the surface control station and sends I2C messages to the relay board to open and close Fried Rice's manipulators. In BlueOS, extensions are implemented as Docker containers which run separately from the core BlueOS services [8]. If there is an error in our custom extension, BlueOS will continue to operate and the pilot will remain in control of the vehicle.

Communication

One major concern for our software system this year was decreasing latency in pilot video feeds and control signals. We considered four protocols for communication over the tethers: Robot Operating System 2, websockets, GStreamer (video only), and Mavlink (thruster control only).

ROS 2 was chosen for all latency-insensitive messages, including manipulator actuation and graphical user interface (GUI) actions, as (1) its highly structured design encourages well-organized networks with strongly typed messages and (2) our previous iterations of the Fried Rice system were designed to integrate with ROS. The ROS paradigm supports easy codebase organization by splitting what would otherwise be monolithic single-file control logic into discrete, parallelizable units called "nodes." By organizing our codebase around ROS nodes, CWRUbotix was able to create a GUI with the highly maintainable model-view-controller paradigm, completely decoupling robot state management from its graphical representation.

Pure Mavlink messaging was chosen for pilot thruster instructions to minimize latency. The original *Fried Rice* system used the ROS 2 package mavros to tunnel these instructions through ROS, but this architecture proved to be too slow when communicating with BlueOS. Websocket streaming was chosen for sending video frames to the surface from the USB cameras on the photosphere independent sensor, as the performance cost of the ROS 2 runtime is too significant for the reduced compute available on the independent sensor.

Propulsion

Fried Rice is propelled by eight T200 [6] thrusters from Blue Robotics. These thrusters were selected for their combination of price and reliability: T200s are thoroughly tested and documented by the manufacturer, and have proven their reliability in previous vehicles from CWRUbotix and many other companies. They are also the most affordable option among reputable vendors who provide testing information.

The eight thrusters are arranged with four vertical and four horizontal thrusters. This arrangement satisfies the piloting requirements of controlling providing thrust in all three translational axes (surge, sway, and

Solutions	Latency	Network Organization	Packet Formatting	Video Support	Refactor Cost
ROS + Mavros	Moderate	Strong	Strong (typed)	Moderate	None
Websockets	Low	None	Poor (untyped)	Moderate	Moderate
GStreamer	Low	None	Poor	Strong	High
Mavlink	Low	None	Strong	None	Moderate

