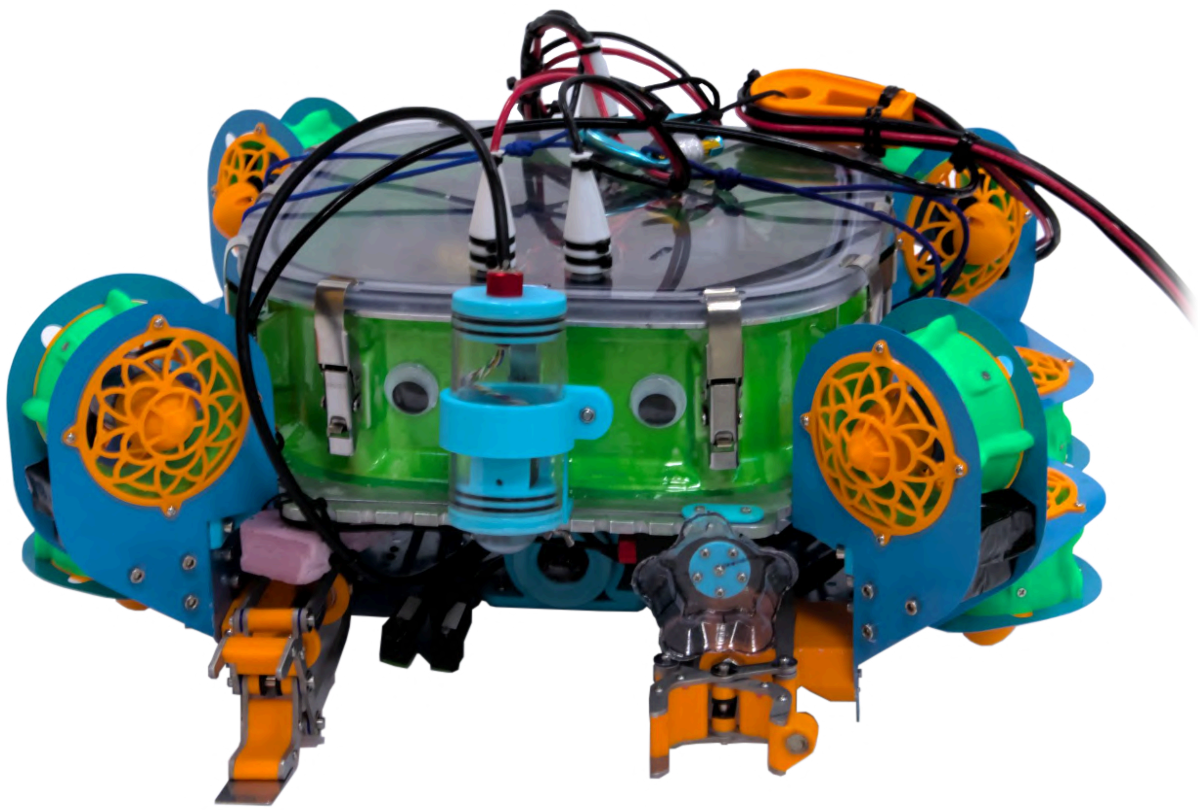
CWRUbotix

2024 Technical Documentation

Observing Our Oceans: Understanding Our World and Creating Our Future

Case Western Reserve University
Cleveland, OH, USA



Scuba Dooba Tuba Electric Beluga

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Abstract

CWRUbotix presents *Scuba Dooba*, a remotely operated vehicle (ROV) designed in response to MATE Inspiration for Innovation's 2024 request for proposals (RFP). *Scuba Dooba* is capable of efficiently completing a variety of undersea tasks including repositioning marine infrastructure, deploying smart sensors on undersea cables, and treating diseased corals. *Scuba Dooba* is the company's fifth ROV, offering significant improvements in functionality, reliability, and maintainability over previous products.

Scuba Dooba is rigorously optimized for MATE tasks. It features a spacious, easy-to-access electronics bay, a modular custom motherboard, and a low-latency vision system ideal for precision manipulation. *Scuba Dooba*'s design embraces modularity and maintainability at every turn, from fully connectorized electronics to easily replaceable 3D printed parts.

CWRUbotix's combination of experience, innovation, and rigorous testing has resulted in the most capable and reliable ROV the company has ever produced. *Scuba Dooba* is ready for deployment at the MATE ROV World Championship.

Project Management

Company Overview

CWRUbotix is an undergraduate student organization at Case Western Reserve University. The MATE ROV team operates under the CWRUbotix executive board, which also serves other competition teams. The MATE ROV Team Lead (CEO) is responsible for setting priorities for the team and communicating progress to the executive board. The MATE ROV team is divided into three subteams: mechanical, hardware, and software, though members are encouraged to participate in multiple subteams. Each subteam is headed by a subteam lead. See the title page for a complete list of members and their roles.

Schedule

In previous years, CWRUbotix employed a traditional approach to project management. A detailed Gannt chart created at the beginning of the project prescribed the team's tasks week by week until its completion. Subteam leads reported to the team lead in weekly leads meetings but otherwise worked independently. Though these strategies have their place, they proved to be ineffective for the needs of the team. The rigid schedule of the Gannt chart could not allow for unexpected setbacks or multiple cycles of iteration, which meant the team was constantly behind schedule. Limited communication between subteams led to integration problems discovered late in the manufacturing process.

This year, CWRUbotix replaced many of its traditional project management strategies with Agile methodologies. The Gannt chart was replaced with a simple list of milestones, target completion dates, and a list of tasks to be completed for each milestone. This allowed the team more flexibility to iterate and deal with setbacks, while still ensuring the team was on track to deliver a complete product on time. Each phase culminated with a clear deliverable. The design phases culminated in design reviews, during which the team members presented their design to faculty and alumni. Feedback from the design reviews informed the next phase of development. The manufacturing phase culminated in the first full-systems test, which marked the beginning of the testing phase. In the testing phase, the ROV was iteratively tested and improved, eventually resulting in a reliable product ready for demonstration at the MATE ROV World Championships.

Project Phase	Task Examples	Outcome	Target Date
Preseason	Onboarding, float and e-bay development	Team ready for season	1/1/24
Conceptual Design	Task analysis, prototyping, electrical SID	Conceptual Design Review	1/27/24
Detailed Design	Integrated CAD model, motherboard routing	Detailed Design Review	2/17/24
Manufacturing	Frame assembly, software completion	Full Systems Test	3/23/24
Testing	Integrated testing, iteration, demo practice	MATE ROV Qualification	5/10/24

Table 01: Project phases for Scuba Dooba

Resources, Procedures, and Protocols

During previous projects, the only organized communication between CWRUbotix's three subteams took place during weekly "leads meetings". While these meetings were open to everyone, non-lead members rarely attended, and the meetings were focused more on administrative work than technical design. This year, to facilitate communication between subteams, leads meetings were replaced with full team "design meetings". These design meetings were held in a classroom rather than the CWRUbotix lab to facilitate discussion and allow team members to present slides. All members were able to present their progress, ask questions, and give feedback. This format created an open forum in which all members of the team were involved in the high-level design of the ROV and understood how their subsystem integrated with the rest of the project.

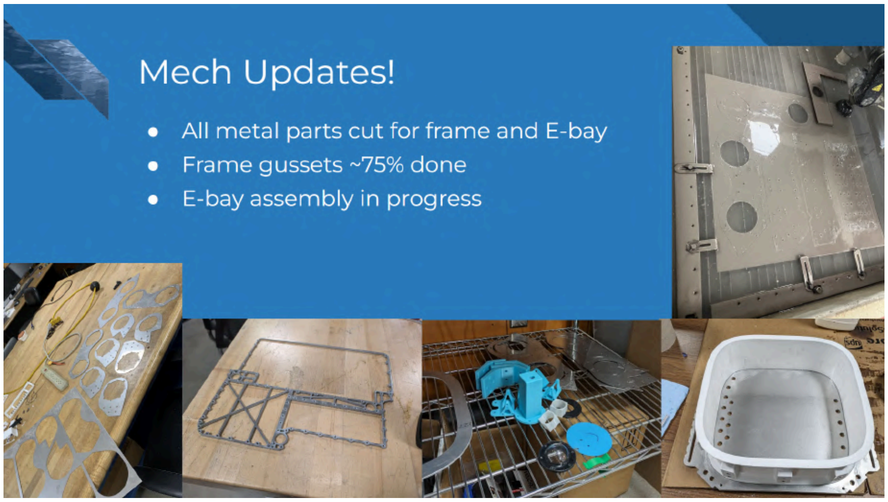

Fig. 01: Slide presented at a design meeting

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

Scuba Dooba was designed to efficiently complete the tasks in MATE's request for proposals. The team's primary design goals for *Scuba Dooba* were effectiveness on the MATE tasks, reliable waterproofing, 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.

