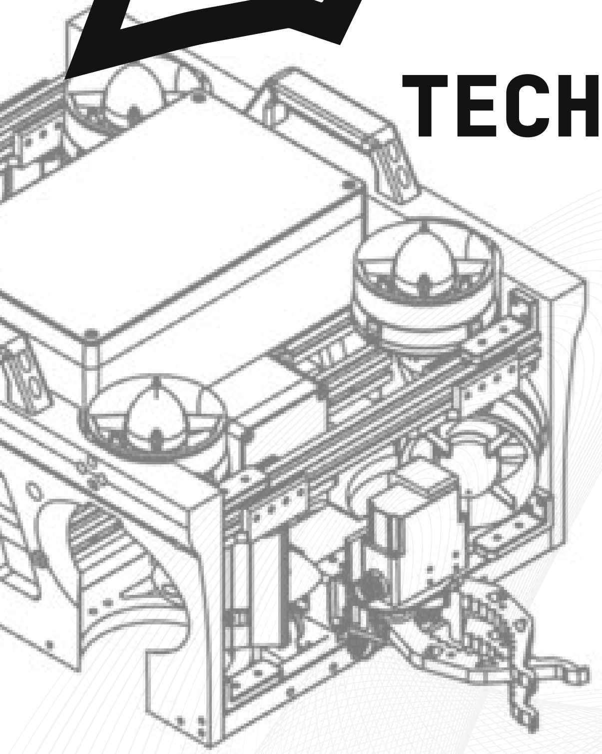
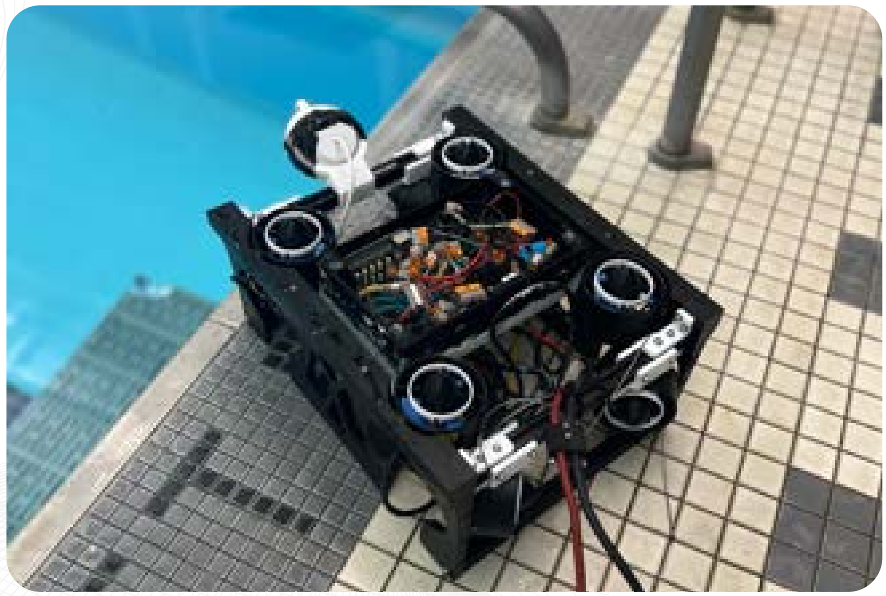
MURFX ROBOTICS

>> MATE UNDERWATER ROBOTICS AT PHILLIPS EXETER
>> EXETER, NEW HAMPSHIRE, USA

// ATTEMPT THE IMPOSSIBLE.

TECHNICAL DOCUMENTATION





//MEMBERS

Max Liu [CEO] (3rd Year/'26)
Anika Sivarasa [CTO] (2nd Year/'26)
Varit Asavathiratham [COO] (2nd Year/'25)
Osbert Chang [Pilot, Mechanical] (2nd Year/'27)
Crane Lee [CSO] (2nd Year/'27)
Fiona Liu [Mechanical] (1st Year/'28)
Andrew Chen [Electrical] (1st Year/'28)

//MENTORS

Mr. Charles Mamolo *[Robotics Coach and Mentor, Instructor of Science]*
Ms. Courtney Shaw [*Mentor, Instructor in Health Education*]
Mr. Doug Hanson *[Mentor, Chief Engineer of Xpress Natural Gas]*

CONTACT: Please email <first name of member>@mrx.ee for inquiries.
Example: max@mrx.ee, or murex@mrx.ee for general inquires.

Photos: V. Asavathiratham and M. Liu. Render: A. Sivarasa

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MUREX ROBOTICS

ATTEMPT THE IMPOSSIBLE

OUR MISSION:* “*MUREX isn't just another high school robotics team. *With a vision to revolutionize and democratize the underwater robotics industry,* ***we push technological boundaries and contribute to the community around us.*** *MUREX doesn't cut corners. MUREX doesn't settle for OK. We do it right.”*

THINK DIFFERENT.

UNLEASH INNOVATION.

ATTEMPT THE IMPOSSIBLE.

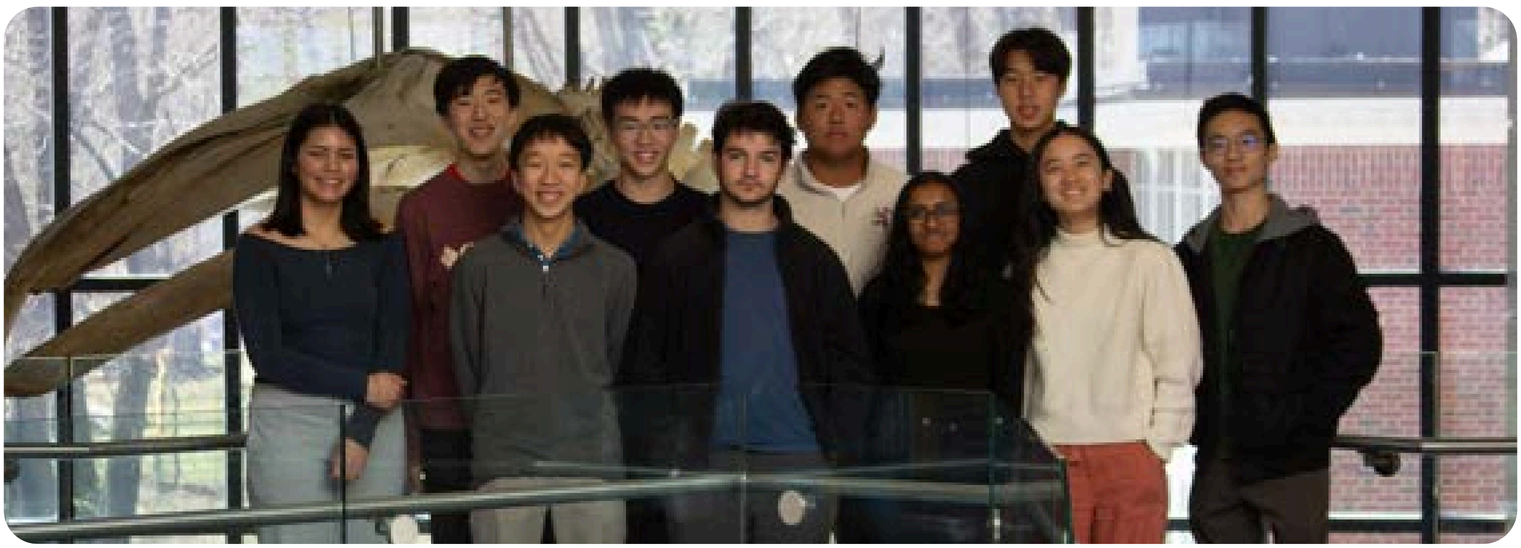
CORE BELIEFS:

- *“The time of youth is the important period, on the improvement or neglect of which depend the most weighty consequences, to individuals themselves and the community."*
- ***“****Goodness without knowledge is weak and feeble, yet knowledge without goodness is dangerous, and that both united form the noblest character, and lay the surest foundation of usefulness to mankind."*
- *“And it shall ever be equally open to youth of requisite qualifications from every quarter."*
- *Most importantly,* ***NON SIBI*** (not for oneself)
- ***Phillips Exeter Academy Deed of Gift****, May 17th, 1781*
    - *Signed by John and Elizabeth Phillips*

ABSTRACT

This year, The MUREX (MATE Underwater Robotics at Phillips Exeter) Robotics Company of Phillips Exeter Academy (PEA) from Exeter, New Hampshire, USA engineered and assembled the MUREX ROV V4, a small, lightweight, low-cost, modular, and fully open source ROV to meet the challenges described in the 2025 Marine Advanced Technology Education’s (MATE) Request for Proposals (RFPs) and to address the needs of the global marine robotics community. The MUREX ROV V4 and crew work to: 1. Deploy undersea devices and analyze marine samples, 2. Install and manage renewable energy technology 3. Engineer, construct, and demonstrate a vertical profiling float.

The MUREX ROV V4 is designed for challenging environments following our 3 years of iterative robotics design experience with strict compliance to safety standards. Our robot uses custom designs to meet our clients’ standards while being completely open-sourced to further ROV development in the underwater robotics community. Our team consists of 11 members with a wide skill set — mechanical engineering, software engineering, and electrical engineering. Our demo team and deck crew are experienced, adaptable, and capable of completing the tasks outlined in MATE’s RFP.