Table 3: Comparison of communication protocols

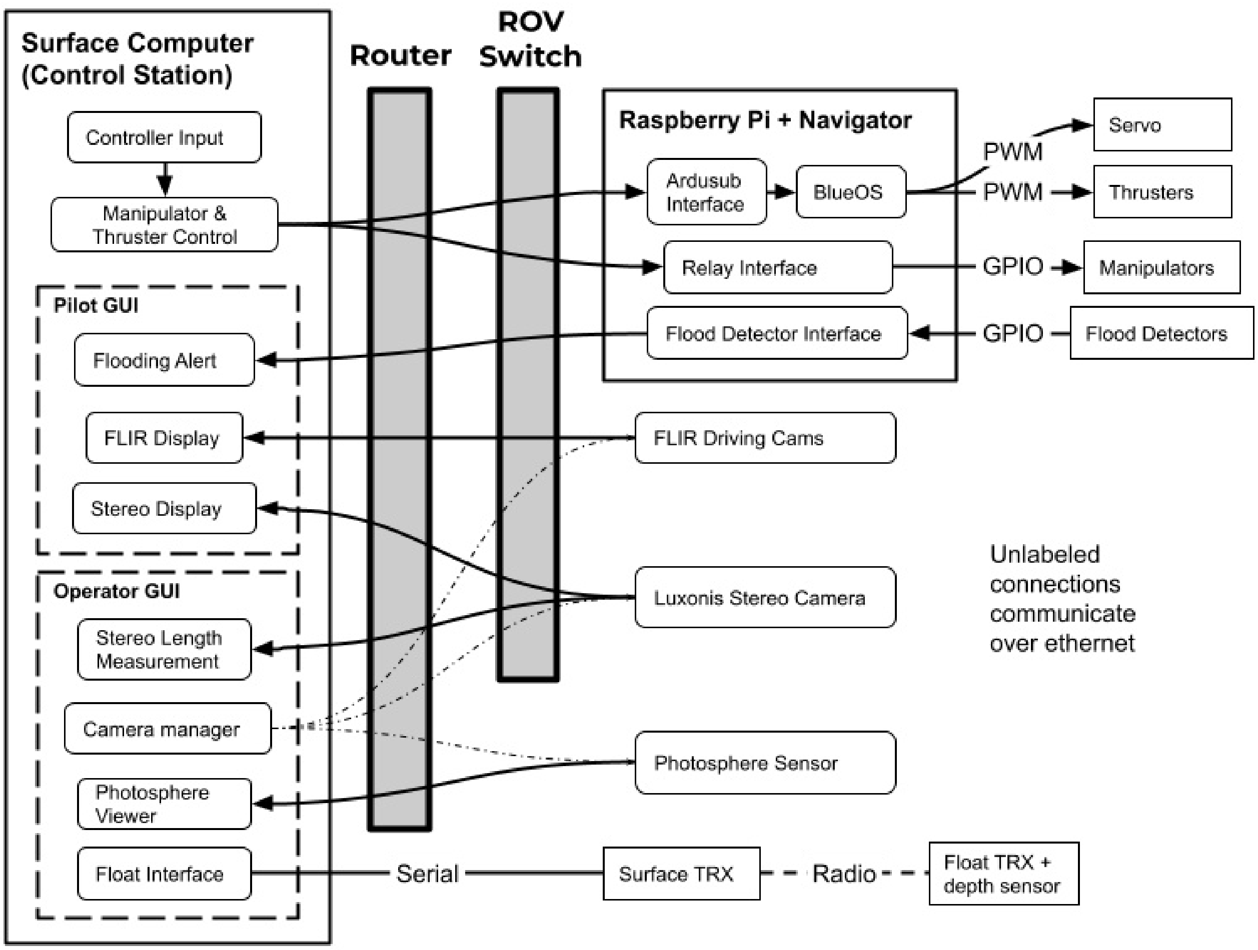

Figure 10: Software system SID

heave) and torque about the yaw and pitch axes (our vehicle is also capable of roll but we found this to be unnecessary for the mission tasks). While these movements could be achieved with six or even five thrusters, using eight thrusters allowed us to place them on the sides of the vehicle, keeping the front and back clear for cameras and manipulators. This arrangement also cleanly separates the thrusters responsible for horizontal movements, simplifying the control system and power distribution.

Buoyancy and Ballast

Fried Rice is designed to be neutrally buoyant and hydrostatically stable when upright. Neutral buoyancy requires that the mass and volume of the ROV be precisely balanced so that its weight is equal to the buoyant force when submerged. Hydrostatic stability is achieved when the center of mass of the robot is directly below the center of volume, at which point the net weight and buoyant forces are collinear, and any change in orientation creates a restoring moment which returns the vehicle to its equilibrium position. In order to achieve these goals, all components of the ROV were modeled in CAD with accurate mass and density. The total mass and enclosed volume, as well as center of mass and center of volume, were determined from the model. From this information, the company determined an estimate of the amount of ballast required and where it should be placed to achieve the desired condition. Using this estimate as a starting point, engineers trimmed the buoyancy of the final ROV by placing it in water and adding, removing, and relocating ballast until the ROV sits level and does not tend to sink or float.

Payload and Tools

Linkage Claws

For general-purpose manipulation tasks, *Fried Rice* features two pneumatic grippers, called linkage claws, on the front of its frame. The linkage claws are able to manipulate objects up to 50 mm in diameter, allowing them to be used for the majority of tasks that involve depositing, retrieving, or manipulating objects. Pneumatic cylinders are fast-acting and naturally compliant, allowing the pilot to quickly and securely grasp a variety of targets with simple controls. The linkage claw is designed to allow for some misalignment between the claw and a prop; it features a wide area in which an object can be placed and still be successfully captured. The linkage mechanism itself is inspired by toy claw grabber arms, modified to fit our pneumatic actuators and PVC pipe. The linkage mechanism was waterjet cut out of 3.175 mm (1/8”) 304 Stainless Steel, chosen for rigidity. The spacers and mounting bracket were 3D printed with PETG filament. The front of Fried Rice features two variations of the linkage claw, oriented at 90 degrees to one another. These two manipulators allow for a wide variety of manipulation tasks without needing to rotate the claws or the ROV. Additionally, both claws can be used simultaneously for certain tasks (e.g. applying an epoxy patch).