Scuba Dooba has a sheet metal frame connected by 3D printed gussets. A number of frame designs were considered, but sheet metal was chosen via trade study due to its high strength and versatility *(Table 02)*. Using a waterjet cutter, sheet metal plates can be cut and mounted together at any angle, allowing components to be mounted securely in any orientation. This is difficult to achieve with aluminum extrusion or PVC pipe. Material selection for the frame is discussed in Vehicle Structure.

Solution	**Cost**	**Strength**	**Weight**	**Versatility**
Sheet Metal	Moderate	High	Moderate	High
Aluminum Extrusion	High	Moderate	High	Moderate
PVC Pipe	Low	Low	Low	Low

Table 02: Trade study of high level frame design approaches

As reliable waterproofing was one of the project's primary design goals, CWRUbotix evaluated a number of approaches for waterproofing onboard components. The team performed a trade study that indicated the best approach for reliable waterproofing was to pot each component in epoxy. However, this approach conflicted significantly with other design goals: functionality and serviceability. For this reason, the team chose a distributed air-filled enclosure approach and designed a robust testing regiment to mitigate the increased risk of water ingress. After the completion of the trade study, several types of enclosures were designed, reviewed, prototyped, and tested. The design of each enclosure is discussed in detail later in this section.

Solution	**Reliability**	**Serviceability**	**Sensor Placement**	**Failure Points**
Potted Components	High	Very Low	Unrestricted	Many
Single Enclosure	Moderate	Moderate	Restricted	Few
Distributed Enclosures	Moderate	High	Unrestricted	Many

Table 03: Trade study of high level waterproofing approaches

Systems Approach

One of CWRUbotix's foremost goals for *Scuba Dooba* was improved systems integration. During previous projects, a combination of bottom-up design and lack of communication between subteams led to difficulties in systems integration after many components had already been manufactured.

The mechanical, electrical, and software systems of *Scuba Dooba* were developed in parallel, with frequent intercommunication facilitated by design meetings. During the design phase, the team 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. To test more dynamic properties of the vehicle, CWRUbotix developed a custom software-in-the-loop (SITL) simulation based on Gazebo. The simulation emulates the onboard flight computer and runs ArduSub firmware. The project's software architecture makes it easy to run all of the onboard computer's software locally during simulation. The result is an end-to-end simulation of the entire software stack. This simulation is especially valuable when developing autonomous flight algorithms; instead of using valuable pool time to debug the program, it can be tested in simulation and deployed on the ROV with minimal additional tuning.

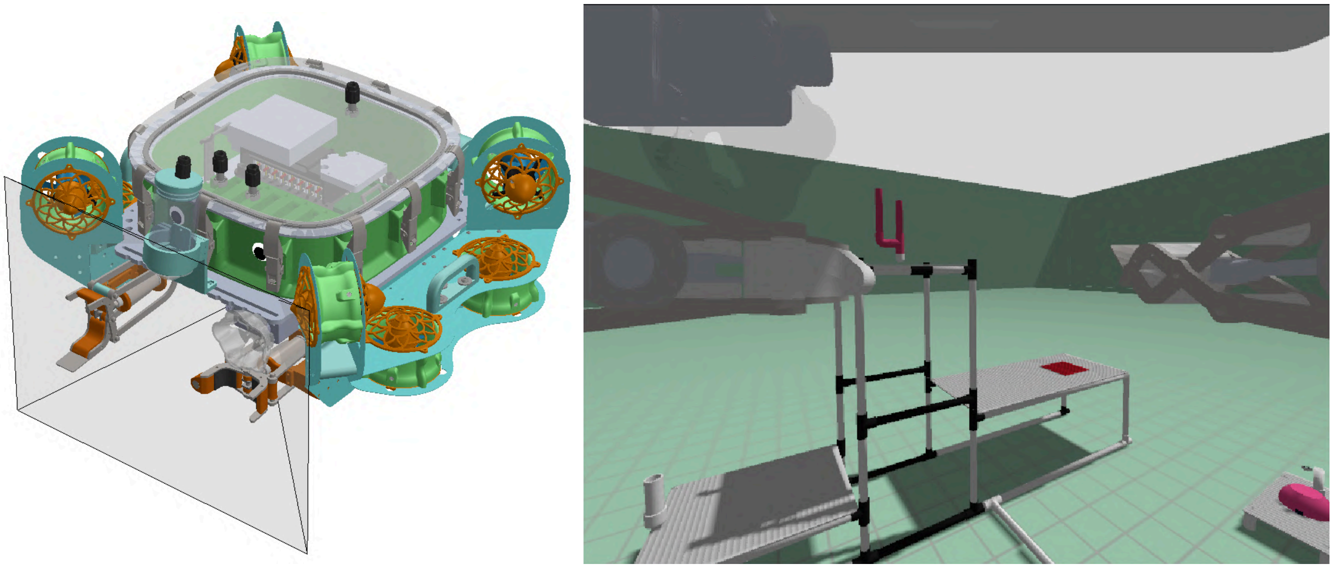

Fig. 02: Camera view in CAD (left) and simulation (right)

Vehicle Structure

Scuba Dooba's primary structural components are a sheet metal frame and a watertight electronics bay, described in detail below. This construction was designed to balance functionality, size, and weight. Understanding the buoyancy of the ROV was paramount for achieving precise maneuverability. *Scuba Dooba* is designed to be near neutral buoyancy at all operational depths. To achieve neutral buoyancy, the mass and volume of the ROV must be precisely balanced during the design stage and fine-tuned after manufacturing (see Buoyancy and Ballast). As requested in MATE's RFP, *Scuba Dooba* was designed to weigh less than 18 kg in air. Within this limit, CWRUbotix opted for a relatively large and heavy robot (approximately 17.5 kg with an envelope of 608 x 568 x 308 mm), 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 vertical profiling float and probiotic irrigation system. The costs of a larger size include reduced acceleration and top speed (due to inertia and drag) and 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 *Scuba Dooba* 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 frame is manufactured from 22 ga (0.762 mm) 304 stainless steel sheet metal, which offers good strength and high corrosion resistance at a lower cost than other comparable materials, such as titanium or 316 stainless. When choosing the material for the frame, the initial trade studies considered various metals and polymers as well as a variety of construction methods. CWRUbotix has previous experience using 6061 aluminum sheets, but the team found that the persistent problem of galvanic corrosion was difficult to overcome when using steel fasteners in contact with aluminum. Additionally, aluminum bolts cross-thread very easily. Since the goal was to achieve neutral buoyancy while minimizing the size of frame components, the team decided to use a more dense material than 6061 to maintain the target buoyancy (8.0 vs 2.7 g/cm^3). After selecting 304 stainless steel, the segments of the frame were manufactured by the team using an OMAX 5555 WaterJet Cutter. The cut parts were deburred to prevent injury when handling the frame and powder coated for additional protection and aesthetics.