Team Photo at Phelps Science Center, Exeter, NH. Photo: V. Asavathiratham

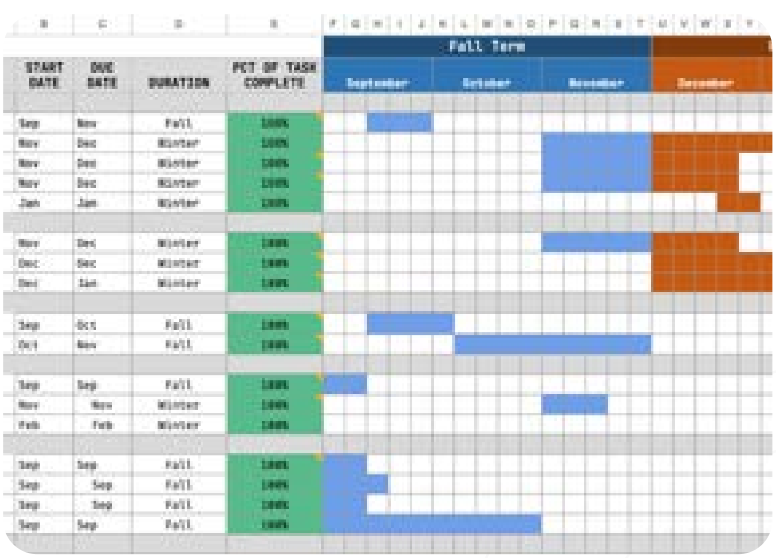
TEAMWORK

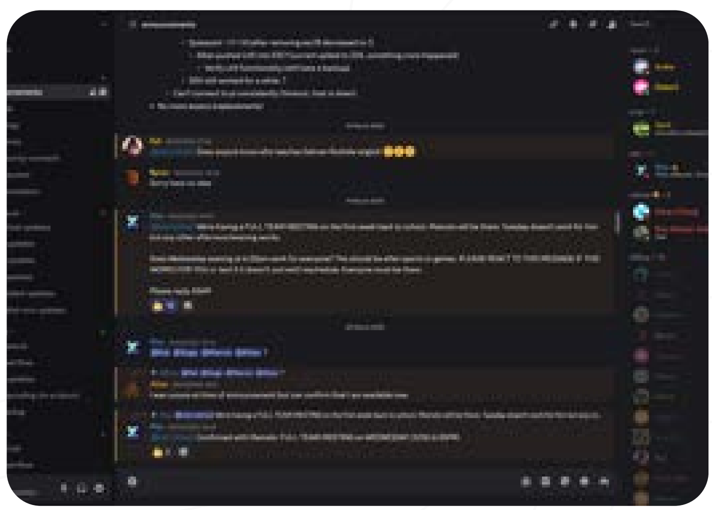
// COMPANY STRUCTURE

High school students operate the MUREX Robotics company to **advance low-cost, environmentally sustainable robots and to democratize ROV development for all. Our team maintains a tight and passionate group of 7 members across our 4 years of operatio**n. The company consists of three subgroups: mechanical, electrical, and programming. Working in parallel, these subgroups maintain constant asynchronous communication through multiple live-updated spreadsheets and documents, as well as weekly team meetings. Newer members of the team can always ask more experienced members for help, and the team fosters an atmosphere of collaboration, respectful interactions, and a tight-knit community so that the company operates to its fullest capacity. MUREX Robotics adheres to strict safety and communication protocols to achieve the best results.

// SCHEDULING AND PLANNING

As the MUREX Robotics Company is based in a boarding school, we are presented with unique challenges and advantages. Half of our members are international, residing in locations around the globe including Istanbul, Mumbai, Bangkok, Beijing, and Hong Kong. The rest of the team resides in **8 different US states from California to New York.** This presents us with global connections in the industry and allows us to source parts from across the world, allowing us to acquire parts like the Raspberry Pi CM4 at greatly reduced costs. However, meeting online over break always presents challenges. We make extensive use of when2meet.com to plan our remote and in-person meetings. As robotics is not a structured activity during the school day at our school, team members must find free time outside of their existing academic, athletic, and extracurricular commitments to work on MUREX. We also have a MUREX team Discord server where we manage all communications and discussions. We extensively utilize spreadsheets to schedule and plan, helping us reach team deadlines.





Top Left: Gantt Chart
Top Right: Discord Server
Right: World Map. Blue locations are where team members are from.

DESIGN RATIONALE

// INNOVATIONS

Problem: Lack of low-cost, advanced electronics for underwater robotics

Solution: One of our biggest breakthroughs is the MUREX electrical system. *Our electrical engineering team works at the cutting edge of industrial, high-performance (HP) robotics.* We focus on making fully open-source electronics that undercut commercial offerings at *5-10% of the cost* while being interoperable with existing options. (See Control/Electrical System)

MUREX is proud to have achieved the following:

- [Jun. 2024] World's smallest and lowest-cost Ethernet Switch, mrxSwitch v2.0. Placed #1 on Hacker News (~6/15/24) with +600 upvotes. Gained +1 million interactions with the website and +100 stars on GitHub in 24hrs. Published on Tom's Hardware, Techspot, ALL3DP, and other various industry platforms/magazines. Reported by various educational creators, reaching over 3 million views on YouTube and Instagram.
- [Nov. 2024] Open-sourced design and demonstration of a 25A ideal-diode protection board for ROVs, mrxShield
- [Dec. 2025] One of the highest data density (triple-channel power monitoring with an embedded controller) power modules, MUREX Smart Power Board
- [Oct. 2024] Ultra compact, 12A custom 5V DC-DC converter board
- [Jan. 2025] World's first open-source USB-modular and highest-power density sensorless field-oriented control ESC hardware design
- [Mar. 2025] Customized open-source BLHELI_S firmware configuration for a 4-1 ESC to drive underwater thrusters based on the BlueRobotics Basic ESC
- [Mar. 2024] World's first open-source CM4-based ROV control board, MUREX Carrier Board
- [Mar. 2024] World's first open-source implementation of a USB3.0, MUREX Carrier Board
- [Nov. 2023] World's first modular serial single ESC, MUREX ANYESC
- [Dec. 2023] One of the smallest open-source dual-output high power modules designed for 12V/5V/3.3V DC applications, MUREX Power Board
- [Dec. 2023] World's first open-source Ethernet Switch, mrxSwitch v1.0
- [Nov. 2023] Open demo of OFDM (orthogonal frequency division multiplexing) over galvanically isolated DC power lines, mrxPLC

// SYSTEMS APPROACH

MUREX designs the ROV's mechanical, software, and electrical systems in parallel. Subgroup leaders handle each respective system. At the start of this year, the team convened to discuss "concrete" systems. These include:

- Software infrastructure for the electrical team to design around
- Standardized electrical connectors between the PCBs
- Enclosure dimensions for the mechanical team to design around

This allowed our team to work asynchronously while assuring each component of the robot could be assembled and function as expected. This was a major improvement to our scheduling and planning in comparison to last year, where the software architecture relied on the completion of the electrical system, which relied on the mechanical requirements.

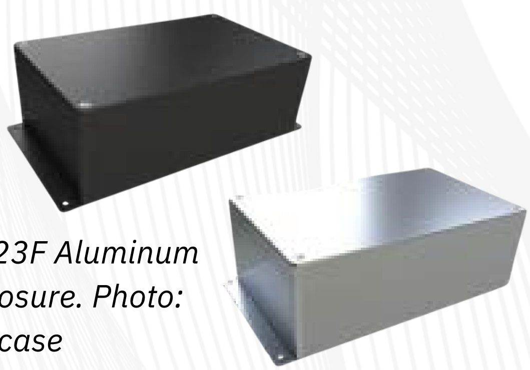
Each system was designed with **adaptability in mind.** The mechanical design offers maximum flexibility while providing a streamlined shape to minimize drag. The use of standard metric measurements across the robot ensured construction and modification were completed as expected.

>> VEHICLE STRUCTURE

This year, the chassis of the MUREX ROV has been CNC milled in-house from marine-grade HDPE. HDPE was chosen due to its **low density and versatility**. It can easily be modified by drilling or cutting to mount parts, while still keeping the overall structure stable. Assembly of the frame is simple and rapid due to its modular design. It measures 45 cm x 36 cm x 20cm, comparable to the size of last year's ROV.

Five aluminum extrusions are utilized alongside T-nut fasteners to mount our enclosures, claw, and cameras. The cuboidal frame design, with thoroughly pocketed side plates, allows 4 vertical and four horizontal thrusters (at a 45 degree angle relative to the midline), to be mounted securely inside of the frame, preventing entanglement without hindering water flow. Our 8-thruster configuration allows for movement in **all six degrees of freedom**. The hydrodynamic shape of the HDPE side panels also contribute to the ROV's smooth motion in the pool.

Last year, we experienced frequent leakages with our rectangular polycarbonate enclosures, and decided the switch to **aluminum enclosures** for the following reasons (see bottom left).



AN-23F Aluminum Enclosure. Photo: Polycase

Chassis Comparison Table

Chassis	Material	Cost	Complexity	Benefits	Concerns
HDPE plate exoskeleton	Marine-grade HDPE	Medium	Medium	Very high strength Streamlined design High flexibility for mounting locations Near-neutrally buoyant	Cannot easily modify overall shape Harder to modify after assembly
Aluminum extrusion exoskeleton	Anodized aluminum	Low	Low	High extensibility strength High adaptability Space-efficient	ROV and mounting spots limited by the extrusion's size and design
Metal plate exoskeleton	Anodized Aluminum	Medium to High (for custom machining)	Medium	High strength, streamlined design High flexibility for mounting	Cannot easily modify design
3D printed design	PLA	Low	Medium	Very high flexibility	Very low strength
Tube design	PVC/Carbon Fiber	Low or High	Medium	High strength and flexibility	Difficulty mounting components securely.

Enclosure Comparison Table

Enclosure	Size	Depth	Features	Concerns
Aluminum Enclosure	Large	High	Easy to design, mount, and repair.	High cost, not visibly inspectable.
Polycase Polycarbonate Enclosure	Large	Low (structural deficiencies beyond 50000 Pa)	Easy to design, mount, and repair. Transparent top for viewing.	Not optimal for underwater use, malleable, easy leaks.
Blue Robotics Cylindrical Enclosure	Small	High	Can withstand depths, designed for ROV usage	High cost, difficult to repair and troubleshoot.
Custom Enclosure	Flexible	Unknown	Flexible to match requirements	High risk of catastrophic failure.

MUREX ROV Frame CNCing. Photo: A. Sivarasa

MUREX ROV Frame WIP. Photo: A. Sivarasa

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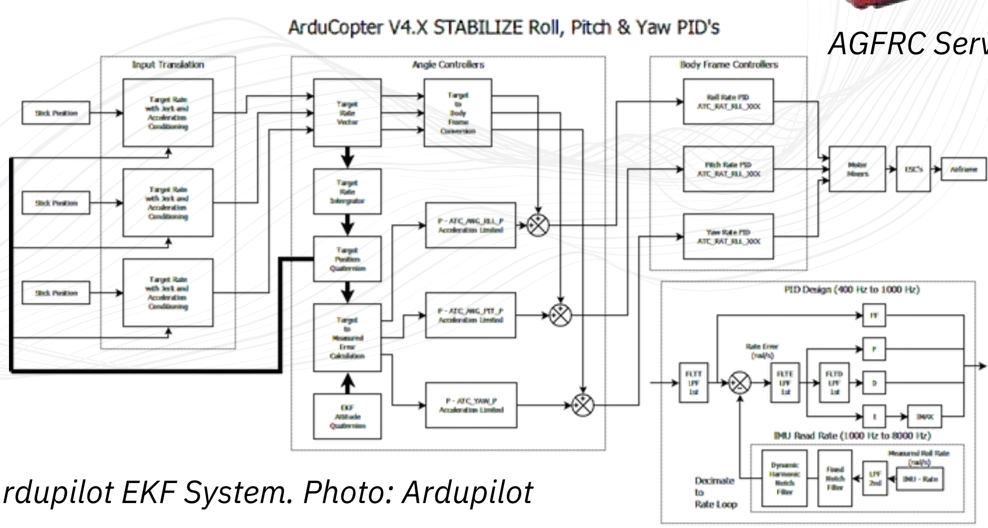
VEHICLE SYSTEMS

CONTROL SYSTEM

The control system accurately controls the 8 thrusters and manipulator servos, allowing the demo team to make real-time observations about the mission. MUREX's tuned EKF (extended Kalman Filter) with **22 estimation states across our 10 DoF** sensing allows our robot to be fully stabilized along all axes of motion.