Figure 11: Vertical linkage claw

Figure 12: Horizontal linkage claw

Water Sampler

In order to collect water samples and return them to the surface, *Fried Rice* is equipped with a pneumatically actuated syringe, inspired by the design of single-acting pneumatic cylinders. Application of compressed air pushes a plunger to the front of the syringe, emptying it. When pressure is released, a spring returns the plunger to its original position, sucking in water from the tip. The syringe is held in the vertical linkage claw, allowing it to quickly be added and removed when not in use so that it does not interfere with other tasks.

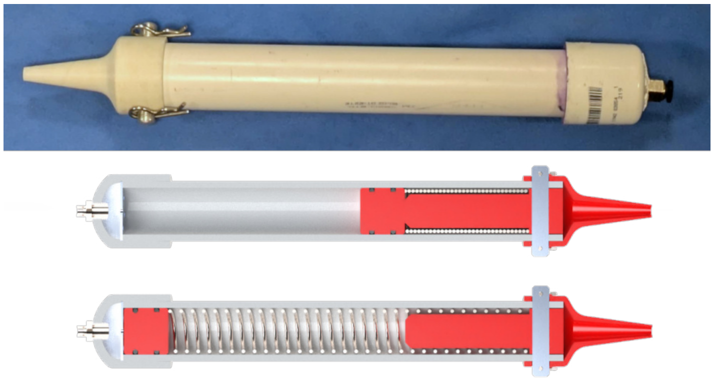

Figure 13: Photo of water sample syringe (top) cross-section renders (bottom two rows)

Removable Manipulators

Certain mission tasks require the collection of biological samples (such as jellyfish polyps and various fish species). For each of these tasks, CWRUbotix has designed a corresponding purpose-built collection device, described below. Since these tools are single-purpose and relatively bulky, they are designed to be easily removable and interchangeable. Each tool can be mounted on the back of the ROV and is held in place by a cam handle, allowing them to be quickly added and removed in the field.

Fish Net

The fish net consists of a rectangular net (bordered by PVC piping) attached to a pole. The fish net is open from below, allowing the operator to collect fish species by raising it above the balls and then diving down. The mesh of the net allows free flow of water and "grips" the fish that get stuck in its slots. The length of the pole puts the net well above *Fried Rice*, allowing the robot to stay fully submerged, maximizing maneuverability.

Figure 14: Fish net

Polyp Hook

The polyp hook consists of a pole with a hooked end. The length of the pole is long enough for the hook to reach the surface of the water while allowing the propellers to remain fully submerged. The hook's design is simple and static to maximize reliability.

Onboard Cameras

Fried Rice's camera system was designed to meet the needs of both piloting and computer vision-based mission tasks while balancing manufacturability and serviceability. The camera system consists of forward-facing and downwards-facing monocular cameras towards the front of the robot and a variable pitch stereo camera on the rear of the robot. The stereo camera can be used horizontally for piloting and taking measurements of underwater structures or rotated upwards for collecting fish and jellyfish samples from the surface. Using this system, we are able to perform every mission task with only three cameras. The monocular cameras are positioned to ensure that the linkage claws can operate comfortably within each camera's FOV (field of view) aiding the pilot in aligning the manipulators with underwater objects. The stereo camera system is designed to rotate either downward to take consistent measurements of the shipwreck (using stereo vision to generate a disparity map from which 3D position may be derived), or upward to view our custom surface manipulators for jellyfish and fish retrieval tasks.

Previous iterations of CWRUbotix ROVs have used both USB3 and Ethernet (IP) cameras. Monocular camera options were reevaluated during *Fried Rice*'s conceptual design phase. Industrial IP cameras were chosen for *Fried Rice* because they meet our latency requirements, do not require additional cables in the tether, and do not consume compute resources on the onboard computer.

