MUREX ROBOTICS

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

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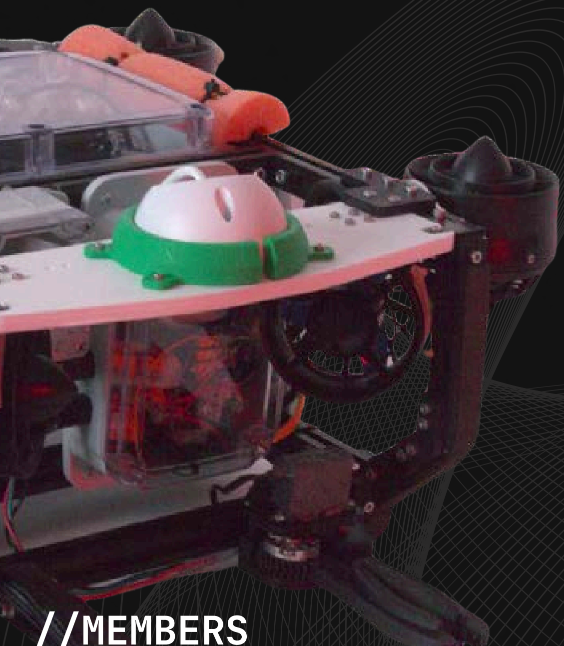
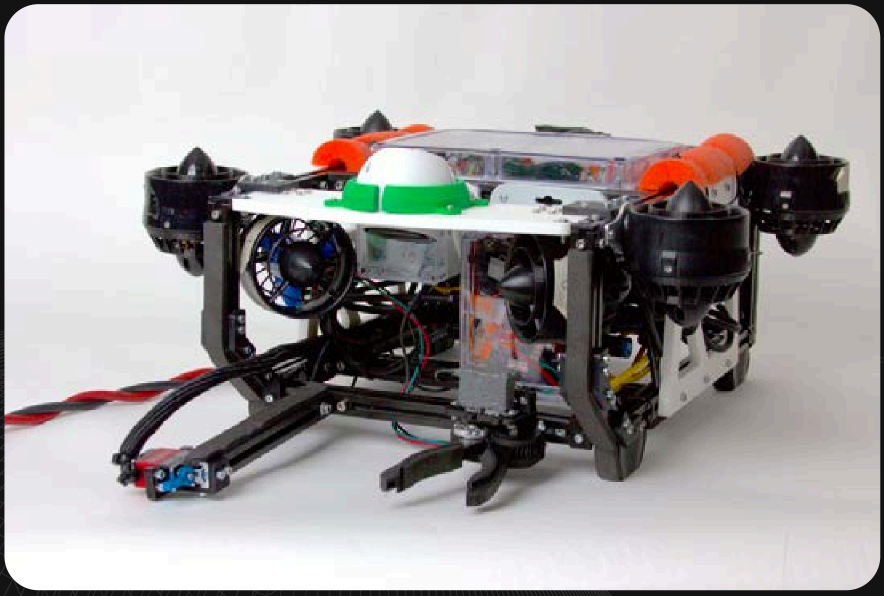
TECHNICAL DOCUMENTATION