Ardupilot EKF System. Photo: Ardupilot

MOTION SYSTEM

The motion system involves driving the 8 BLDC thrusters and controlling all servos. A major factor we considered this year was the complexity of existing ESC systems and their interoperability. The MUREX Motion System is designed with **universalization in mind**, allowing for rapid expansion and modification of the system with minimal downtime and modifications.

T200 Thruster. Photo: Blue Robotics

AGFRC Servo. Photo: AGFRC

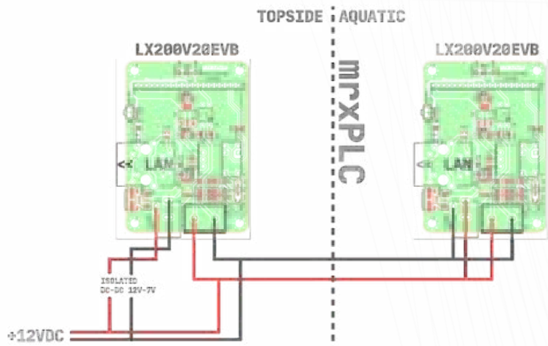
Enclosure Photo. Photo: M. Liu

VISION SYSTEM

The vision system integrates our two IP (internet protocol) cameras to stream live video to the topside. The MUREX Vision System includes a top-mounted, wide FOV camera and a lower, angled narrow FOV camera from Amcrest Technologies. These cameras were chosen for their **low cost, robust enclosures, and H.264 compression**. Many existing vision system implementations use USB cameras with multiplexing. However, that means only one camera can be displayed at a time. This is an inherent issue with video encoding on low-performance hardware, so MUREX bypasses the issue completely with our IP-based system. These concurrent camera views, providing the best clarity and lowest delay. The cameras have intersecting FOVs, minimizing parallax. Commercial IP cameras also use robust outdoor enclosures, often made of cast aluminum with included O-rings, rubber seals, and desiccant. MUREX furthered the cameras' existing waterproofing with Molykote 111 and O-rings on each screw entry for further waterproofing. The ethernet outputs of the IP cameras connect to the MUREX Ethernet Switch.

Amcrest Camera. Photo: Amcrest

Topside Photo. Photo: M. Liu



mrxPLC Functional Diagram. Diagram: M. Liu.

TETHER DESIGN RATIONALE

The strain relief system on the back of the ROV uses metal wire as a medium **to take the 99.5% of the physical strain off the main tether**. The tether wires are friction clamped to two metal wire loops, connecting to the structural frame of the ROV in the back. MUREX conducted multiple iterations of strain relieving, ultimately settling on this design for its simplicity and reliability. The distributed stress from using two metal wires allows the strain relief to be so robust that it supports the weight of the robot for extended periods of time.

The tether is highly flexible and experimentally modified with flotations to be neutrally buoyant. Tether managers are trained in communication and deployment to avoid possible entanglement.

Notes: [1] Explained in Electrical System

TOPSIDE SYSTEM

The MUREX Topside is built around an Amazon Basics Suitcase that has been heavily modified. A 23.8” monitor is attached to one side, while the other has DC and AC wiring. The demo team has access to all topside wiring through an easily removable PETG top layer. The suitcase has ample space to hold all the required electronics as well as tools and the controller. All connections into and out of the topside are strain-relieved. The Anderson Powerpole input is fused on the high side and passed through the emergency stop button and power monitor in series. **The main DC input is passed to the robot through the tether connection and the mrxPLC system in parallel [1].** In particular, the power tether is secured to the topside with two industrial locking connectors, rated to support 30A within temperature regulations. The topside uses USB-C to enable USB-C charging, USB device connection, and HDMI output to the monitor. A suitcase was selected for its low price, wide availability, and thin shell which allowed for modifications to be made. Costly pelican cases, unreliable DIY options, and unprotective enclosure-less/exposed options were also considered, but the commercial suitcase struck a fair middle ground. Upon completing a deployment, the demo team can be ready for departure efficiently by pressing the stop button, detaching from AC power and DC power, and zipping up the suitcase. The wheels on the suitcase also allow the topside to be transported with ease.

Strain Relief. Photo: O. Chang

Tether Managers. Photo: K. Lopez

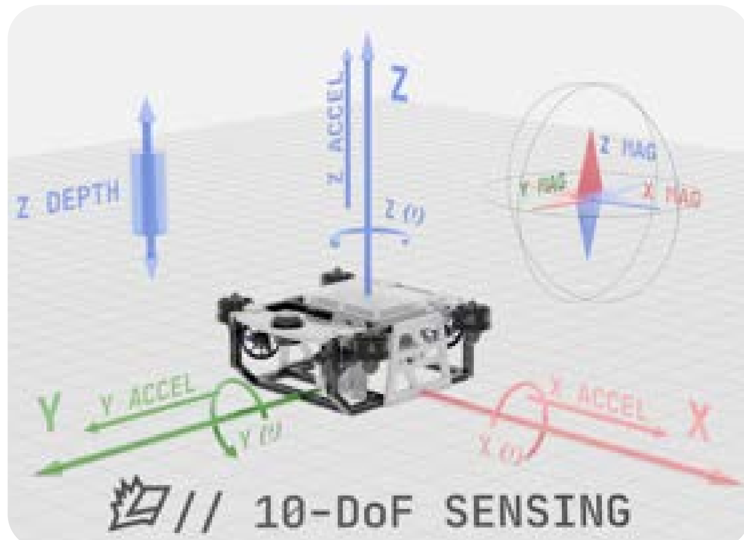
CONTROL/ELECTRICAL SYSTEM

> OVERVIEW

The MUREX Aquatic Electrical System is an ***advanced, open-source design offering 10-DoF sensing, input power, transient protection*** on every major connection, and various innovative PCBs. The MUREX ROV V4 system utilizes a custom Linux distribution, mrxOS, a custom control software built on top of Ardupilot, mrx, and many custom software systems such as MASCP (MUREX Asynchronous Serial Communication Protocol) and custom scripts for Ardupilot. A optimized software in combination with the advanced electrical system enable the MUREX ROV V4 to glide through water and reliably carry out tasks such as placing brain coral, enabling irrigation systems, and deploy subsea cabling.

The system communicates through PWM to two RuiBet's 4 in 1 ESCs, which drive the T200 thrusters. The Murex 5V buck converter provides up to 12A for powering the BlueRobotics' Navigator Flight Controller, which communicates with the ESCs as well as the other servos for the arm through PWM. Video is streamed from two IP cameras through the Ethernet switch, the mrxPLC system, and then decoded into Ethernet in the topside.
MUREX ROV V4 utilizes various custom PCBs, enabling various functionality at costs <30% of existing commercial options [2]. MUREX will now provide further descriptions and functionalities for custom boards and methodologies in use.

Notes: [2] Please see build/buy section.



3D Render Demonstration. Render: M. Liu.

> NAVIGATOR FLIGHT CONTROLLER

Last year, MUREX used its custom controller board called the Carrier Board, an ROV control system featuring the world's first open-source CM4-based ROV control board and the world's first open-source implementation of a USB3.0 controller in any form. However, after a devastating underwater short-circuit, the Carrier Board was severely damaged, along with MUREX's power electronics and custom ESCs (ANYESCs).
Eventually, MUREX chose to select a commercial solution that matched the performance of the Carrier Board, landing on the Raspberry Pi 4 with the BlueRobotics Navigator Flight Controller. **The HAT is an ROV control system featuring a CM4-based ROV control board.** The board features high-accuracy sensors, industry-level control, and **runs ArduSub**, a derivation of ArduPilot for ROVs.

> NAV FLIGHT CONTROLLER Cont.

Features include:

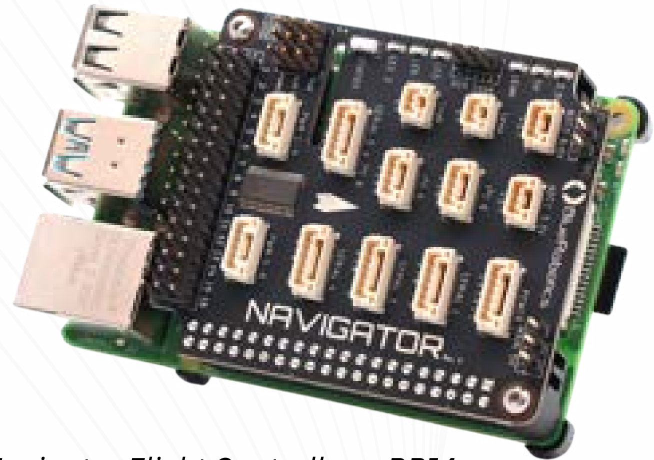
- 16 servo PWM channel outputs (8 channels are used for ESCs, and 3 are used for the claw, and additional channels for servos).
- 2 I2C ports and 4 serial ports with 3.3V logic on each port and 5V tolerance on serial ports.
- 6-axis IMU and dual three-axis magnetometers allowing for 10 degrees of freedom sensing (XYZ acceleration, XYZ angular velocity, XYZ spatial orientation, pressure/water column depth).
- The Navigator comes with a custom designed aluminum heatsink that fits between the Navigator and Raspberry Pi and allows the Raspberry Pi to operate at high CPU usage in poorly cooled environments.

> MUREX Buck Converter

The mrx Buck Converter is an **ultra compact custom 12A 5V DC-DC converter** the size of a thumb, measuring just 22 mm x 27 mm. Its compact size and efficient design reduce its cost to ~50% of other available commercial options. It powers the Navigator Flight Controller and servos with 5V, maintaining 95% efficiency during the DC-DC conversion, which is higher than many commercial options.