Teledyne Marine graciously donated two Blackfly S GigE FLIR cameras for use on *Fried Rice* [4]. These are high quality machine vision cameras designed for industrial use. Each FLIR camera is connected to the e-bay by a single Cat 6 Ethernet cable, which carries both data and power. A Power over Ethernet (PoE) capable network switch in the e-bay injects 48 V power from the tether to power the cameras. It also routes network traffic from the cameras to the Cat 6 Ethernet cable which runs up the tether to the surface managed router, where the streams are routed to the surface laptop and displayed to the pilot. This streaming solution results in a glass-to-glass latency of less than 100 ms. A ROS camera management node provides ROS services to toggle individual camera streams, keeping any unnecessary streams off the network to avoid wasting bandwidth.

Luxonis provided CWRUbotix with a discounted Luxonis OAK-FFC 4P PoE stereo camera main board and two OAK-FFC OV9782 W sensors [9]. Using separate Luxonis PoE and camera sensor boards allows for configurable baseline distance between stereo camera sensors (as opposed to all-in-one stereo options like the OAK-D Lite), which in turn improves disparity map accuracy for large objects. The Luxonis OAK lineup also provides onboard compute, allowing us to run image processing pipelines directly on the camera board, offloading image rectification and freeing up the Pi's resources for other tasks. The selected camera sensors do not detect infrared light, as CWRUbotix determined that infrared wavelengths are attenuated too significantly in water to be useful for measuring distant objects.

Solutions	Latency	Onboard Hard-ware	Onboard Compute Cost	Tether Girth	Cabling
USB3 Cams	Moderate	Simple	High	Slim	Simple
Analog Cams	Very Low	None	None	High	Simple
MIPSI Pi Cams (USB C)	Moderate	Simple	High	Slim	Difficult
IP Cams + PoE	Low	Moderate	None	Slim	Simple