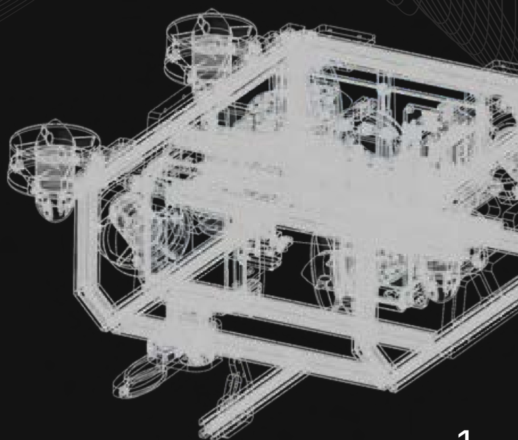


//MEMBERS

Byran Huang [CEO, EE Lead, Drive Team] (3rd Year/‘25)
Ethan Cheng [CFO/Software] (3rd Year/‘24)
Altan Unver [CTO, Drive Team] (2nd Year/‘25)
Yash Shah [Mechanical Lead, Drive Team] (1st Year/‘25)
Varit Asavathiratham [Electrical, Pilot] (1st Year/‘25)
Max Liu [Electrical, Safety, Drive Team] (2nd Year/‘26)
Anika Sivarasa [Mechanical, Drive Team] (1st Year/‘26)
Adam Tang [Mechanical Lead] (3rd Year/‘25)
Marvin Shim [Software] (1st Year/‘27)
Crane Lee [Electrical] (1st Year/‘27)
Osbert Chang [Mechanical Engineer] (1st Year/‘27)
Kat Lopez [Aquatics, Logistics, Mechanical] (1st Year/‘25)

//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.
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Photos: V. Asavathiratham + Photographer E. Liu. Render: B. Huang

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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.

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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 V3.5, a small, lightweight, low cost, modular, and fully open source ROV to meet the challenges described in the 2024 Marine Advanced Technology Education's (MATE) Request for Proposals (RFPs) and to address the needs of the global marine robotics community. The MUREX ROV V3 and crew work to: 1. Collect and analyze oceanic data, 2. Manipulate and maneuver undersea cabling 3. Conserve ecosystems and save wildlife, 4. Engineer, construct, and demonstrate a vertical profiling float (mrxFloat).

The MUREX ROV V3.5 is designed for challenging environments following our ***3 years of iterative robotics design experience*** *with strict compliance to safety standards. Our robot is fully custom-designed to meet our customers' 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 2024 MATE ROV New England Regionals. Photo: V. Asavathiratham

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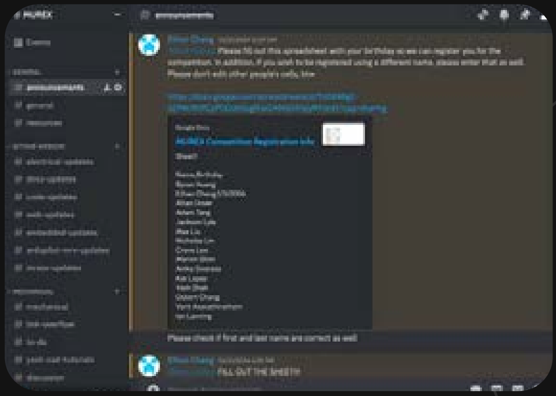
TEAMWORK

// COMPANY STRUCTURE

The MUREX Robotics company is operated by high school students with the goal of ***advancing low-cost, environmentally sustainable robots and a vision to democratize ROV development for all.*** Our team has kept a tight and passionate group of 15 members across our 3 years of operation. 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 the company can operate at its fullest capacity. MUREX Robotics adheres to strict safety and communication protocols to ensure the highest quality result.

// 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 *Gantt charts to schedule and plan, helping us reach team deadlines.*



Top Left: Electrical Gantt Chart
Central Left: Programing Gantt
Bottom Left: Discord Server
Right: World Map. Red locations are where team members are from.

>> CHALLENGES

In following our mission to attempt the impossible, it is easy for our team to get carried away with too many ambitious goals. We have researched and attempted many ideas, but most remain on the drawing board. Deciding whether or not to put time and effort into an idea is incredibly difficult. It is a constant challenge we tackle every day, from small decisions that might save us a few minutes, to large overhauls of the robot. Small decisions are always discussed on the spot by the team members. Each member will list their idea and opinion and our well-meshed team always concludes quickly. Larger decisions are split into three parts: ideation, research, and conclusion. When an idea is created, it is introduced to the corresponding subgroup (mechanical, electrical, and programming). It is then researched by the person or people who came up with the idea. **All members then conduct “viability checks”. A few main questions are considered:**