Power Board Features:

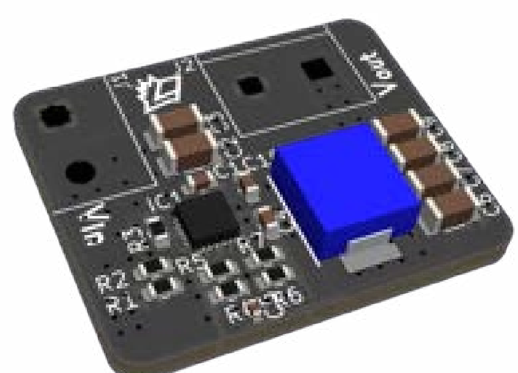
- Beat-frequency correction, high-power, and efficient DC-DC conversion with the TPS568230 Synchronous Buck Converter [3].
- SRP7028A Shielded Power Inductor reduces electromagnetic interference, handles peak currents without saturation, and great thermal performance.



Navigator Flight Controller + RPI4.
Photo: BlueRobotics

> ETHERNET SWITCH

The mrxSwitch v2.0 is **the world's smallest and lowest cost ethernet switch.** With a focus on minimizing physical footprint and cost, the MUREX Ethernet Switch utilizes external magnetics, a high-performance unmanaged switch IC, and 1.25mm pitch Fast Ethernet (100BASE-TX) connectors. **It cuts commercial costs by 90% and acts as the central communications center of the MUREX ROV, combining the 2 IP cameras, the LX200V30, and the BlueRobotics Navigator Flight Controller.** This board was developed out of necessity as full-size Ethernet switches were too large to fit into the system and commercial options were priced extremely high.



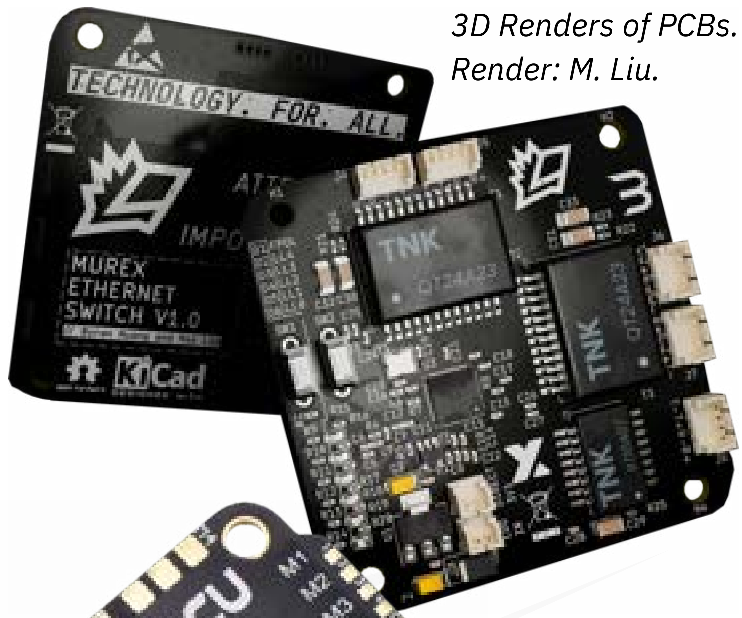
3D Model of PCB.
Photo: C. Lee

Notes: [3] Referenced ***TI white papers*** SLVAED3, SLVAEG8, SLVA882B and more.

> ETHERNET SWITCH Cont.

Features include:

- **5** 802.3u compliant Ethernet ports with the IC Plus IP175G [4].
- 4.5 - 15V protected input through the LM1117MP-3.3 800mA LDO.
- Direct 3.3V power input for high efficiency.



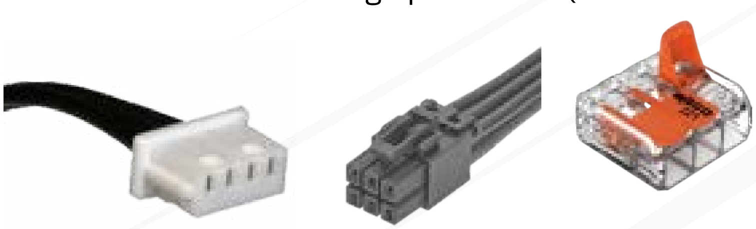
3D Renders of PCBs. Render: M. Liu.

> *mrxPLC AND TETHER ELECTRICAL*

MUREX has conducted extensive research and development on a novel galvanically isolated orthogonal frequency division multiplexing (OFDM) system across the power tether, **allowing our robot to have over *30-60 MBits* of data bandwidth with only power and ground on our tether**. A system explanation diagram is provided in the Topside System section. We have named this development the MUREX Power-Line Communication System (mrxPLC). It enables the robot to use only two wires for the tether, minimizing cost and possible damage. This system is even more effective for high-voltage tethers.

> *CONNECTORS AND WIRING*

To comply with ELEC-017R, all wiring is standardized into either: Molex Picoblade/Header Pins, Molex Mini-Fit, WAGO, or heatshrinked. All data lines are Picoblades or 2.54mm header pins for their compact size. All high power connections are Molex Mini-Fit or WAGO connects if on a high power bus (like main 12V).



Left to Right: Picoblade, Mini-Fit (Molex), WAGO 221 (WAGO)

RuiBet ESC Photo: RuiBet

> *RuiBET 4 IN 1 ESCs*

RuiBet's 4 in 1 ESC boasts a compact design, reducing the size of four ESCs into one, which helps maintain an organized environment inside of the enclosure. The ESC's tiny footprint and quad ESC channels lead it to cost less than **25% of other commercial options** without sacrificing efficiency.

Last year, MUREX utilized our custom ANYESCs and mounted them onto an ESC Carrier board. However, the sheer size of the ESC Carrier and the ANYESCs proved difficult to fit all of the electronics into the enclosure. After careful consideration, MUREX decided that the 4 in 1 ESCs were a better use of space and efficiency. MUREX reflashed the original drone motor parameters with BLHeli_S firmware modelled from the BlueRobotics Basic ESC to enable underwater thruster compatibility and maximum performance.

Notes: [4] See this.

SOFTWARE SYSTEM

Before settling on MRX, **a modified codebase upon Ardupilot tailored for our system**, we extensively tested alternative control systems. Our codebase has seen 3 major revisions, each with its own benefits and disadvantages. Using MRX ensures that we make full use of our ROV capabilities.

Control System	System Coverage	Setup Difficulty	Debugging Difficulty
MRX V1: Python	Low (no sensor integration)	Low	Low
MRX V2: Rust	Medium (telemetry collected from most sensors + minimal active monitoring	High	High
MRX V3: Ardupilot	High (active stabilization + real-time telemetry)	Medium	Medium

By using an off-the-shelf approach for programming we spent our time modifying the codebase, tailoring it to our system rather than writing our own system and fixing bugs as they arise. This way, we ensure that the minimum viable system worked and MUREX spends time optimizing a system that already worked reliably and consistently. **ArduSub fulfills many of our system requirements but falls short of a few important ones:** thruster control, camera integration, and peripheral arm control. The final state of our codebase can be split into the following categories: ArduPilot tooling, Lua Scripting, Component Test Scripts, ANYESC Firmware, MASCP, and Diagnostics Program.

Notes: [5] See ArduPilot EKF explanation + theory.
[6] Understanding altitude.

../ ARDUPILOT TOOLING

ArduSub is the glue that brings together the electrical system. A well-designed control system is the crux of MUREX's granular and reliable driver control. A 22-state Extended Kalman Filter (EKF) accurately estimates the ROV's attitude and heading by **fusing sensor data from our IMU, gyroscope, magnetometer, and depth sensor [5].** ArudPilot's advanced EKF and Attitude and Heading Reference System (AHRS) allows for active stabilization on all 6 degrees of freedom, ensuring that the ROV only moves when intended [6]. Active stabilization corrects imperfections in the ROV construction allowing for more flexibility in component placement around the ROV. Any imperfections in buoyancy and balance become unnoticeable when stabilization active.

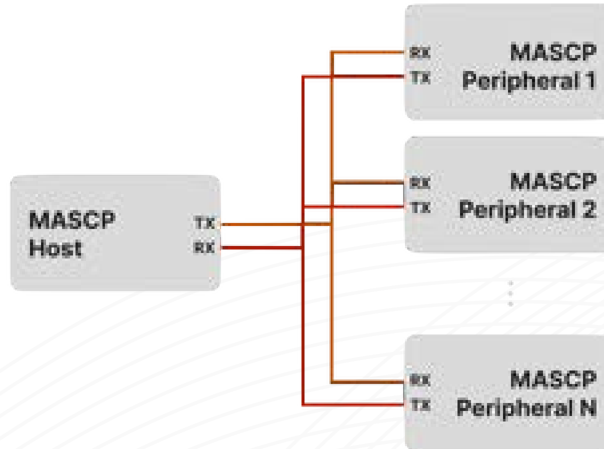
Our driver interface/ground control system is also part of the ArduPilot software suite. MUREX uses a custom version of QGroundControl (QGC) compiled specifically for our topside computer to **aggregate telemetry and communicate instructions** from the driver to the ROV. QGC greatly simplifies the testing and tuning of the system. Our programming and electrical teams can focus on parts of the system that were developed in-house without worrying whether a bug is caused by the systems that control it or the systems that were built to observe it.

mrxGCS (Custom QGC). Photo: A. Ünver

~/ MASCP

A simple standardized communication scheme that could be easily modified in software and implemented in hardware was critical for minimizing complexity in communication within the electrical enclosures. As a result, MUREX Asynchronous Serial Communication Protocol (MASCP) was created. **MASCP is a half-duplex communication protocol capable of enabling communication between any devices connected with only 2 wires and on common ground.** MASCP is built on top of UART [6], a very simple and reliable serial communication protocol. The data format for MASCP was inspired by I2C. The working principles of MASCP involve the host and several peripheral devices. Every device can communicate with every other device in the network using unique addressing. The host device acts as a transmitter for messages that don't contain the host address. So, we make the most powerful processor in the system the host.

Every device is assigned an 8-bit address which cannot be modified without reflashing the firmware on the device. **Every device must have a unique address to enable individual addressing and effective communication between intended devices.** To communicate any device in the system can send an MASCP payload with the target address at the first byte. The host has logic implemented to distinguish between packets intended for itself and other devices in the network, forwarding any messages as needed. While we originally proposed MASCP as a solution for communication between our motion systems and the carrier board, we now use MASCP for any peripheral that requires external instructions for operation.