Table 4: Comparison of monocular camera types

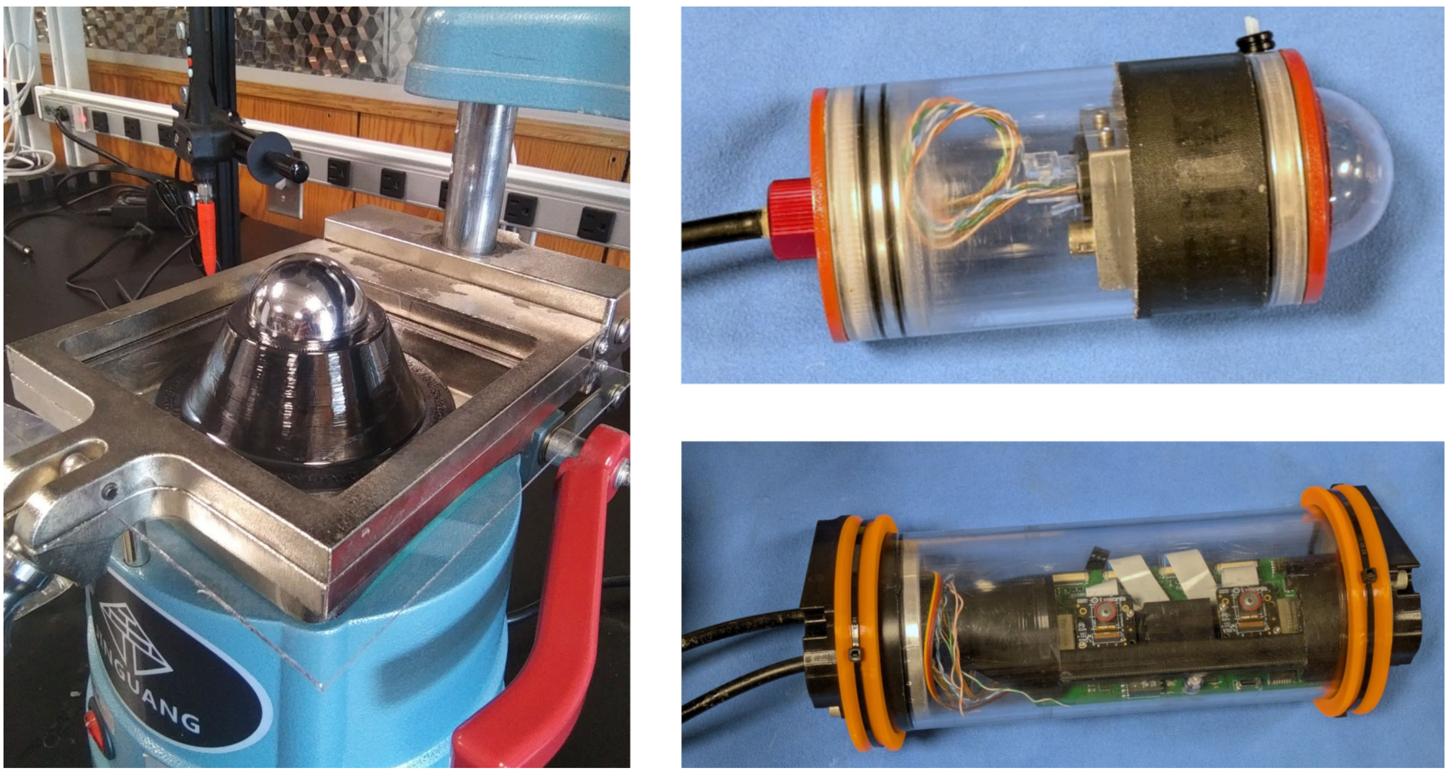

Figure 15: In-house dome vacuum forming process (left), Flir camera with enclosure (top right), rotating Luxonis stereo camera (bottom right)

An air-filled enclosure for each camera was manufactured completely in-house, with durable aluminum end caps and clear polycarbonate tubing to ensure visibility. The Flir camera enclosures use a custom vacuum formed dome which reduces distortion to the lens (as compared to a flat interface), and have a quick-release locking cord for serviceability. The stereo camera enclosure uses a servo motor supported by ball-bearings to ensure the camera is consistently supported and aligned throughout its 270 degrees of rotation.

Leak Sensors

Fried Rice includes several Blue Robotics leak detectors which are monitored over GPIO on the Pi. On water ingress, these sensors will become electrically closed, sending a message to the surface laptop over ROS. The pilot GUI then displays an obvious warning text and starts an audio alert to ensure the control station team presses the emergency stop quickly.

Independent Photosphere Sensor

To meet MATE's request for 360° photospheres of shipwreck environments, CWRUbotix developed the independent sensor Calamari. The independent sensor comprises a Raspberry Pi Zero 2 with USB and Ethernet hats, two USB camera sensors with overlapping 190° fields of view, and an enclosure made from a polycarbonate cylinder with transparent vacuum-formed domes for each fisheye camera. The electronics are mounted inside a 3D-printed frame that compartmentalizes the computer and cameras. This frame is then fit into the polycarbonate cylinder, and the cameras are pushed out into the vacuum-formed domes to fully utilize the field of view. Two aluminum end caps were turned to enclose the system, and the domes were epoxy coated onto the polycarbonate cylinder for waterproofing.

This independent sensor is tethered to the surface by an Ethernet cable and 12 V power cables. It exposes a Websocket stream for each camera over its Ethernet connection, which is then accessible by the surface laptop through the surface router. These streams are ingested by a ROS node, which caches the most recently received frames. Instead of streaming the full photosphere, compute resources are conserved by requiring the equirectangular [7] projection of each stitched photosphere to be requested manually by the operator over a ROS service. The position of the independent sensor may be corrected using the raw camera streams.

CWRUbotix originally considered mounting the photosphere system to a telescoping pole attached to *Fried Rice*. The proposal was discarded due to worries that the pole would interfere with surface manipulators and that the e-bay would obscure too much of the photosphere image for all targets to be visible. Alternative camera arrangements were also considered, including a single sensor rotated by a servo motor and three static sensors with smaller FOV. CWRUbotix chose to use two static sensors to avoid variation in sensor yaw across photospheres (caused by servo jitter) and to simplify the manufacturing process by requiring only two camera domes.