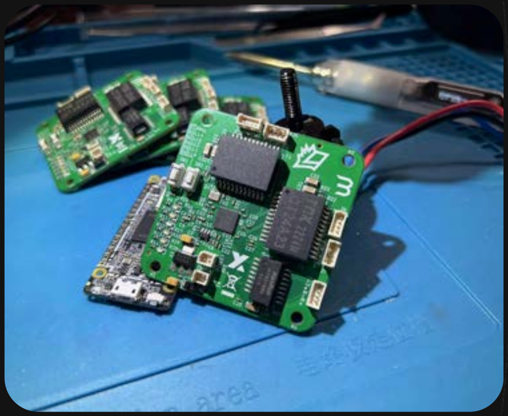
- “What issue is it trying to solve?”
- “How long does it take?”
- “How much work would it take?”
- “How much money does it cost?”
- “Does the benefit outweigh the downsides?”

B-Roll of the MUREX Ethernet Switch V1.0 Photo: Byran Huang

After careful consideration, a conclusion is reached. This process can be as fast as one online search to a multi-day journey of reading whitepapers or learning new knowledge. Although an idea might not come to fruition, we know we’ve done all we can and there is knowledge to be gained. As Thomas Edison said, “I have not failed. I’ve just found 10,000 ways that won’t work”.

We are also grateful to have mentors who can provide us with invaluable resources. Our robotics coach, Mr. Charles Mamolo, aids us in logistics, funding, and day-to-day operations (and providing moral support!). Our mentor, Mr. Doug Hanson, uses his extensive engineering experience in the natural gas industry and previous service in Army Aviation to provide advice on all our systems. Despite our mentors’ experience in their fields, MUREX Robotics follows our school’s model of student leadership and decision-making. Our mentors only offer logistical assistance and have not given technical advice on the MUREX ROV V3.5.

>> MUREX Robotics is a fully student-led and student-developed team.



Our electrical system was fully developed by the team.

Left: MUREX Ethernet Switch V1.0 Photo: B. Huang

Center: December Progress Report. Photo: M. Liu

V. Asavathiratham explaining the vision system. Photo: C. Shaw

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// 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:

- [Dec. 2023] World's first open-source Ethernet Switch, MUREX Ethernet Switch
- [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 controller
- [Nov. 2023] World's first modular serial single ESC, MUREX ANYESC
- [Dec. 2023] World's smallest open-source dual-output high power module designed for 12V/5V/3.3V DC applications, MUREX Power Board
- [Nov. 2023] World's first open demo of OFDM (orthogonal frequency division multiplexing) over galvanically isolated DC power lines, mrxPLC
- [Jan. 2024] World's first use of H.264 hardware encoding on the Allwinner H3 SoC using a mainline Linux kernel, unnamed
- [Dec. 2023] Novel, direct-compilation of the Linux Kernel with a virtualized Apple Silicon macOS enviornment and minimal overhead, unnamed
- [Apr. 2024] Xbox trigger support for Ardupilot + QGroundControl, unnamed

ALL DEVELOPMENTS ARE OPEN SOURCED ON GITHUB

CEO B. Huang answers questions from Cornell researcher Mr. Jordan Aceto, who found us through our work on USB3.0 controller implementations. Photo: M. Liu

DESIGN RATIONALE

// SYSTEMS APPROACH

MUREX designed the robot's mechanical, software, and electrical systems in parallel. Each aspect was handled by its respective subgroup leads. At the start of this year, the team convened to discuss "concrete" systems. These included:

- 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 design relied on the completion of the electrical system, which relied on the mechanical design.