MASCP Wiring Diagram. Diagram: A. Ünver

./ LUA SCRIPTING

We use Lua Scripting with ArduPilot to extend the functionality of ArduSub to the **MUREX ecosystem without increasing its complexity [7].** ArduPilot exposes a Lua Scripting API that supports reading and modifying the execution of ArduPilot.

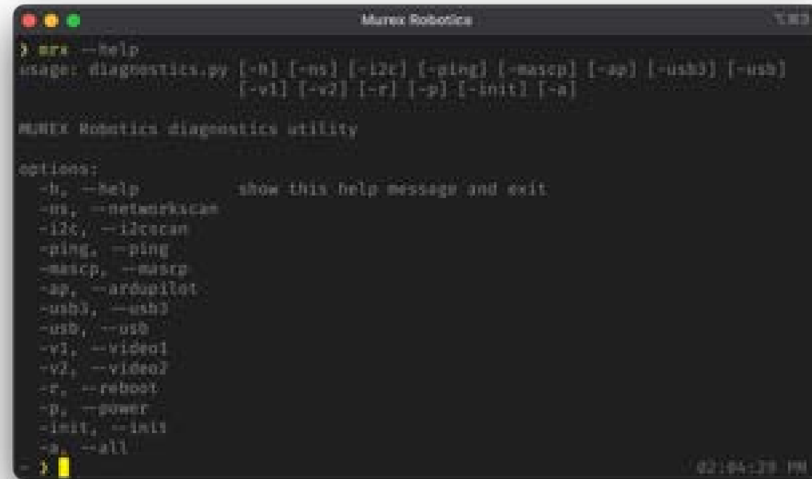
/ COMPONENT TESTING SCRIPTS

In addition to the tools provided by ArduPilot, we also have our own set of scripts to ensure that modifications to the electrical system maintain functionality. Most of our test scripts are written in the Rust programming language and are cross-compiled to run on the MUREX Carrier Board. Before switching to ArduPilot, MUREX conducted extensive research on using Rust for embedded and high-level applications. Ultimately, we found that the Rust ecosystem was underdeveloped and too young to be used effectively in our system. Since the scripts worked well and did not need to be re-compiled, we continued to use them to test the system integrity even after switching to ArduSub.

Notes: [7] See Lua Scripting. [6] See Footnotes on Page 25.

../ DIAGNOSTICS AND TESTING

The diagnostics program is a ***Python script that can run on any topside computer.*** It helps facilitate testing and brings together many of the component testing scripts. The *diagnostics program also helps us rapidly deploy the ROV* and start the camera streams. It automatically goes through all safety and initialization steps required for *a successful deployment.* The diagnostics program also abstracts some steps of deployment since it does not require connecting directly to the robot, *only being present on the same network.*



MRX Diagnostics "--help" Screen. Photo: A. Ünver

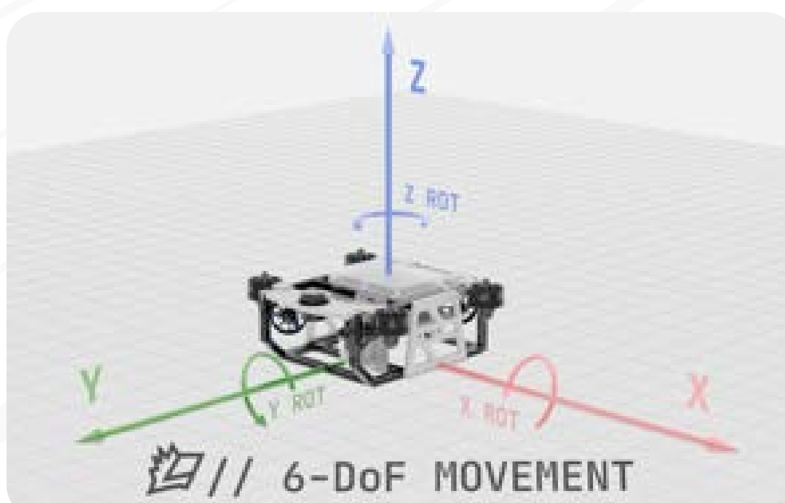
// ANYESC FIRMWARE

The ANYESCs were the first component in the system to integrate MASCP. The core of the ANYESC firmware revolves around initializing the thrusters and listening for MASCP packets for throttle information.

The ANYESC firmware also provides debugging information through Serial lines and status LEDs. We experimented with various embedded approaches like using Rust and MicroPython but finally settled on using C with PlatformIO. PlatformIO is robust and easy to debug allowing for rapid prototyping.

PROPULSION

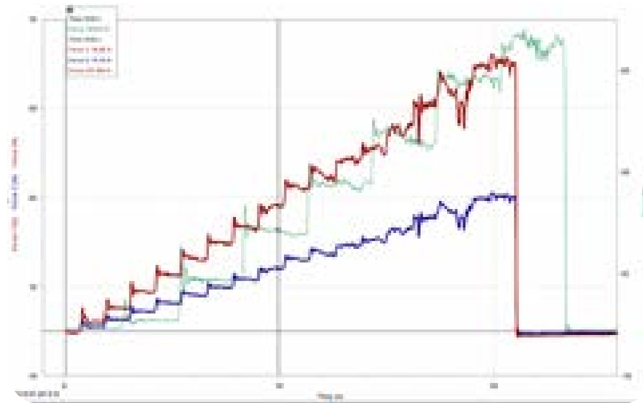
The MUREX propulsion system consists of 8 Blue Robotics T200 thrusters driven by MUREX ANYESCs. The MUREX ROV has 8 thrusters in a vectored configuration, allowing movement in all 6 DoFs. This is a standard thrust vectoring configuration, allowing for rapid electrical and software expansion. **Using our custom control system framework, mrx, the MUREX ROV's advanced 10-DoF electrical system allows the robot to stabilize and depth-hold** at any location and depth in the deployment environment. Their external position to the ROV, provides a greater torque and stability but increases chances of entanglement with tether, and SMART Cables. This increased chance of entanglement has been solved with the use of reflective tape and thruster guards around all directions off the thrusters.



6 Degree of Freedom Movement Diagram. Render: B. Huang

PROPULSION CONT.

MUREX conducted extensive experimentation of the current draw and efficiency of trapezoidal, field-oriented control (FOC), and sinusoidal drive of brushless DC motors. FOC offers clear advantages of higher torque and efficiency at the cost of higher computational requirements. Our schedule didn't allow for further experimentation of FOC driving of BLDCs, so we continued our use of trapezoidal drive ESCs running a custom version of the BLHeli_S firmware. Mounted in each ANYESC is a XILO 25A ESC, chosen for its very high performance-to-cost ratio.


FOC and Trapezoidal Thruster Profiling. Photo: A. Ünver

BLDC Control Method Comparison [8]:

Control Method	Trapezoidal	Field-Oriented Control	Sinusoidal
Software Complexity and Motor Efficiency	Low	High	Medium
Maximum Speed	High	High	Medium
Noise	High	Low	Low
MOSFET Switching Losses	Low	High	High
Final Choice	Selected	Under development	Unsuitable

BUOYANCY AND BALLAST

The MUREX ROV was specifically designed with buoyancy and ballasts in mind. We used CAD software such as Onshape, and Fusion 360's simulation tool, to determine the center of gravity and approximate density, and to improve the efficiency of our pocketing. With an **overall ROV weight of 11.75 kg** and an initial frame density greater than that of water due to the aluminum enclosure, pool noodles were strategically placed to achieve a **neutrally buoyant ROV** with its center of mass directly below the main enclosure. This is due to HDPE’s density of around 0.97g/cubic centimeter, making it an ideal material for ROVs. Alongside the control system, the MUREX ROV can hover at any position when completing tasks which is an immense aid to the driver who wishes to complete tasks designated in the RFP requiring the most accuracy, such as removing a pin to release the hydrophone.

The initial mass of the mrxFloat rests at about **1495 g,** but weights have been added to make it neutrally buoyant. Once 300mL of water is taken through the syringe, the mass increases to 1795g while the volume of the float stays constant at 1760 cubic centimeters. Thus, the intake of water changes its density from **0.96 to 1.17 g/cubic centimeter**, resulting in descension. The inverse is repeated for ascension.

BUOYANCY MODULE (mrxFloat, Versions 1 and 2)

The compact **mrxFloat V1** consists of an open syringe moved by a continuous rotation Axon servo motor and lead screw mechanism, resulting in a buoyancy engine that **changes its volume by approximately 300mL**. This particular motor was chosen for its **high torque and fast rotational speed**, which alongside the lead screw allows the float’s density to change rapidly.

Notes: [8] Decisions made with reference to Texas Instruments’ SLVAES1A whitepaper

Unfortunately, due to this design not initially working as intended, we pivoted to the mrxFLoat V2. It features an acrylic enclosure with aluminum endcaps, and a thruster mounted on the bottom. The enclosure holds a 12V Nickel metal hydride battery, a XILO ESC flashed with BlueESC firmware, an inline 5.0A fuse, a 12V to 3.3V buck converter, and an ESP32 LoRa V3. For communication, MUREX considered options such as Wi-Fi and Bluetooth, but preferred the simplicity and long range of LoRa 915 MHz. The ESP32 LoRa V3 in the float transmits signals (915 mHz) consisting of the ROV's company number, local time, and depth in five second intervals throughout its descent and ascension. Another ESP32 LoRa V3, located on the surface, receives these signals and data points in which MUREX can then graph.

Using the **BlueRobotics BAR02 Depth sensor,** and their MS5837 library, the ESP32 is able to successfully communicate the depth of mrxFloat.
In both versions, the enclosure has been verified to comply with MECH-001 (pressure tested to 5m water column depth). The pressure relief system consists of a top cap that disengages from the acrylic tube in the event of high pressure, which is also paired with a standard BlueRobotics pressure cap rated to 12 psi. Additionally, to follow safety specification ELEC-NDR-005, a 5.0A fuse is attached within 5cm of the power wire of the battery.