Build vs. Buy, New vs. Used

The decision to build or buy components is based primarily on three factors: experiential value, reliability, and cost. As a club, CWRUbotix's purpose is to provide an avenue for its members to gain hands-on engineering experience, and to that end we try to design and build as much as we can in-house. However, when making this decision, the reliability of the part as well as time and monetary costs must also be taken into account. If a part is particularly complex or expensive to make, such as cameras, thrusters, and cable penetrators, we typically choose to buy rather than build those components. For the vast majority of parts, however, the desire to gain experience and learn from designing and building parts ourselves usually outweighs the time cost and potential risk, even for critical components such as enclosures, the power supply unit, and manipulators, which are all custom designed and built by the team.

Whether to reuse components is dependent on whether the part was purchased or built, and the potential value associated with using a new part. Purchased parts such as cameras and thrusters are often reused to reduce waste and monetary costs, while custom built parts such as enclosures are often remade year-to-year for the experiential value and so the designs can be iterated and improved upon.

Safety

The safety of team members is CWRUbotix's highest priority, along with the safety of the fellow design teams in CWRU's makerspace, Sears think[box]. CWRUbotix team members follow industry-standard safety practices at all times, and the team has a dedicated Lab and Safety Manager who enforces these safe practices, ensures that the workspace is clean, as well as maintains and makes available safety equipment. In the lab, first aid kits and fire extinguishers are placed in convenient locations with good visibility, all flammable materials are stored in the fire cabinet unless they are being actively used, and aisles are kept clear. Team members in the lab are required to wear safety glasses and closed toed shoes, and wear additional safety equipment when necessary.

There are several safety features implemented on *Fried Rice*. The thrusters are surrounded by IP20 guards that prevent objects from contacting the blades of the propellers, protecting operators and wildlife and avoiding objects becoming tangled in the thrusters. All metal components of the robot are deburred to prevent injury when they are handled. The strain relief system ensures that the ROV can be safely held by the tether without damage to the cables, preventing electrical faults and electrocution. During testing, the ROV is confirmed by a team member to be powered off between tests before touching the electronics.

The ROV construction safety checklist and ROV operation safety checklist are detailed in Appendices A and B.

Testing & Troubleshooting

In order to ensure the safety of electronic components, all watertight enclosures must be thoroughly tested before being populated. As a preliminary test, empty enclosures are placed underwater in a bucket or sink for 30 minutes or longer, providing a quick and easy way to detect major leaks. Once all leaks have been eliminated in low-pressure tests, enclosures are tested at depth. During testing, enclosures are filled with paper towels; in the event of a leak, these towels absorb the water and retain it near the source, allowing the faulty component to be identified. After an enclosure has survived a test of one hour at a depth of 3 m (10 ft) with no water ingress, it may be put into operation.

Electronics testing is typically performed with an oscilloscope or multimeter. Oscilloscopes are used to measure the performance of the new ScuPSU-Mini power supply, and multimeters are used to measure voltages at a point, such as during testing of custom Navigator flight controller boards. Multimeters are also used when running tests combining software and hardware as a quick way to verify that code works as expected without connecting all the hardware components which the code could affect.

The *Fried Rice* software stack is designed to constantly provide useful debugging information through a tiered logging system, including messages about the connectivity of the onboard Raspberry Pi, Navigator flight controller, Ethernet and cameras, I2C board, and float communication system. The system allows for variable severity depending on how critical each of these connectivity issues are, and will periodically attempt reconnections where applicable. To summarize the most important of these messages, the operator GUI displays whether the onboard Raspberry Pi is connected to the ROS network and whether the Pi can communicate to the Navigator flight controller, tracking the latest reception of a "heartbeat" message from the Pi. These heartbeats also provide wireless and Ethernet LAN IP addresses for easy connection to the onboard Pi when rapid debugging is required.

In the earlier stages of the design process, CWRUbotix utilized a previous ROV model, *Scuba Dooba Tuba Electric Beluga*, as a platform to test new designs for manipulators, electronics, and camera systems. This platform allowed the company to quickly validate designs, and substantially accelerated the prototyping process.