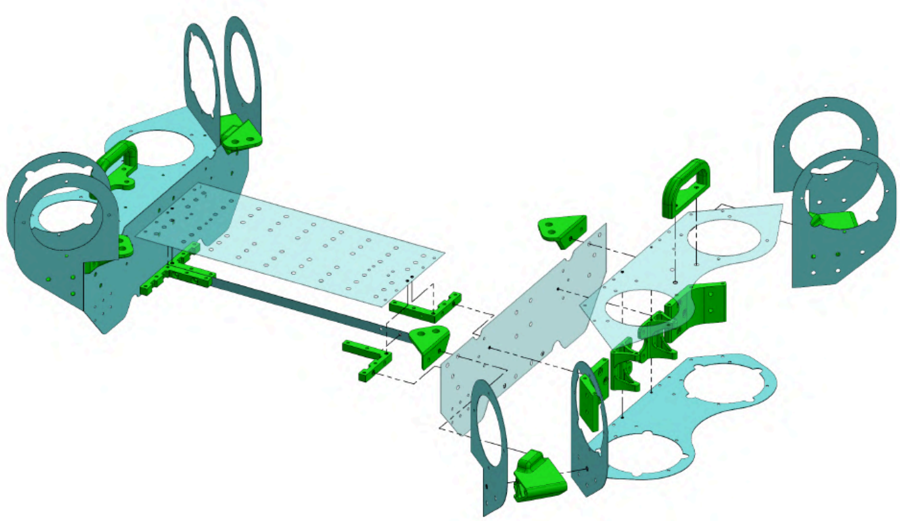

Fig. 03: Exploded view of Scuba Dooba's Frame

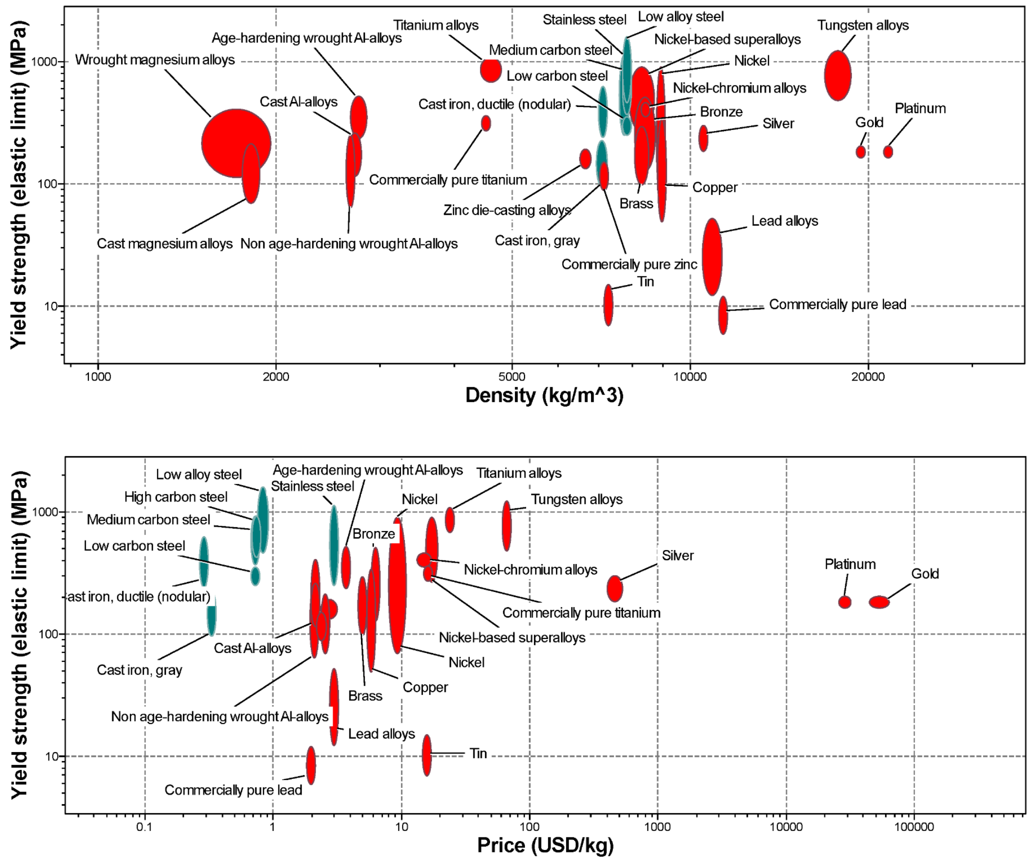

Fig. 04: Metal materials considered for the frame are compared in cost and strength (top) and in strength and density (bottom) using CES EduPack.

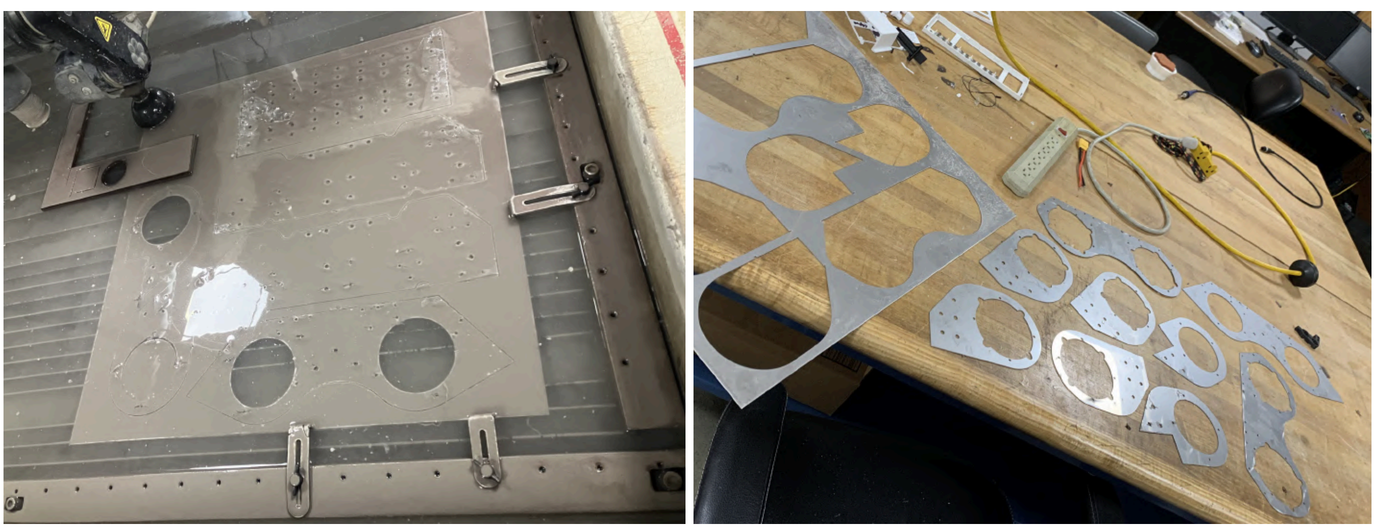

Fig. 05: Set-up (left) and product (right) of waterjet cutting

Utilizing a sheet metal design for the frame provides the flexibility of modular construction. The components of the frame are attached together with 3D printed PETG (Polyethylene Terephthalate Glycol) gussets. Additive manufacturing was used to be able to include complex geometries and modularity for the ROV's gussets, and to achieve maximum compactness. To make replacement and redesign of gussets simple and uniform, standard M3 and M5 stainless steel fasteners were used.

Electronics Bay

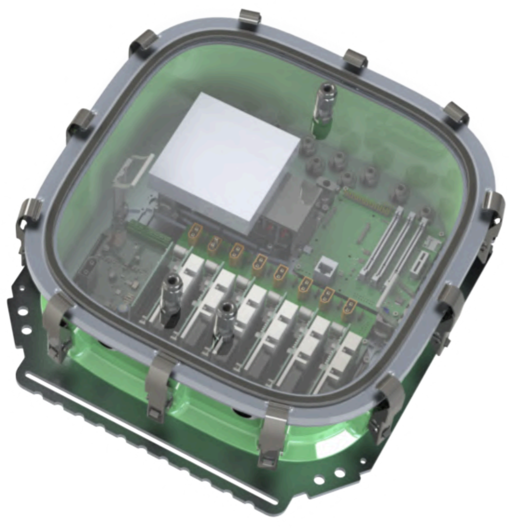

Fig. 06: The Scuba Dooba e-bay

The Electronics Bay (e-bay) houses the majority of the electronics onboard the robot in a waterproof enclosure. 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 ¼ inch thick aluminum plate to heat sink the electronics within. The final e-bay design measures 328 mm x 328 mm at the outermost point of the walls, leaving a 300 mm x 300 mm squircle interior for the electronics. The interior has 100 mm of height, large enough to fit some of the larger electronics such as the 48V power supply.

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 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 the water jet 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 *Scuba Dooba*, 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 confirm the strength of the e-bay and determine the minimum thickness of the walls, finite element analysis (FEA) was performed using SolidWorks' Simulation package. 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 5 m, corresponding to a pressure of approximately 50 kPa. The results of these simulations are shown in *Fig. 07*. The maximum stress on the model in the simulation was 5.7 MPa; this is well below the yield strength of PETG, at around 47 MPa.