L to R: 2024 float, 2025 mrxFloat V1, mrxFloat V2. Photos: F. Liu

BUILD/BUY,NEW/USED

At MUREX Robotics, our approach to choosing the right components is very simple; **if we find that a task can be done better than commercial alternatives (higher efficiency for same price, same efficiency for lower price, higher efficiency for lower price, features that cannot be purchased) we design and test in-house.** If industry standards exceed our team's capabilities for a reasonable price, we use the commercial alternative. This rationale is demonstrated extensively throughout all subgroups at MUREX. We make extensive use of custom boards in our electrical system because they greatly reduce the cost and space while increasing performance relative to what we could purchase. Shown below is a table exemplifying the cost-effectiveness and innovation of our electrical system. The performance and cost of the electrical system are crucial to exceed our customer's requirements as it allows more budgeting towards other areas of research and development while providing a state-of-the-art control system that can adapt to any deployment environment.
The custom parts in our frame design were scrutinized to ensure that the value they contributed justified their added complexity. In pivoting to our newest ROV design, nearly all aspects of the system have been reconsidered, and appropriate parts have been re-used in the MUREX ROV V4.2. **To conserve costs, we have reused the ROV's thrusters, cameras, servos, and custom servo casings.** Our new 3D-printed parts and CNC-cut HDPE plates are produced for free and provide mounting configurations that would not be possible with off-the-shelf parts. Our new aluminum enclosure was also well worth the investment, since it is reliable, unlike our previous enclosures which were prone to leaking or cracking.

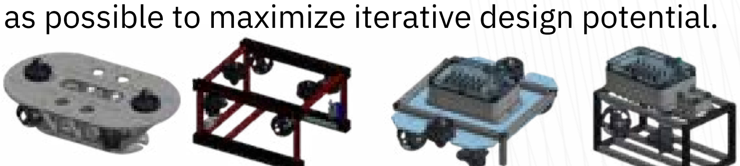
BUILD/BUY, NEW/USED CONT.

System	Function	Prototype Price (ea) [9]	Commercial Option Price (ea) [10] [11]	Cost Savings
MUREX Ethernet Switch	Packet switching on robot network	$9	Blue Robotics Ethernet Switch: $175 BotBlox Swtichblox: $72	95%-59%
MUREX Carrier Board	Full system control	$30	Holybro Pixhawk RPi CM4 Baseboard: $446.99	93%
MUREX Power Board	Power conditioning and dual DC/DC converter	$20	Sky-Drones SmartAP PDB: $90	78%
MUREX ANYESC	Motion control system	$14 * 8	Flyduino KISS ESC: €22.9, ~$25 * 8 Holybro Kotleta20: $57.99 * 8	76%-44%
OFDM Data Injection (mrxPLC)	Data transfer across tether	$0	Fathom ROV Tether: > $220 (increases with length)	N/A (Zero Cost)
Total		**$171**	**$1,395.91**	**>88%**

CRITICAL ANALYSIS AND TESTING

MUREX's extensive use of custom electrical and software components result in high performance at the expense of complex testing methodologies. **Our testing methodology focuses on variable isolation and finding the root of the problem as quickly as possible.** Our mechanical team utilizes extensive use of iterative design and 3D printing to improve designs. We conduct pool tests as often as possible to maximize iterative design potential.

MUREX's Mechanical subgroup has produced four major chassis designs, three float designs, and five versions of a claw to achieve our final product. Each design has been thoroughly modeled and tested, maximizing its versatility and coordination with other subsystems. Each new design tailors more toward the RFP's task requirements by modifying the placement of mission sensors and orientation of manipulators. In the future, we hope to advance our manipul, as well as fully integrate all of our thrusters into the ROV frame,



V1.8, *HDPE Frame*

~ excess water resistance for vertical profiling, unadaptable mounting opportunities

V2.0, *First Exoskeleton Frame*

~ bulky, unstable and weak acrylic base

V3.1, *Hybrid Winged Design*

~ unreliable vertical profiling due to water resistance, no manipulator space

V3.2, *Compacted Wing Design*

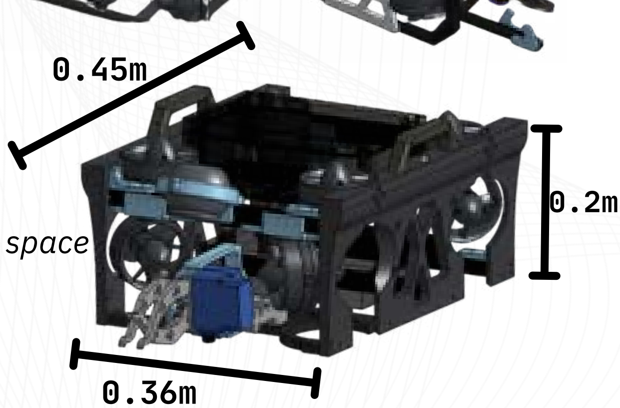
~ too small, no carrier claw space

V3.3 + V3.4, *Medium Wing Design with Front Bezel*

~ Thruster Mounting Unstable

V3.5, *Finalized Wing Design*

~Thrusters protruding from frame, limited space for mounting



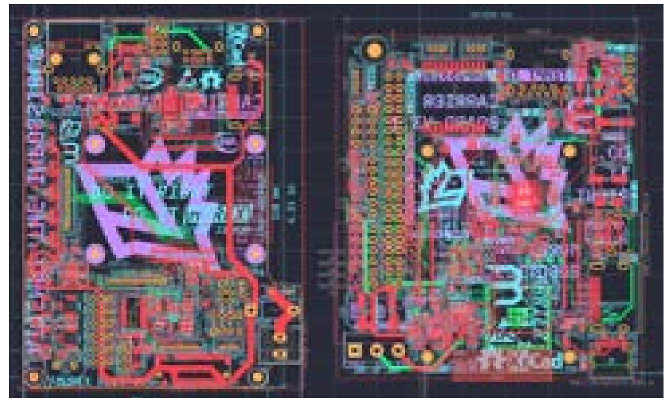
Top left to bottom right: V1.8, V2.0, V3.1, V3.2, V3.3, V3.4, V3.5, V4.2

Notes: [9] Price based on JLCPCB production cost, tax and shipping included. [10] Tax and shipping not included. [11] Most commercial options lack features and power protection compared to MUREX systems.

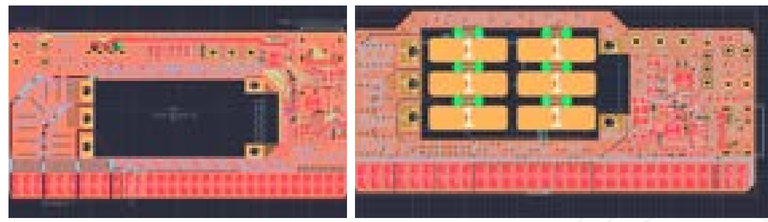
CRITICAL ANALYSIS

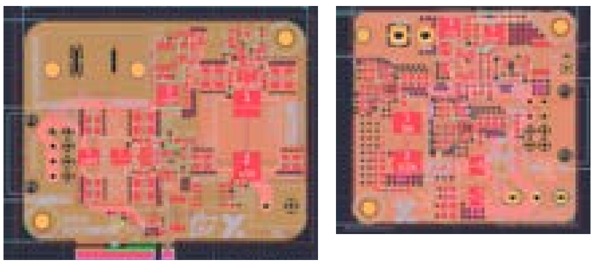
> ELECTRICAL R&D

Much of the beginning of the year was invested in conducting research and development of the electrical system. Our initial designs lacked EDS, transient, and other circuit protection systems. The PCBs were also routed inefficiently, resulting in unnecessarily dangerous and large boards. **After multiple revisions on each of our electrical systems, we were able to create reliable boards that implement state-of-the-art protection and performance improvements.** All R&D is conducted under the mrxEE [12] (MUREX Experimental Engineering) subsidiary of MUREX.



Carrier V1 -> V3 | 42% area decrease. Photo: B. Huang





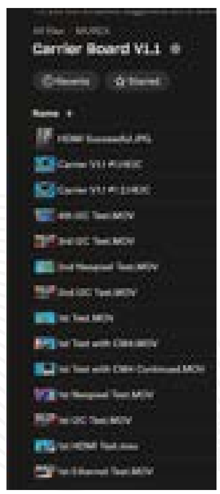
Power V1 -> V2 | 20% area decrease. Photo: M. Liu

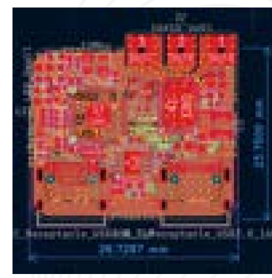
> ELECTRICAL TESTING

MUREX follows rigorous testing procedures and a system to version manage circuit board designs. **We have developed the follow procedure:**

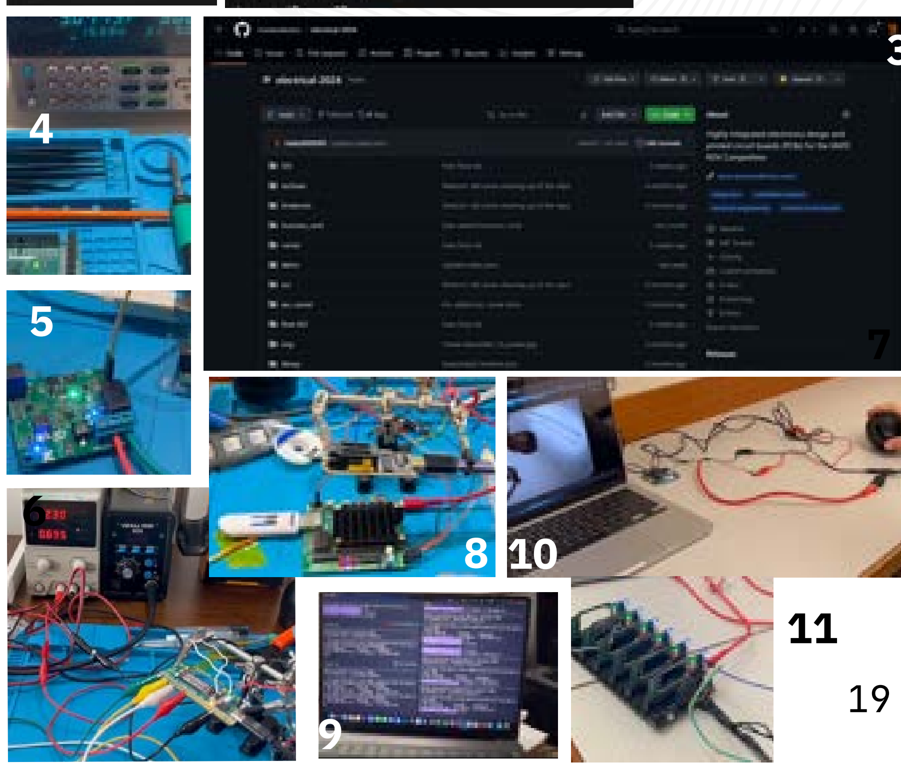
1. Research and determine main components.
2. Design your schematic (KiCAD eeschema)
3. Design your PCB (KiCAD pcbnew)
4. Design your silkscreen (KiCAD pcbnew)
5. Tapeout verification with the team (Discord)
6. Production with Fabricator (JLCPCB)
7. PCB Testing (mrxEE)
   - Incremental testing of every feature. Every test must be recorded and marked. (Dropbox)
8. Update documentation and generate renders. (Web Dev + Blender Visualization)

Through this process, we use GitHub to version manage as well as share our work with others in the underwater ROV community. Again, our work is fully open-sourced and documented. ***Explanations in footnotes, section [a]***





STESC -> ANYESC → MINI_FOC ESC. Photo: M. Liu.