Once *Fried Rice* was fully assembled, CWRUbotix prioritized full systems integration testing. During these tests, the performance of the ROV was evaluated while completing the majority of the tasks available at competition. A pilot, operator, tether manager, prop manager, judge liaison, and coach were designated during these tests in order to practice for product demonstration. The tasks the team performed tested waterproofing, visibility through the ROV's cameras, and the ROV's ability to maneuver and grip objects. To ensure safety during operation, the product demo crew followed our safety protocol checklist (Appendices A and B). After these tests, we assessed the performance of the ROV and determined if there were any problems that needed to be addressed. Issues were then discussed further at our MATE ROV full-team meetings, where all members were encouraged to attend to propose design solutions.

Accounting and Budget

The CWRUbotix ROV team's budget is allocated each year out of the larger CWRUbotix organization's funds, which are split between each of the competition teams operating under the CWRUbotix umbrella. Specifically, the ROV team is allocated a portion of each relevant major funding source, as some funds are earmarked for specific purposes (e.g. robot parts or travel). Under this system, non-specialized purchases, such as general tools or lab safety equipment, come out of the overall CWRUbotix budget and not the ROV team's. These are therefore not included in this document. Projected budget requirements are estimated through an analysis of the previous year's spending in conjunction with any expected significant changes such as expensive materials or differences in travel costs. For a detailed view of the CWRUbotix ROV team's budget and project costing, see Appendix C.

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Appendix A: ROV Construction Safety Checklists

Construction

1. Ensure that the power is off
2. Check that the inside of the e-bay is dry
3. Make sure there are no loose wires and connections to penetrators are secure
4. Put on latex gloves
5. Check that the sealing surface is clean
6. Lubricate O-ring as needed
7. Set the e-bay lid on top of the e-bay
8. Flip the latches to secure the e-bay lid

Disassembly

1. Ensure that the power is off
2. Dry the lid as best as possible, especially on the outer edges to prevent water from entering the e-bay
3. Release the latches
4. Technician 1 quickly and carefully lift the e-bay lid
5. Technician 2 quickly disconnect Ethernet between penetrator and electronics
6. Technician 1 place the lid down to the side
7. Ensure that the e-bay is dry

Appendix B: ROV Operation Safety Checklists

Pre-Dive

1. Ensure that the power is off
2. Make sure the e-bay lid is sealed.
3. Verify poolside and ROV-side strain relief are secure
4. Connect control box to power supply and compressor
5. Unspool the tether and check for tangles
6. Verify electrical and pneumatic connections are secure
7. Check that the thrusters are free from obstructions
8. Turn on power to control station
9. Wait for surface computer to connect to ROV
10. Verify all camera streams are displayed on the surface computer
11. Operator calls "Arming" and arms the ROV
12. Verify all thrusters and manipulators are functioning correctly
13. Disarm the ROV

Launch

1. Verify the ROV is disarmed
2. One person grab the ROV by the tether strain relief and put it in the water
3. Check that no bubbles are escaping from the e-bay. If there are bubbles, follow the Leak procedure.
4. If no bubbles are present, the poolside crew calls "Ready to arm"
5. Operator calls "Arming" and arms the ROV

Recovery

1. Operator calls "surfacing" as the pilot directs the ROV to the poolside surface
2. As the ROV reaches the surface, operator disarms the ROV and calls "Disarmed"
3. A poolside crew member pulls the ROV out of the pool by the tether strain relief and sets it down on the poolside
4. Operator turns power off from control station
5. Poolside crew checks for water in e-bay before relaunch or completion

Leak

1. Crew member calls "Leak"
2. Operator hits the emergency stop button in control station
3. Tether manager uses the tether to pull the ROV to the poolside
4. Visually check for water in e-bay. If water is present, remove the lid and dry all components with towels.
5. Check for corrosion on all electronics
6. Ensure all entry points are watertight with hydrophobic grease
7. After drying, test full system to ensure complete functionality