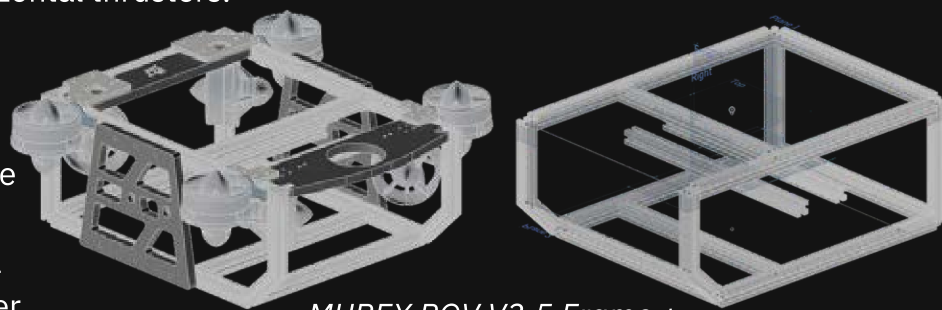
Each system was designed with **adaptability in mind.** The mechanical design offers maximum flexibility while providing a streamlined shape to minimize drag. The use of standard metric measurements across the robot ensured construction and modification were completed as expected.

Our team is highly experienced and are building extensive industry experience in: commercial mechanical design (Y. Shah, right middle), particle physics research and software development (A. Unver, rightmost), advanced electrical engineering (M. Liu, leftmost), and electrical engineering design and research. (B. Huang, left middle). Photos: V. A.

>> VEHICLE STRUCTURE

The MUREX ROV V3.5 (0.65m x 0.55m x 0.3m, 11.5kg) is made of 20 x 20 mm anodized aluminum extrusions, a standard size that has readily available parts and offers a **rapid building ecosystem** due to the infinite mounting capabilities of aluminum extrusions and T-slot nuts. The aluminum extrusions create a **large exoskeleton-like chassis** that is further reinforced with recycled marine-grade HDPE. The side HDPE sheets are pocketed to reduce water resistance in all directions. The HDPE plates also offer mounting for the Main Enclosure, Junction Box and four horizontal thrusters.

The vertical thrusters are mounted on both sides of the chassis on custom laser-cut aluminum parts which serve as rigid, corrosion-resistant mounting plates that are securely fastened to the extrusion.
The front of the robot is angled to provide a wider reach of the manipulators and a better view from the vision system. It also acts as a visible marker of the direction of the robot.
The Main Enclosure is mounted in the center of the robot to provide balance in the water. The area underneath the Main Enclosure allows for easy wire management and modifications. The Junction Box (Polycase ML-46F) is mounted vertically across the front to compensate for the tether's weight in the back of the robot.
MUREX ROV 3.5 is neutrally buoyant allowing for stable depth hold. This provides reliable successes with mission tasks requiring a stationary robot such as activating the irrigation system that will protect and restore ecosystems and biodiversity.



MUREX ROV V3.5 Frame + Chassis CAD. Photo: Y. Shah

Chassis Comparison Table

Chassis	Material	Cost	Complexity	Benefits	Concerns
Aluminum extrusion exoskeleton	Anodized aluminum	Low	Low	High extensibility strength	ROV is limited by the extrusion's size and design
HDPE/Metal exoskeleton	Marine-grade HDPE/Aluminium	Medium	Medium	Very high strength Streamlined design	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
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, especially at depths.
Blue Robotics Cylindrical Enclosure	Small	High	Can withstand depths, designed for ROV usage	High cost, difficult to repair and troubleshoot.
Metal Enclosure	Large	High	Easy to design, mount, and repair.	High cost, not visibly inspectable.
Custom Enclosure	Flexible	Unknown	Flexible to match requirements	High risk of catastrophic failure.

We chose a *rectangular enclosure (Polycase ML-70F)* rather than a commonly used cylindrical enclosure, for reasons presented in the table to the left:

MUREX ROV V3.5 Main Enclosure CAD. Photo: Y. Shah

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VEHICLE SYSTEMS

CONTROL SYSTEM

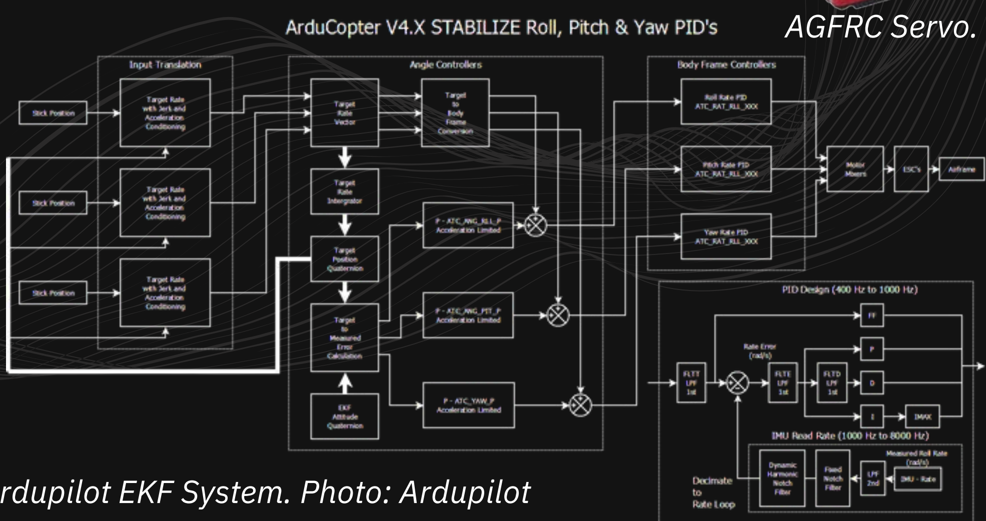
The control system accurately controls the 8 thrusters and manipulator servos, allowing the demo team to make real-time observations about the mission. MUREX's tuned EKF (extended Kalman Filter) with **22 estimation states across our 10 DoF** sensing allows our robot to be fully stabilized along all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

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



Ardupilot EKF System. Photo: Ardupilot

Enclosure Photo. Photo: B. Huang

VISION SYSTEM

The vision system integrates our two IP (internet protocol) cameras and our main USB camera to stream live video to the topside. There is also a Logitech C270 upwards-facing camera. 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. Our robot has three concurrent camera views, with the main USB camera (hardware encoded on the Carrier Board) providing the best clarity and lowest delay. The three 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

Brio 101 USB Webcam. Photo: Logitech

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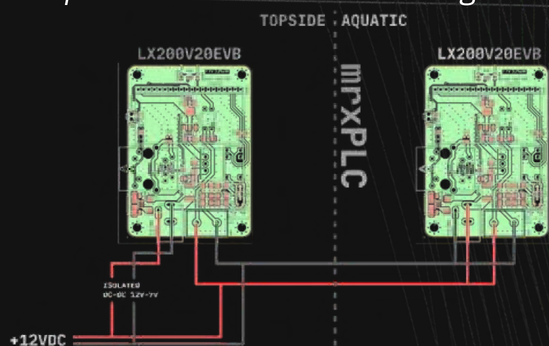
Topside Photo. Photo: B. Huang



mrxPLC Functional Diagram. Diagram: B. Huang

TETHER DESIGN RATIONALE

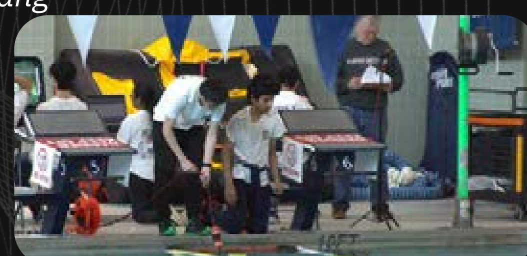
The strain relief system on the back of the ROV uses metal wire as a medium **to take the 99.5% of the physical strain off the main tether**. The tether wires are friction clamped to two metal wire loops, connecting to the structural frame of the ROV in the back. MUREX conducted multiple iterations of 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. In addition, tape around the thrusters creates an imaginary box around the ROV disallowing entanglement with tether, SMART cables, and recovery lines.