CWRUbotix also considered the industry standard e-bay design: a length of round tube sealed with plastic or aluminum caps at either end. The team elected to use this approach for camera enclosures, but not the e-bay, as a cylindrical enclosure is less effective at packing the ROV's electronics and would have to be balanced with added weight. Furthermore, the squircle form factor (relatively wide and shallow with a large, horizontal lid) allows for easy access to the electronics for assembly and troubleshooting. For these reasons, the walls were 3D printed and the e-bay was constructed from multiple parts and materials. To save material, the walls are 2.4 mm thick with columns and rims added for stiffness and strength.

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.

Several steps were taken to waterproof the e-bay. The bottom aluminum plate is permanently attached to the walls with epoxy. This plate was aligned to the walls with aluminum dowels that were inserted and epoxied into holes machined in the plate and e-bay walls. The walls of the e-bay were also painted with epoxy to fill any gaps between the layers resulting from the 3D printing process. An aluminum ring was epoxied to the top edge of the 3D printed walls to add strength and to provide a smooth and flat surface for the o-ring to seal against. This o-ring rests in a groove machined into the polycarbonate top lid. The lid is then fastened against the top surface with twelve latches mounted using heat-set inserts in the wall.

Previous iterations of this design used twelve bolts to attach the lid. While this method is effective, it means that opening and closing the e-bay requires the use of tools and is time-consuming. Furthermore, it requires special care to avoid over or under-tightening the bolts, which could compromise the seal or damage the e-bay. In order to address these issues, the team replaced the bolts with latches, which allow for rapid tool-free access to the electronics and produce a repeatable clamping force. This reduces the time spent opening the lid from 2 minutes down to 15 seconds and guarantees consistent compression on the o-ring. The full layout can be seen in the following cross section in *Fig. 07*.

The e-bay includes seventeen 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.

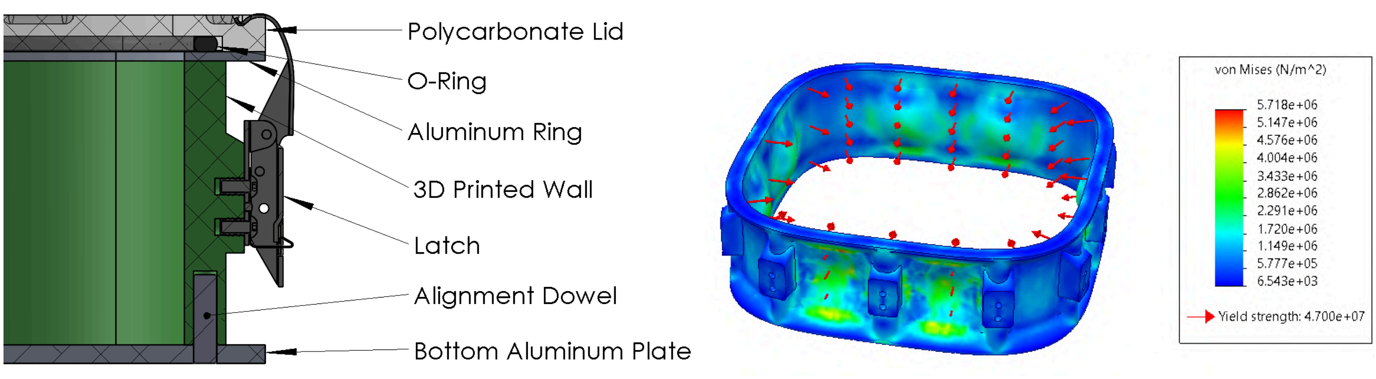

Fig. 07: Construction of the e-bay (left) and an FEA simulation of the e-bay wall (right)

Vehicle Systems

Control and Electrical Systems

Scuba Dooba's control and electrical system consists of two main components: a control station on the surface and the ROV's onboard electrical system, which are connected by a tether. The onboard electrical system can be further divided into a power system, responsible for converting electrical power coming from the surface and distributing it to all powered components, and the control system, responsible for communicating with the surface control station and controlling the systems of the ROV. See the SIDs for a complete diagram of the components of the electrical and control systems.

Power

The 48 V power from the tether is received by the Modular Multiphase Power Supply Unit II (MMPSU II), a 6 phase DC-DC buck converter designed by Repowered Electronics - an electronics company founded by CWRUbotix alumni. MMPSU II converts the 48 V from the tether to 12 V for the thrusters and auxiliary voltages for other components. It is rated for 2.4 kW, more than enough to convert the full output of the 1.44 kW power supply provided by MATE. MMPSU II was selected because there are few commercial solutions capable of providing the needed output, and the solutions that do exist are either prohibitively expensive or rely on putting under specced DC-DC modules in parallel to support the required load. MMPSU, by contrast, is a native multiphase design which allows high current output and ensures stable operation and regulation through dynamic load balancing and phase shedding. MMPSU II is also capable of reporting back detailed telemetry over UART, which can be used by the control system to avoid brownouts or blowing a fuse.

Solutions	Cost	Telemetry	Reliability	Ease of Implementation
MMPSU II	Moderate	Good	Good	Good
Prodrive MP5612	High	Some	Good	Poor
4x Golf Cart Buck	Low	None	Poor	Moderate

Table. 04: Trade study of power conversion solutions

CWRUbotix designed a simple distribution board that bolts to the output of MMPSU and connects to the PWM outputs of the flight computer via a keyed ribbon cable. It breaks out power and PWM using XT60 and DuPont headers for the eight speed controller, greatly simplifying the wiring of the e-bay.

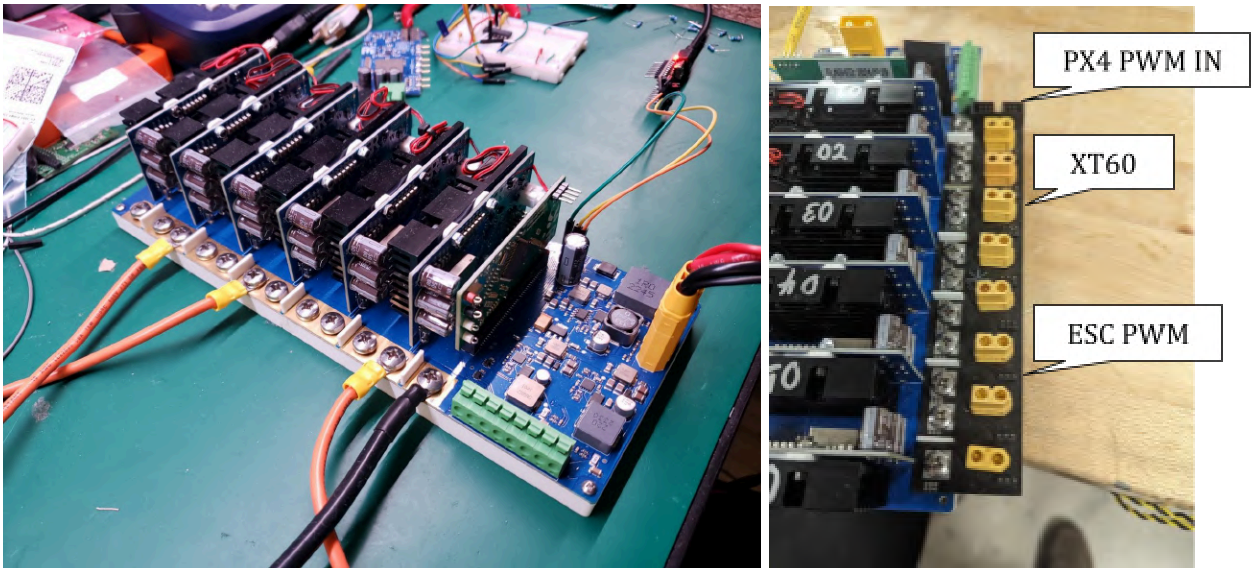

Fig. 08: MMPSU II (left) and Power Distribution Board (right)

Control

The core of *Scuba Dooba's* control system is the motherboard, built with a focus on cable routing, debugging, and serviceability. This board serves to connect the surface computer to the main onboard computer: a Raspberry Pi Compute Module 4. The device was selected because of its high-speed operation, robust ecosystem, and integrated IO. Compared to popular alternatives such as the Nvidia Jetson Nano, the Pi CM 4 has superior support for ROS (see Software) and more available hardware design documentation. The Pi's PCIe x1 lane connects to a USB controller card to provide four high-speed USB 3.0 connections, which allows for a range of high speed IO. The Pi's onboard USB 2.0 controller connects to the ROV's flight computer, and the integrated Gigabit Ethernet is used to communicate with the surface computer. The motherboard has a 5V to 3.3V regulator, in order to comply with the PCIe specs as well as to power some MUXs. It also has UART, GPIO, and card edge expansion slots that are used to connect to various daughterboards. The team chose to design this board in-house, allowing the inclusion of all the necessary features while keeping the cost and size of the board down. Designing a custom board also minimizes the cable runs needed in the e-bay, which makes the ROV easier to assemble and service.