PAYLOAD & TOOLS

There are two cameras on the ROV, each providing the ROV with a deliberate, unique view. The downward angled camera, mounted at a 45 degree angle on the chassis' front aluminum extrusion is an Amcrest IP5M-T1277EW-AI. It provides a frontal and slightly downward view of the claw and its surroundings. Although not pictured, it will be mounted to a servo on the front extrusion, enabling it to pitch upwards. This will help improve photosphere generation and enable it to see objects floating on the surface of the pool. The second camera, angled 45 degrees downwards in the back of the ROV, is an Amcrest IP5M-T1179EB-28MM. While at the back of the ROV, this camera can see forwards and gives the driver an overview of the pool floor and a wider view of the ROV's surroundings. The camera can also be securely mounted within the 3D-printed mount at various angles due to its spherical shape. These cameras allow the driver to operate the ROV, track its movements, and approximate its location remotely. The downwards facing Amcrest **focuses on the two claws and target various objects**, while the other camera provides **upward and downward facing angles** to give the driver an approximate idea of the ROV depth.

Left to Right: 3DoF Claw, Front Amcrest, Back Amcrest. Photos: A. Sivarasa

The manipulator is a 3d-printed claw that features **three degrees of freedom**, allowing it to swivel to virtually any position. An especially useful aspect of this is that the claw can yaw to clasp around both horizontally facing objects such as the cargo lid, and vertically facing objects such as the thermistors. The claw utilizes **custom-designed herringbone gears**, giving it an increased grip and reduced chance of wear. An innovative three-pronged design with interlocking tips provides a more secure grasp around objects of all diameters and shapes. The claw can **swivel continuously in the plane perpendicular to its prongs**, allowing for installation of the sacrificial anode. Additionally, MUREX utilizes a **mini peristaltic pump** connected to an extended tube with a sharp end, to puncture the cling wrap and gather a water sample from a soft water bottle as part of task 1.3. It is powered by a separate DC power supply connected to an AC rail on the topside. It is able to rapidly collect the sample, delivering 50 mL to a container on the surface in under 30 seconds. A **pH sensor** also mounts onto the frame, and can be held by the claw to measure the water sample's pH in situ.

Peristaltic Pump. Photo: Hilitand Store

pH Sensor. Photo: GAOHOU

SAFETY

/ SAFETY RATIONALE

MUREX Robotics regards safety as the **top priority at all times**, whether it be during research and development, large-scale tests, or deployments. Our robot has a wide range of safety features. This includes MUREX's IP20-grade thruster guards, electrical transient spike protection, system voltage and current monitoring, mechanical limits, and an extensive software pre-arm checklist. Our advanced electronics and software system actively monitor voltage and current in the system, the power loss across the tether through a comparison of topside power supply and ROV power reception, temperature, pressure, moisture, and gas resistance monitoring, AHRS heading system calibration, and more. The claws have programmed and mechanical limits to prevent unwanted rotation, and the frame has no sharp edges to prevent damage to its deployment environment. Every electrical system is assembled in accordance with the Restriction of Hazardous Substances Directive (RoHS) such that in the case of a failed deployment, the electronics contain acceptable levels of hazardous material. In addition, we have devised an extensive safety protocol for each subgroup. **Summaries of the protocols are listed below.**

Mechanical: Wear appropriate personal protective equipment (PPE) at all times. This includes, but is not limited to: safety goggles, gloves, closed-toed shoes, and hearing protection. In addition, all common safety protocols should be followed. Rationale: Preventing injury when constructing and testing the robot.
All subgroups: A thorough safety inspection is performed before and after each deployment. Rationale: Robot performs as expected and is maintained in good condition.

Mechanical: Pressure test to 15 inches of Hg (in compliance to MECH-001) after any modification or opening of any sealed system. The pressure may not drop more than 3400 Pa (1 in Hg) after 1 hour, and 17000 Pa (5 in Hg) after 24 hours. The servos present in the ROV are filled with mineral oil and coated with epoxy. The lower specific gravity of mineral oil compared to water prevents the upward flow of water through the downward facing shaft into the servo. Additionally, there are 3 O-rings: 2 for the shaft, while 1 that covers the perimeter of the servo. The shaft is further waterproofed with a 4-layer shaft seal. *Rationale:* This protocol ensures that the robot maintains its watertight integrity at any point during testing, repairs, and deployment.

Electrical: Verbally announce and count down "power on" and "power off" while recording the system in question for any live testing. *Rationale:* MUREX keeps video records of every electrical test should further analysis be required. Verbal confirmation allows every member in the vicinity to either clear away or pay specific attention.

Electrical: All wiring is secured and all persons maintain a distance from any exposed wiring. *Rationale:* This protocol protects both team members and the equipment. It means even if the wiring is accidentally jostled, all systems remain unaffected.

Programming: Hard-programmed limits present on all moving systems. *Rationale:* Limits ensure that the robot will not perform movements outside of its expected range.
Programming and Electrical: Independently verified testing on all subsystems before integration. *Rationale:* All parts of the system must be tested and known to be electrically and programmatically sound before further integration.

> DEPLOYMENT SAFETY CHECKLIST

Prior to and after every deployment, the team will have their respective members for mechanical, programming, and electrical check every system with audible responses. ***One member is designated as the safety manager who coordinates all the protocols.***

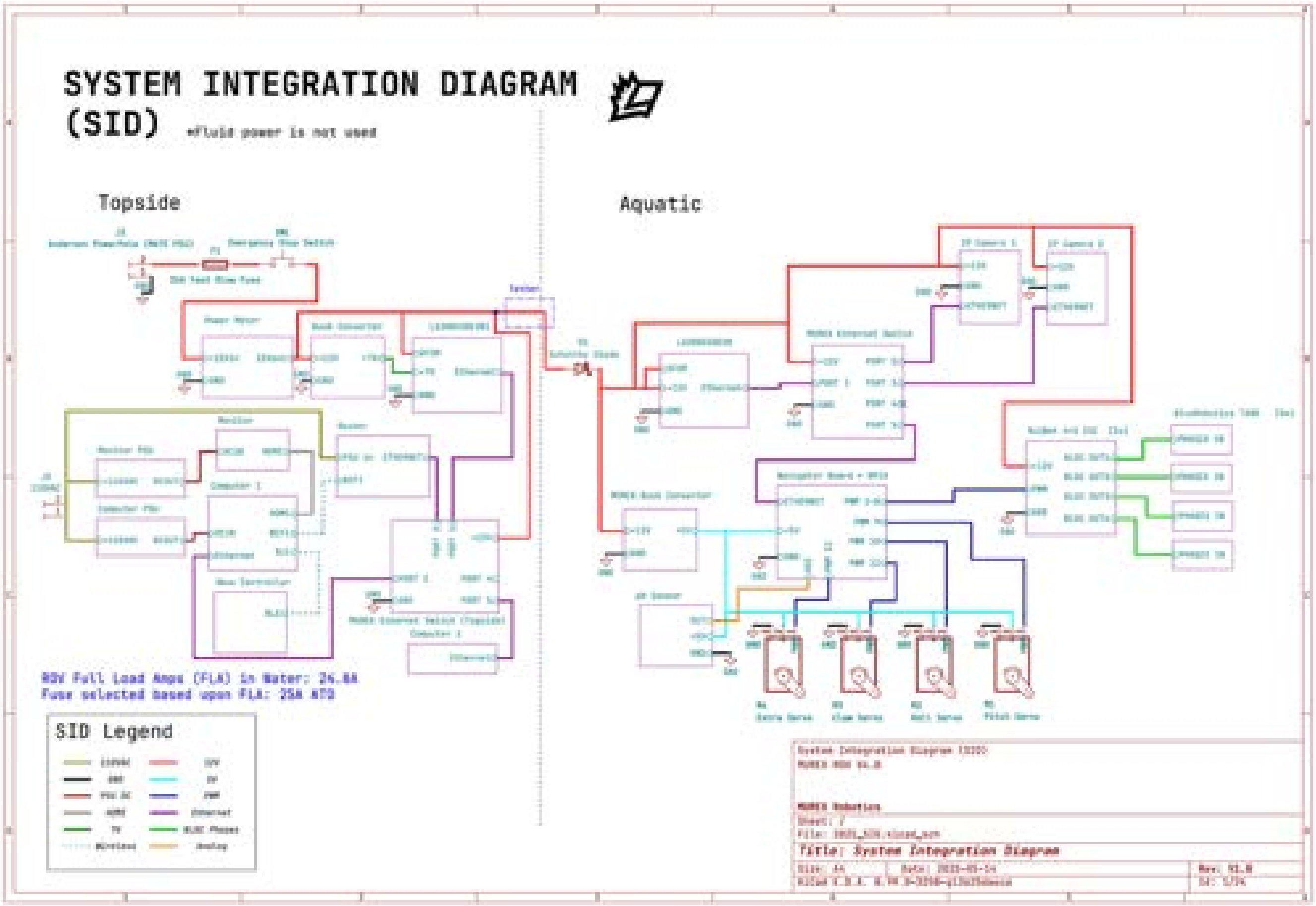
- Chassis supports at least 600N force applied. **“CHASSIS CLEARED”**
- Thrusters attached securely + cannot move over ±2mm in any direction. **“THRUSTERS CLEARED”**
- All propellers, servos, and any other motors are free spinning. **“MOTION CLEARED”**
- All manipulation devices attached securely and lubricated. **“CLAWS CLEARED”**
- Tether supports weight of robot. Spaced out flotations securely mounted to tether. **“TETHER CLEARED”**
- All potential ingress points lubricated and sealed with lubricated o-rings. **“INGRESS CLEARED”**
- All vacuum plugs and seals free of debris and other unwanted substances. **“SEALS CLEARED”**
- All wiring in robot, topside, and float secured and unexposed. Main tether not continuous (shorted). **“WIRING CLEARED”**
- All software is launched and the topside computer has over 50% charge. **“PROGRAMMING CLEARED”**
- Topside powered, controller connected, demo team ready for power on. **“TOPSIDE CLEARED”**
- The topside emergency stop button “OFF” (pressed in). If all other protocols are cleared, the demo team announces “ON STANDBY”. If all protocols are followed correctly, the safety manager announces **“READY FOR POWER ON”.**