Appendix C: Budget and Project Costing

Budget Category	Sub-Category	Item Description	Type	Worth	Budget	Spent
Electrical	Onboard Hardware	PSU buck converters, RPi, Connectors	Purchased	$558.62	$600.00	$558.62
		T200 Thrusters x8, ESCs x8	Reused	$2,064.00	-	-
		POE Switch	Reused	$94.99	-	-
	Custom PCBs	Board manufacturing, Components	Purchased	$2,840.65	$2,845.85	$2,840.65
	Float Electronics	Motor, Batteries	Purchased	$117.94	$150.00	$117.94
		Depth sensor	Reused	$75.00	-	-
	Control Station Electronics	Router, Monitor, Control laptop	Purchased	$1,459.71	$1,500.00	$1,459.71
		Power Supply	Purchased	$700.00	$700.00	$700.00
		Tether	Reused	$150.00	-	-
		Control station pnuematics, E-Stop button	Reused	$115.00	-	-
		USB dock	Donated	$70.00	-	-
	Spare COTS Components	Flight computer, Solenoid valves	Purchased	$117.49	$300.00	$117.49
		T200 Thrusters x2	Reused	$516.00	-	-
Mechanical	Manufacturing	Waterjet machine time	Purchased	$76.60	$80.00	$76.60
	Fasteners & Mech. Hardware	Nuts/Bolts, Pnuematics, Misc mech compnents	Purchased	$711.99	$770.00	$711.99
		E-bay latches	Reused	$252.00	-	-
	Waterproofing	O-Rings, Penetrators, Grease	Purchased	$55.88	$200.00	$55.88
		Penetrators, Leftover o-rings	Reused	$116.00	-	-
	Raw Material & Stock	Sheet metal for frame & ebay, stock for enclosure endcaps	Purchased	$511.18	$750.00	$511.18
		Control station box	Reused	$169.95	-	-
		Onboard pnuematic pistons	Reused	$128.00	-	-
	Float Components	Tube, O-Rings/X-Rings, Rods, Fasteners, Waterproof connector	Purchased	$322.25	$350.00	$322.25
		Aluminum stock	Reused	$70.00	-	-

(continued on next page)

Budget Category	Sub-Category	Item Description	Type	Worth	Budget	Spent
Sensors & Testing Hardware	Cameras, Sensors	Camera lenses, Photosphere components	Purchased	$807.98	$825.00	$807.98
		FLIR Blackfly cameras x2	Donated	$742.00	-	-
		Luxonis stereo camera	Donated	$550.00	-	-
	Testing Hardware & Supplies	Test flight computer, servo, wide angle lenses	Purchased	$412.67	$425.00	$412.67
Production Costs				$13,805.90	$9,495.85	$8,692.96
Competition Expenses	Registration & Fluid Power Quiz	Competition registration fees, Fluid power quiz	Purchased	$675.00	$675.00	$675.00
	Document Printing	Marketing display, Tech docs	Purchased	$350.00	$350.00	-
Misc.	Prop Mockups	PVC pipe & fittings, Screws, etc.	Purchased	$240.88	$250.00	$240.88
	Tools & Equipment	Rivenut tool, Fume extractor, Hydraulic crimp tool	Purchased	$248.26	$200.00	$248.26
		Underwater cam to document pool tests	Purchased	$397.48	$400.00	$397.48
	Tax & Shipping	Tax & shipping on all purchases	Purchased	$751.81	$700.00	$751.81
	Pool Time	Lifeguard for weekly pool tests	Purchased	$728.00	$728.00	$728.00
Lodging & Travel (Int'ls)	Housing	Lodging for team in Alpena, MI	Purchased	$2,502.90	$2,502.90	$2,502.90
	Team Meals	Meals for team during competition	Purchased	$1,100.00	$1,100.00	-
	Gas	Gas for cars driving from CLE	Purchased	$350.00	$350.00	-
	Flights	Airfares for members not in CLE	Purchased	$782.40	$800.00	$782.40
Administrative Costs				**$8,126.73**	**$8,055.90**	**$6,326.73**
Total Costs				**$21,932.63**	**$1,755.75**	**$15,019.69**

Funding Source	Income
Case Alumni Association	$8,029.15
CWRU Undergraduate Student Government	$4,170.11
CWRU Student Executive Council	$2,390.73
Gene Haas Foundation	$1,433.76
2023-2024 Rollover	$728.00
Total Income	**$16,751.75**