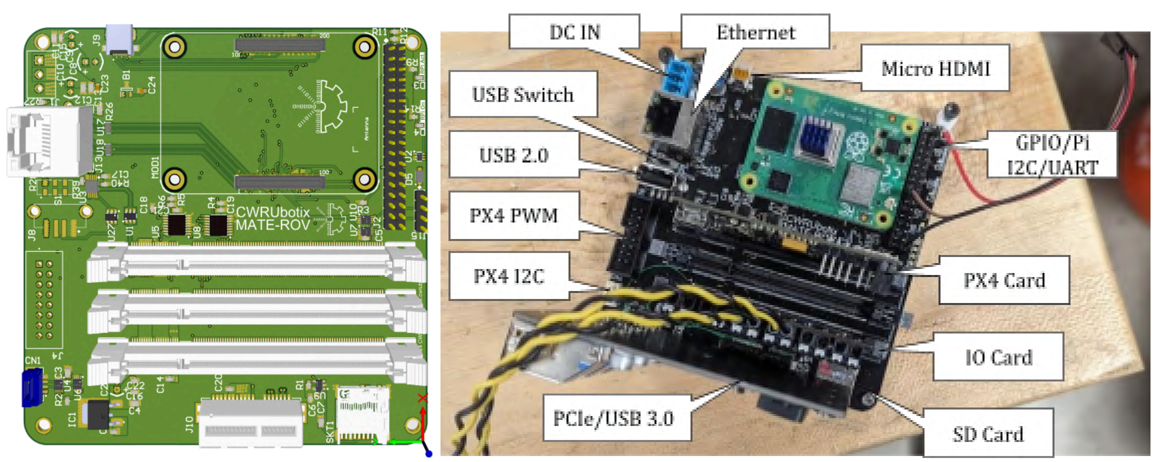

Fig. 09: CAD view of Motherboard from Altium Designer (left) and finished Motherboard (right)

In addition to the motherboard, the team also designed a custom relay daughterboard. This board contains six solid-state relays which are used to turn on and off external devices such as lights and solenoids. This daughterboard connects directly to the motherboard through the use of a SODIMM slot. This board allows us to bundle our 12V IO together and makes it easy to wire and remove.

Scuba Dooba uses a custom flight computer based on the open source hardware PX4 to control its thrusters. CWRUbotix chose to design a custom daughterboard instead of using an off-the-shelf PX4 to improve its integration with the motherboard and reduce unnecessary cabling. For redundancy, an external flight computer can be connected via a usb port on the motherboard.

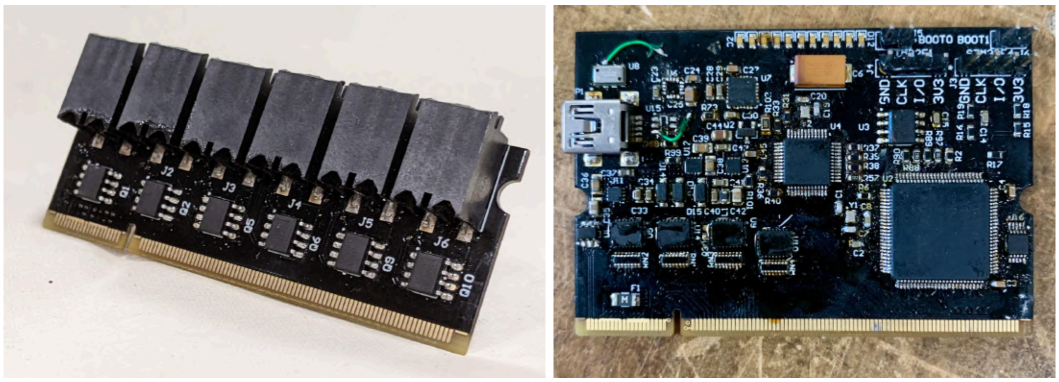

Fig. 10: 12V IO Board (left) and PX4 Board (right)

All boards were designed in Altium Designer. CWRUbotix placed an emphasis on using keyed connectors and interconnected systems to enable a high degree of modularity, and simplify manufacturing and maintenance. All boards are mounted to a removable aluminum tray with handles, so the electronics can be lifted out of the e-bay within a few minutes.

Fig. 11: The e-bay tray and electrical assembly

System Integration Diagrams (SIDs)