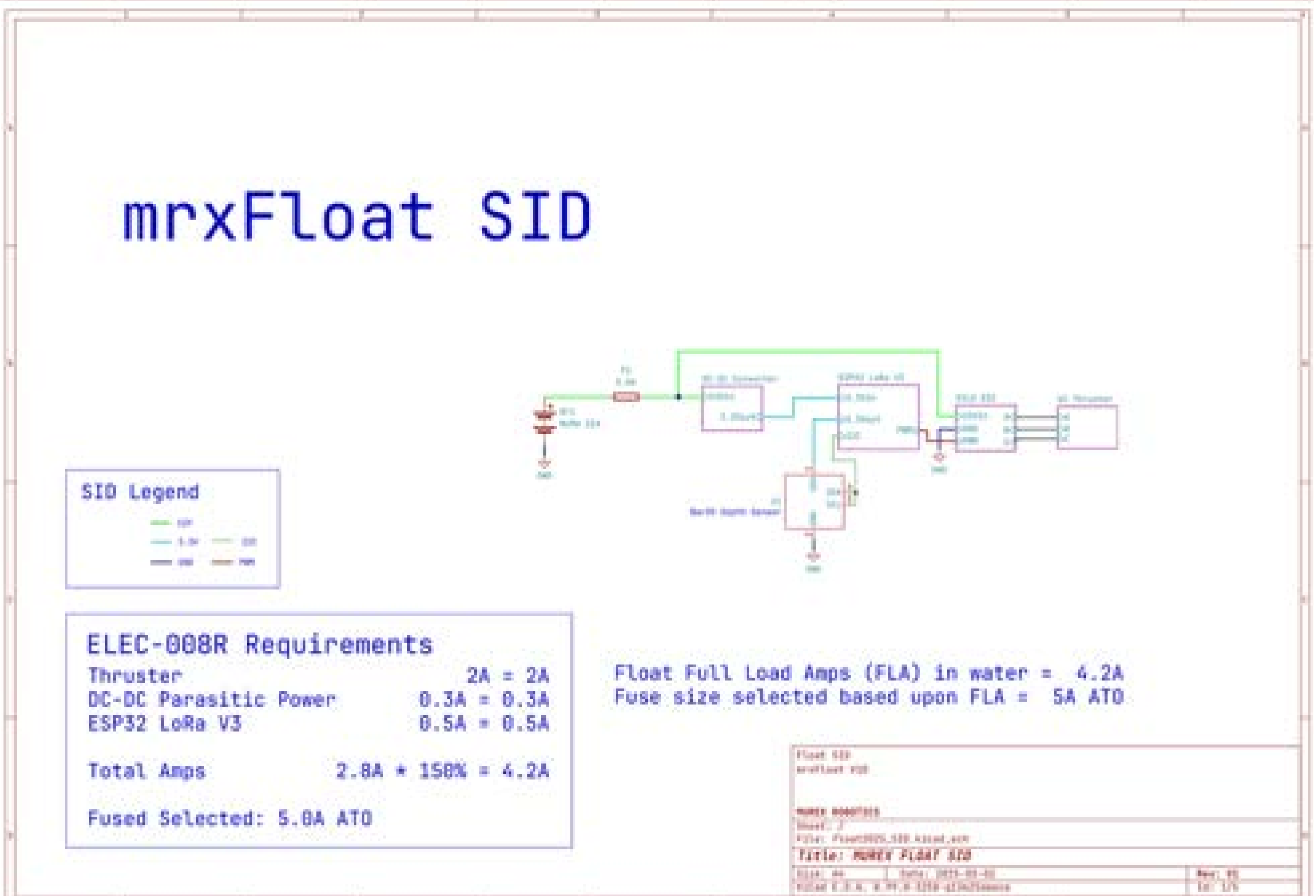
> PRE/POST DEPLOYMENT SAFETY PROTOCOL

Demo team conducts final visual inspection of topside wiring and setup. If passing inspection, demo team announces **“POWER ON CLEARED. POWER ON IN... 3... 2.... 1”**. If not passing inspection, demo team announces “POWER ON WRONG”. Appropriate measures then taken.

Demo team moves emergency stop button to the “ON” position (pulled out). The motors produce power up (3 beeps in increasing pitch) and arming sequence (1 high pitch beep, then 1 low pitch beep). An electrical member on standby announces **“MOTOR ARMING CLEARED”.**
Demo team waits for “MUREX TOPSIDE” Wi-Fi SSID to appear or is assigned an IP address by the topside router depending on the connection method. **“CONNECTION CLEARED”.**
Demo team enters the OpenWRT portal (192.168.8.1) and verifies the following devices are listed: 1. Amcrest Camera 2. Reolink Camera 3. MUREX Carrier Board and demo team executes system check software. **“SYSTEM CLEARED”**
Demo team initializes all softwares. **“SOFTWARE INITIALIZED”**, then **“ROBOT IS ARMED”**
Demo team conducts a dry run of the thrusters and the cameras are verified. **“TESTING THRUSTERS”**, **“TESTING CAMERAS”**. Tether manager(s) respond **“THRUSTERS GOOD”**, **“CHECKING CAMERAS”**. Demo team responds **“CAMERAS GOOD”**
Tether manger(s) pick up the robot and rotate in all axes. **“ROTATING <ROLL/PITCH/YAW>”**. Demo team responds **“<ROLL/PITCH/YAW> GOOD”**
If all systems are intact, the demo team announces **“ALL SYSTEMS GOOD”**. The safety manager echos **“READY FOR DEPLOYMENT”**
Tether manager(s) lower the ROV into the water. **“ROV DEPLOYED”**. Tether manager(s) ceases communication with the demo team except for tether management issues.

SYSTEM INTEGRATION DIAGRAMS





COST ACCOUNTING

1	Type	Source	Amount
Income	Funds	Hessel Fund	$5,000.00
		Total	$2,780.51

1	System	Category	Type	Description	Budgeted Amount	Actual Cost	Net Difference
Expenses	**Electrical Costs**	Vision	Purchased	Cameras	$200.00	149.99	$50.01
		Electrical Wires/ Connectors/Components	Purchased	Cable Assembly, Header Pins, Header Sockets, US	$200.00	71.58	$128.42
		Electrical Circuits	Purchased	PLC Module, Murata Non-Isolated Programmable	$700.00	1053.23	-$353.23
		Total	Purchased	**Net electrical costs**	$1,100.00	1274.8	-174.8
	Mechanical Costs	Waterproofing	Purchased	Shaft Seal, Blank End Caps, Acetal Servo Casings,	500	493.45	
		ROV Frame Construction	Purchased	Black HDPE sheets, craft foam blocks, enclosure t	700	588.9	
		Props	Purchased	PVP Pipe, Plastic Sheets, Rope, Gallon Bucket, Ad	300	217.64	
		Float	Purchased	Large Syringe, shaft coupling	[illegible]	[illegible]	?
		Motors	Purchased	High Torque Continuous Rotation Servo, Dual Mo	300	191.74	
		Total	Purchased	Net mechanical costs	1900	1505.71	394.29
	Operational Expenses	Registration Fees	Purchased	Mate ROV Ranger class competition entrance fee	$500.00	$450.00	$150.00
		Travel (Regional)	Purchased				$0.00
		Merchandise	Purchased				

// BUDGETING PROCESS

MUREX makes use of ***Google Sheets*** to keep track of available funds and purchased resources. We keep our budgeting, logistics, and purchase orders together to compare and contrast our predicted expenses with realized costs effectively. Meticulously keeping track of all things purchased, we not only kept our inventory sorted but also were able to make corrections based on observed trends. We realized that not all of our initial budgeted estimates aligned with our spending trends, requiring ingenuity and redistribution of funds.

All MUREX funds are provided and managed by ***Phillips Exeter Academy.*** The school administration mediates access to funds through purchase requests; we created documents compiling information about item costs, sources, and quantities required. This process allows for effective tracking of purchased items and a digital receipt of team funding usage.
Initially, MUREX had a budget of 5500$ to build and test the ROV.
We are sincerely grateful to John H. Hessel and Sidney A. Hessel for their continued donations and support to the PEA Science Department. Without the Hessel Innovation Fund, MUREX would not be able to operate.

ACKNOWLEDGEMENTS AND REFERENCES

THANK YOU TO:

- ***MATE II*** for hosting the MATE ROV Competition
- ***MATE ROV NE Regionals*** for invaluable advice and providing this opportunity
- ***The Phillips Exeter Academy Theater Department*** for providing CNC machining
- ***JLCPCB*** for printed circuit board production
- ***PTC OnShape*** for CAD
- ***KiCAD*** for electronics design software
- ***Bambu Lab and Prusa Research*** for providing 3D printers

PURCHASES / VENDORS

- *AGFRC and Savox for supplying servos.*
- *McMaster-Carr, Amazon.com, Digikey, Mouser, Polycase, Fabworks, Misumi, Lowes, Blue Robotics, Adafruit, GoBilda, GetFPV, and others for supplying parts.*

ONLINE RESOURCES

- *TI, STMicro, IC Plus, Bosch Sensortec, TE Connectivity, Diodes Incorporated, Winbond, Molex, Qualcomm, Broadcom, Raspberry Pi Foundation, Rockchip, Allwinner, Logitech, TNK, Murata, Panasonic, WAGO, Würth Elektronik* and others for providing online resources and whitepapers. Our system either includes/uses electrical components designed by the above companies or has read whitepaper publications. ***However, the team did not receive advice from any company listed above.***

SINCERE GRATITUDE TO:

- ***Phillips Exeter Academy*** for providing space, funding, and support to the MUREX Robotics Company.
- ***John H. Hessel '52 and Sidney A. Hessel*** for providing funding as part of the Phillips Exeter Academy Hessel Fund.

> FOOTNOTES

[a] 1. Testing videos for all PCBs are stored on Dropbox
[a] 2. Detailed documentation hosted at docs.murexrobotics.com
[a] 3. github.com/murexrobotics/electrical-2024 commit history
[a] 4 + 5. INA226 Load Testing on Power Board
[a] 6. ANYESC Power Testing
[a] 7. electrical-2024 main GitHub page
[a] 8. Carrier Board V3 USB3.0 debugging
[a] 9. Ethernet Switch stress testing (iperf)
[a] 10. C. Lee tests Ethernet Switch with IP camera
[a] 11. ANYESC + ESC Carrier First Test

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