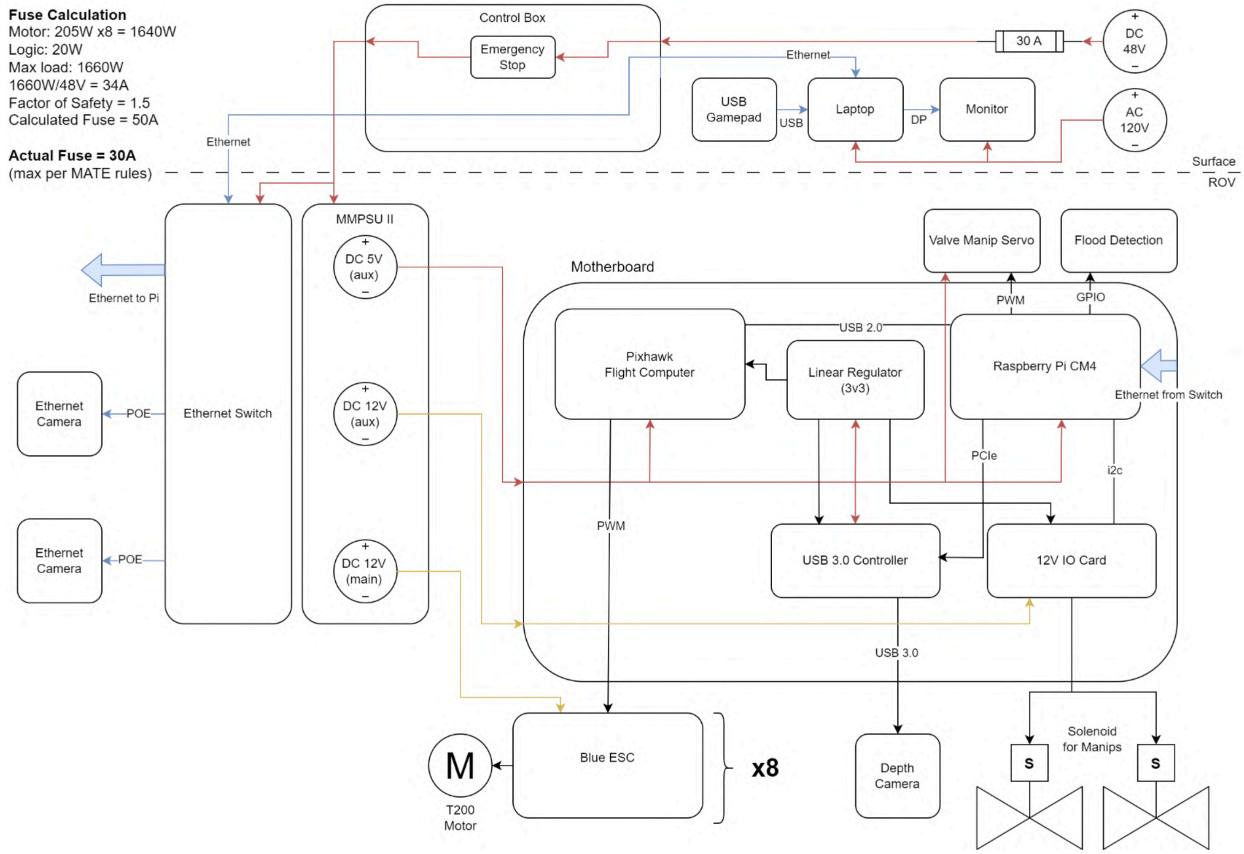

Fig. 12: Electrical SID

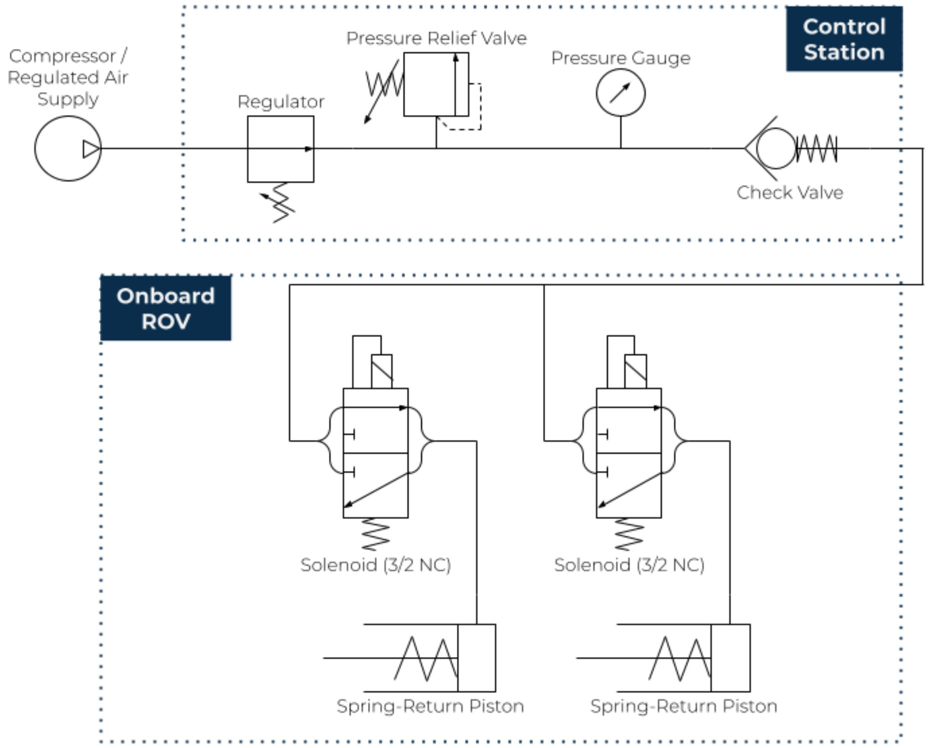

Fig. 13: Pneumatic SID

Tether, Emergency Cutoff, and Tether Management

Scuba Dooba's tether is designed to be reliable by prioritizing flexibility and durability. It contains two power cables, a CAT6A ethernet cable, and a 6mm (¼ inch) polyurethane pneumatic line. The power cables are 10 AWG UL Standard 1426 marine grade wires designed to be lightweight and flexible. The positive wire connects to a 30A 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. Flexible strain relief cones (3D printed in TPU) 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 and short enough that there is only a small voltage drop of approximately 2.3V along the power line when the maximum current, 30A, is drawn. The poolside connection to the tether is made through the control box. This box runs the provided 48V DC power through an emergency stop button, and the compressed air through a pressure regulator set to 40 psi.

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, they will hold onto the tether and ensure that it does not become a tripping hazard. Before deployment, they will coil the tether in a neat circle by the side of the pool and make sure no one steps on it. Then, as the ROV navigates the pool, the tether manager will adjust their grip on the tether so that there is always an extra meter of tether in the pool.

Control System Software

Scuba Dooba's control system is split into three subsystems: the surface system, which is hosted by a laptop on the surface, the ROV system, hosted on the Pi CM4 module onboard the ROV, and the float system, comprising two Adafruit Feather transceiver boards. As discussed in the Cameras section, the team chose to connect our surface and ROV subsystems with an ethernet cable running along the tether, minimizing camera feed latency and encoding computational loads while minimizing tether size. The team considered three solutions to facilitate communication along this ethernet bridge: Robot Operating System 2, websockets, and GStreamer (with Mavlink for non-video message types).

Solutions	Latency	Network Organization	General Communication	Video Support	Inherited Codebase	Simulation Support
ROS 2	Moderate	Strong	Strong (typed)	Moderate	Large & recent	Strong
Websockets	Low	None	Moderate (untyped)	Moderate	Old	Moderate
GStreamer/ Mavlink	Low	None	Moderate	Strong	Old	Moderate

Table. 05: Comparison of trans-tether communication methods

ROS 2 was chosen for all communication over the tether (except for video streaming, which is covered by our IP cameras), as (1) its highly structured design encourages well-organized networks with strongly typed messages, (2) it adds insignificant latency, and (3) our previous iterations of the *Scuba Dooba* system were designed to integrate with ROS.

The ROS paradigm also 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 graphical user interface (GUI) with the highly maintainable model-view-controller paradigm, completely decoupling robot state management from its graphical representation.

This year, the team replaced several custom packages with better ROS alternatives for improved maintainability and usability. We replaced our custom *pymavlink*-based code for controlling the Pixhawk flight computer with the *mavros* package, gaining support for many new MAVLink messages which the team used to implement heartbeat and thruster testing systems. CWRUbotix also made several contributions to the open source ROS 2 and *ros-perception* projects, improving static type checking, generic type support, and documentation.

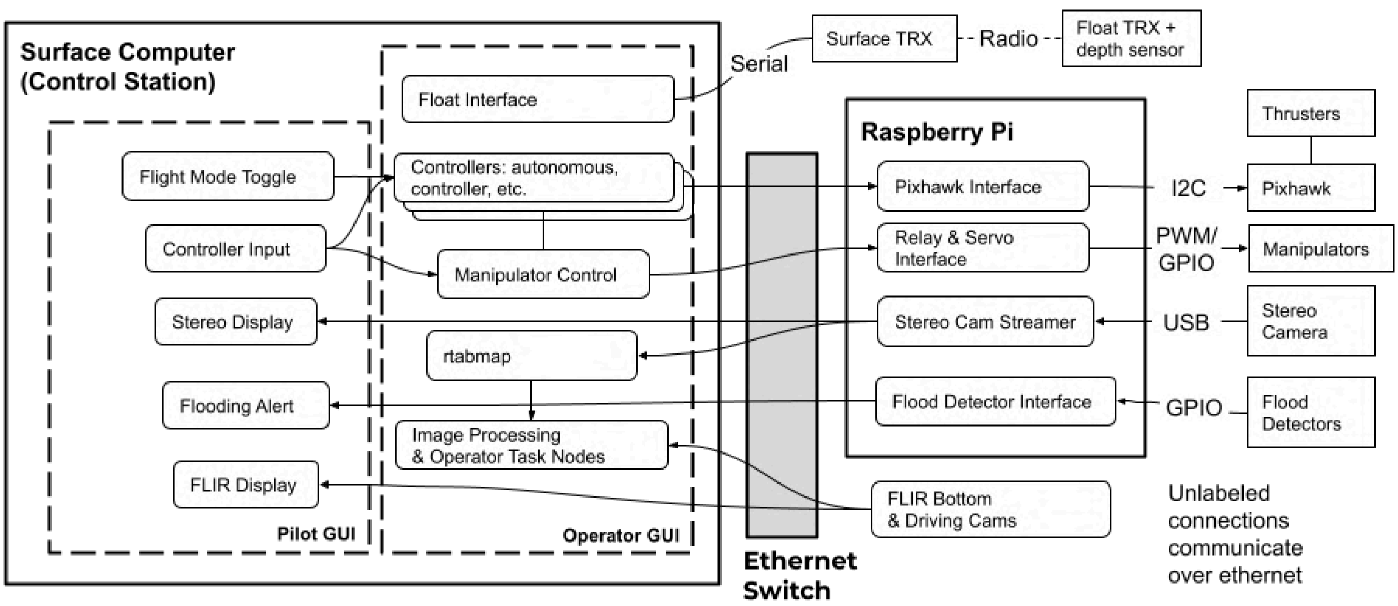

Fig. 14: Software SID

Coral Modelling

Scuba Doo's robust vision and software systems allow it to complete some tasks fully autonomously. MATE's request for proposals called for ROVs capable of autonomously creating a dimensionally accurate 3D model of a large coral recovery area. CWRUbotix considered a number of approaches to solve this challenge. Photogrammetry—using a series of images taken from different perspectives to recover the geometry of an object—could be effective because the ROV is already equipped with high-resolution cameras. However, photogrammetry requires the ROV to spend a lot of time flying around the object to take pictures from various perspectives, and it produces an unscaled model, meaning the ROV must measure the object in another way to create a dimensionally accurate model.

An alternative approach, known as visual SLAM (Simultaneous Localization And Mapping), uses two cameras a fixed distance apart. The two cameras working together allow the system to calculate the distance from the camera to the objects it sees, similar to how animals with two forward-facing eyes are able to perceive depth. This depth perception allows the ROV to measure the position of objects in 3D space relative to the camera. However, the ROV cannot view the entire coral nursery at once, so it must fly around to get multiple perspectives. When the ROV moves, the SLAM algorithm estimates the movement of static objects relative to the camera, and therefore the movement of the camera (and the ROV). An accurate estimate of the ROV's current and previous positions are essential for fusing the three dimensional views together into one cohesive model.

A key advantage of SLAM for MATE's application is that the model is inherently scaled based on the known distance between the two cameras, negating the need for a separate scaling step. Because of this advantage, CWURbotix installed a stereo (two lens) camera on the back of *Scuba Dooba* and implemented SLAM using the open-source RTAB-Map package for ROS. A previous project used an Intel Realsense Depth camera as the stereo camera, but this was found unsuitable for the current task because of its use of infrared camera sensors. Infrared light is heavily attenuated by water, meaning the Realsense camera could only see objects within 50 cm of the camera. This short range is not suitable for scanning a large object like the coral recovery area. To address this issue, the depth camera was replaced by a stereo camera with two visible light sensors, as visible light penetrates water much better than infrared.

Once the model has been created, it is sent to a separate interactive application which allows the operator to select points and measure the distance between them. This application is independent from the primary GUI and was created with the Unity game engine.

Propulsion

To maximize speed and maneuverability, *Scuba Dooba* has eight T200 thrusters from Blue Robotics - four vertical and four horizontal. The vertical thrusters are located near each corner of the frame, allowing the ROV to translate vertically, pitch, and roll. The horizontally oriented thrusters are located on 40° angles at each of the frame corners, allowing the ROV to translate horizontally in both axes and to yaw. All of these thrusters combined allow the ROV to move with six degrees of freedom. Only six thrusters are required for six degrees of freedom control, but using eight allows them to be placed in more convenient locations and increases the maximum thrust output of the ROV. The primary downside is increased power consumption, but this is mitigated by *Scuba Dooba*'s robust power architecture. Blue Robotics T200s were chosen over similar products or an in-house solution because they are powerful, easy to use, and well-documented. Additionally, the team already had a full complement of T200s from previous ROVs which it was able to reuse for *Scuba Dooba*, resulting in significant cost savings.

Buoyancy and Ballast

Scuba Dooba is designed to be neutrally buoyant at all depths, which is crucial for precise maneuverability. To ensure neutral buoyancy, an accurate mass and density of all components was included in the team's CAD model of the ROV. The total mass, center of mass, and total enclosed volume were calculated from the model. This analysis of the CAD model showed that *Scuba Dooba* would be naturally negatively buoyant, and thus require no ballast. To achieve neutral buoyancy, the frame was designed with lots of available space to mount buoyancy foam. By adjusting the volume and location of buoyancy foam, the team could easily control not only the ROV's total buoyancy but also its center of buoyancy. The center of buoyancy is positioned directly above the center of mass so the ROV will passively maintain an upright orientation. The amount of buoyancy foam in each location is estimated based on the CAD model and fine-tuned based on observations during pool tests.

Manipulators

Linkage Claws

Scuba Dooba features two pneumatic manipulators, called Linkage Claws, on the front of its frame. The Linkage Claw is able to manipulate up to 2" PVC and various non-PVC objects. 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, and modified to fit our pneumatic actuators and PVC pipe. The linkage mechanism was waterjet cut out of 3.175mm (1/8") 304 Stainless Steel, chosen for rigidity. The spacers and mounting bracket were 3D printed with PETG filament. The front of *Scuba Dooba* features two variations of the Linkage Claw, oriented at 90 degrees to one another. To aid with grabbing non-PVC objects, there is a plate attached to the bottom arm of the Horizontal Linkage Claw, which provides more surface contact and aids with picking up objects resting on the pool floor. The Vertical Linkage Claw includes a permanent magnet for manipulating ferrous pins.

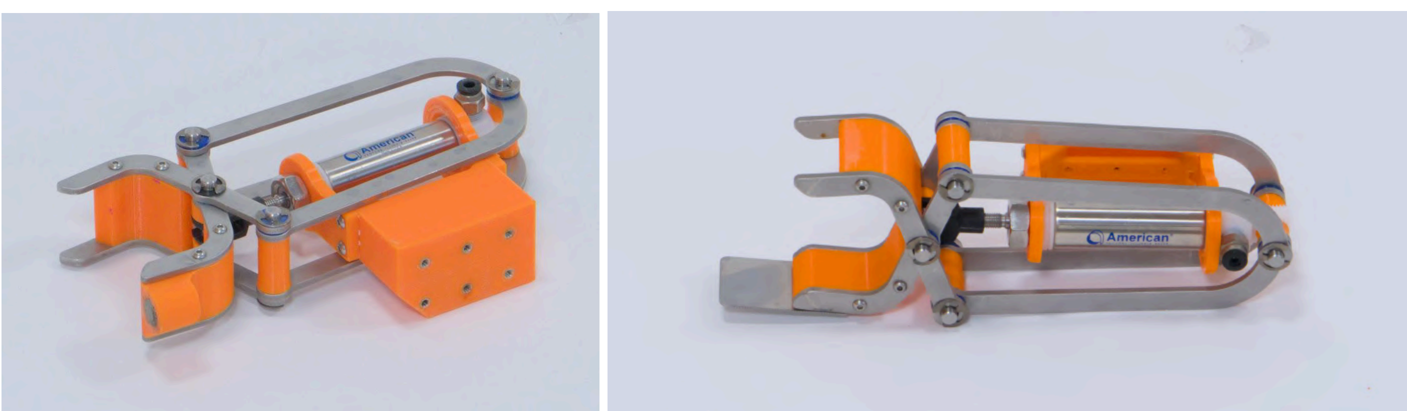

Fig. 15: Vertical (left) and horizontal (right) linkage claws

Valve Manipulator

The Valve Manipulator is a specialized tool designed to turn the valve on the probiotic irrigation station. This manipulator is actuated by a continuous rotation electric servo motor housed in a waterproof enclosure. The servo was chosen for its ability to create smooth and precise rotary motion with a reasonable speed and torque output. Attached to the motor's output shaft is a tapered manipulator that engages with the handle of the valve, made by vacuum forming a sheet of clear PETG. This combination of material and manufacturing process produces a clear manipulator so that the valve handle is never obscured and its rotation is clearly visible. The Valve Manipulator is tapered to allow it to self-correct for some misalignment between the manipulator and the valve.

Fig. 16: Valve manipulator prototype (left) and final integration (right)

Cameras

To allow the pilot to perceive the ROV's environment, *Scuba Dooba* features two monocular cameras. To position the cameras, the camera views were simulated in SOLIDWORKS, which provided a view of the ROV and the environment from the pilot's perspective. Both cameras are positioned such that the two Linkage Claws and the Valve Manipulator are in their field of view, which aids the pilot in aligning the manipulators with underwater objects.

CWRUbotix's previous ROVs used USB3 cameras connected to a Raspberry Pi, which encoded the video before streaming it to the surface. The encoding step caused significant latency in the video streams, as well as consuming compute resources on the Pi. During the design phase of *Scuba Dooba*, a number of alternatives were considered. Ethernet (IP) industrial cameras were chosen because they meet our latency requirements, do not require additional cables in the tether, and do not consume computer resources on the onboard computer.

Solutions	Latency	Onboard Hardware	Onboard Computation Cost	Tether Girth	Cabling
USB3 Cams	Moderate	Simple	High	Slim	Simple
Analog Cams	Very Low	None	None	Large	Simple
MIPSI Pi Cams Over USB C	Moderate	Simple	High	Slim	Difficult
IP Cams + PoE	Low	Moderate	None	Slim	Simple

Table. 06: Comparison of camera types

Teledyne Marine graciously donated two Blackfly S GigE cameras for use on *Scuba Dooba*. These are high quality machine vision cameras designed for industrial use. Each 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 48V 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 computer, where the streams are displayed to the pilot. This streaming solution resulted in a glass-to-glass latency less than 100 ms.

Camera Enclosures

All cameras are sealed in individual watertight enclosures. The enclosures are constructed from 50mm (2 in.) ID polycarbonate tube and are sealed with two 3D printed PETG end caps, each of which seals against the tube with two o-rings. The monocular cameras require one clear end cap. In order to minimize the lensing effect of the water-air interface, these caps incorporate a clear spherical dome, which is vacuum formed from a 1mm sheet of PETG.

A second style of camera enclosure was prototyped, consisting of a single 3D printed housing and a cap, sealed by a single o-ring. This design proved more difficult to manufacture and less reliable, so the company standardized on tube-style enclosures for all cameras.

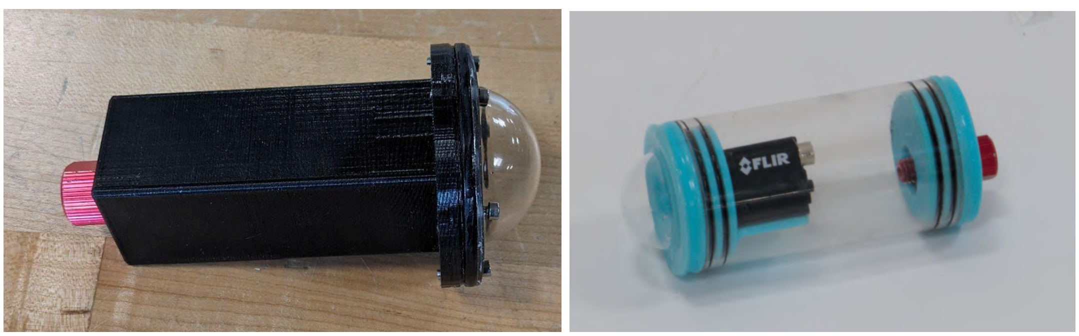

Fig. 17: Printed enclosure prototype (left) and finished tube-style enclosure (right)

Build vs. Buy, New vs. Used

In order to maximize opportunities for learning and innovation, CWRUbotics aims to design and manufacture components wherever possible. Off-the-shelf solutions are used for parts that are beyond the manufacturing capabilities of the company, or where they present substantial improvements in cost or efficacy. In order to minimize cost and waste, purchased parts are reused as long as they continue to meet the design requirements. All custom components are manufactured new each year to maintain the relevant skills and knowledge and train new members. This approach also allows incremental improvements of designs that are reused from previous ROVs, such as manipulators. For a full list of reused components, see Appendix C.

Safety

The safety of team members is CWRUbotix's highest priority, as well as 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 safe practices. The lab and safety manager also ensures that the workspace is clean and that safety equipment is always available. 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.

More safety considerations are taken into account when working on construction of the ROV. Teammates are only permitted to use equipment that they have training for. Additionally, teammates need to wear gloves and an apron when handling potentially hazardous materials, such as epoxy.

There are several safety features implemented on *Scuba Dooba*. The thrusters are surrounded by IP20 guards that prevent objects from contacting the blades of the impellers. All metal components of the robot are deburred to prevent injury when they are handled. Additionally, the strain relief mentioned in the tether section ensures that the ROV can be safely held by the tether. During testing, the ROV is confirmed by a team member to be 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 and 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. This provides 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. The oscilloscope is used to measure the performance of the new MMPSU II power supply. Meanwhile, a multimeter was used to measure voltages at a point, such as during testing of custom Pixhawk flight controller boards. One of these boards was not connecting over USB, so the USB line was traced with a multimeter to find the source of this problem. 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 *Scuba Dooba* 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, Pixhawk 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 Pixhawk 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.

CWRUbotix prioritized full systems integration testing once the ROV was built. 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 competition. The tasks the team performed tested waterproofing, visibility through the ROV’s cameras, and the ROV’s ability to maneuver and grip objects. When issues were encountered during testing, the operator removed power to the ROV, and the team deliberated over the source and solution to the issue. If the team could not solve the issue immediately, but determined that the ROV was still safe to operate, testing continued.

Accounting and Budget

The CWRUbotix ROV team’s budget is allocated each year out of the larger overarching CWRUbotix organization’s funds, which are split accordingly between each of the competition teams operating under the CWRUbotix umbrella. More specifically, the ROV team is allocated a portion of each relevant major funding source, as some funds are earmarked for specific purposes (ex. robot parts vs. 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, and are therefore not included in this document. 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 Checklist

Construction:

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

Disassembly:

- ☐ Ensure that the power is offDry the lid as best as possible, especially on the outer edges to prevent water from entering the e-bay
- ☐ Release the latches
- ☐ Technician 1 quickly and carefully lift the e-bay lid
- ☐ Technician 2 quickly disconnect ethernet between penetrator and electronics
- ☐ Technician 1 place the lid down to the side
- ☐ Ensure that the e-bay is dr

Appendix B: ROV Operation Safety Checklist

Pre-Dive

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

Launch

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

Recovery

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

Leak

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

Appendix C: Budget and Project Costing

Reused and Donated Components			
Budget Category	**Item**	**Type**	**Value**
Electrical	Tether Power Cables (x2)	Reused	$50
	Tether Ethernet Cable	Reused	$15
	Blue Robotics ECSs (x8)	Reused	$304
	Blue Robotics T200 Thruster (x8)	Reused	$1,600
	Control Monitor	Reused	$350
	Control Laptop	Reused	$300

Reused and Donated Components (cont.)			
Mechanical	Control Box and Associated Components	Reused	$500
	304 Stainless Steel Sheets (for ROV Frame)	Leftover	$124
	Pneumatic Pistons (x2)	Reused	$130
	Pneumatic Tubing (Tether and Onboard ROV)	Reused	$34
	Polycarbonate Sheet (for E-Bay Lid)	Leftover	$121
	Strain Relief	Leftover	$12
	Buoyancy Foam	Leftover	$28
Software (Controls, Sensors, ect.)	FLIR Blackfly S GigE Cameras (x2)	Donated	$742
	Stereo Camera	Reused	$70
		Total Reused and Donated Value	**$4,380**

Allocations and Expenses (USD)					
Budget Category	**Item Category**	**Purchased**	**Budget Allocated**		**Total Purchased**
Electrical	Onboard Hardware	$2,571.70	$3,000.00	$3,800	$3,328.02
	Custom PCBs	$309.93	$300.00		
	Float Electronics	$446.39	$500.00		
Mechanical	Manufacturing	$21.60	$50.00	$1,900	$1,811.82
	Fasteners and Mechanical Hardware	$811.96	$800.00		
	Waterproofing (O-Rings, Penetrators)	$489.21	$500.00		
	Raw Material and Stock	$467.06	$500.00		
	Float Components	$21.99	$50.00		
Software (Controls, Sensors, Supporting Resources)	Control Station (Electronics)	$383.38	$400.00	$700.00	$611.29
	Cameras, Sensors	$181.96	$200.00		
	Testing Hardware and Supplies	$45.95	$100.00		
Miscellaneous	Prop Mockups (PVC Pipe, etc)	$153.19	$200.00	$1,000.00	$906.99
	Tools and Equipment	$753.80	$800.00		
Lodging and Travel (Internationals)	Housing	$2,127.34	$2,500.00	$4,275	$3,902.34
	Team Meals (Expected)	$800.00	$800.00		
	Gas (Expected)	$500.00	$500.00		
	Registration and Fluid Power Quiz	$475.00	$475.00		
Spare Parts and Unexpected Expenses	Electronics, Mechanical Components, etc.	$564.99	$1,325.00	$1,325	$564.99
	Miscellaneous Unexpected Expenses	$0.00			
			Grand Totals	**$13,000**	**$10,560.46**