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

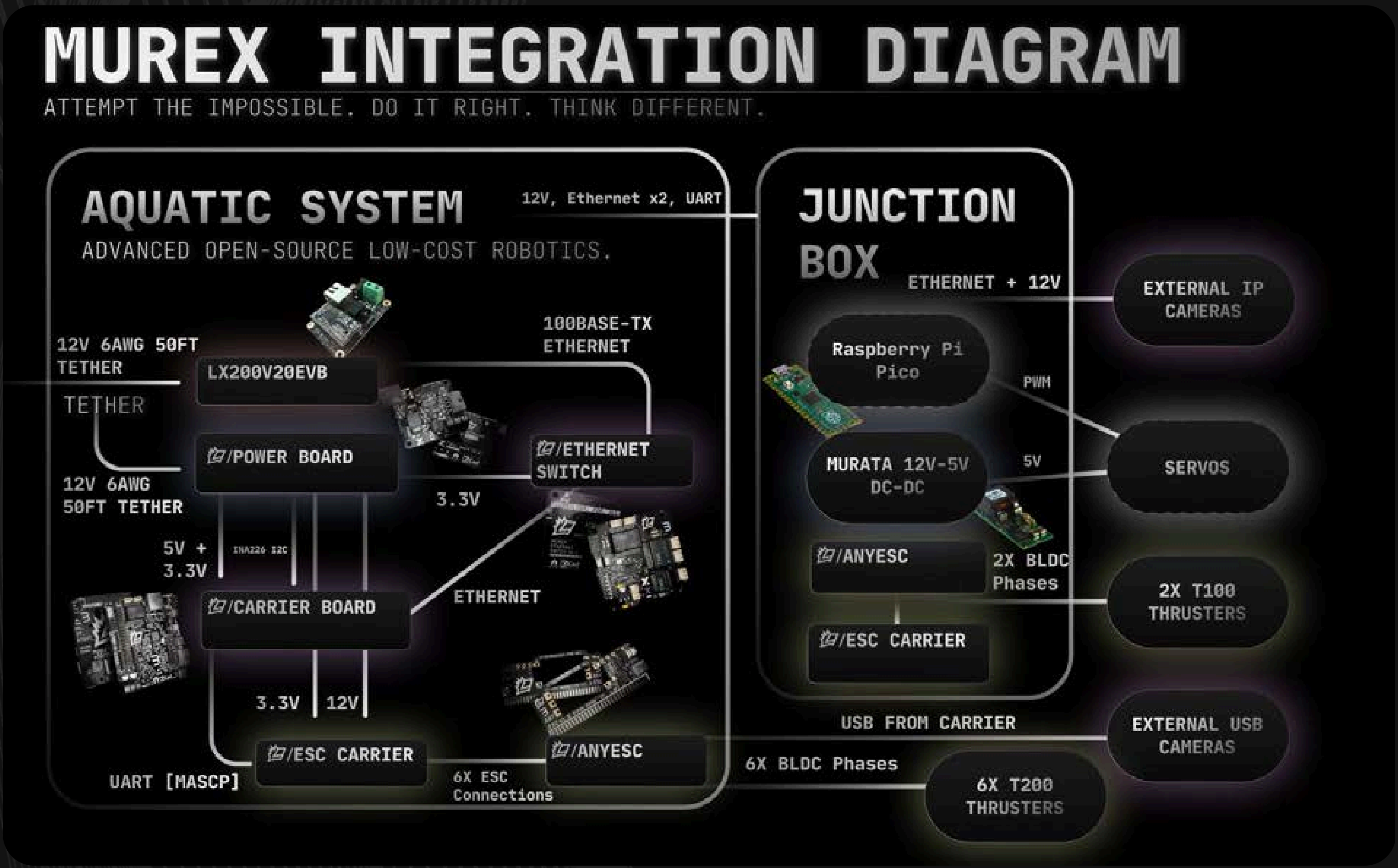
MISSION SENSORS

MUREX dedicated countless R&D hours to developing accurate and effective mission sensors. This includes a high-accuracy (0.5C deviation) **temperature sensor** communicating over the Dallas One-Wire protocol to the Carrier Board that is checked with the smart cable sensor readings and a **hall-effect rotation sensor** on each manipulator for sub degree level rotational accuracy on ADCP probes, retrieving acoustic receivers and transplanting coral.

Notes: [1] Explained in Electrical System

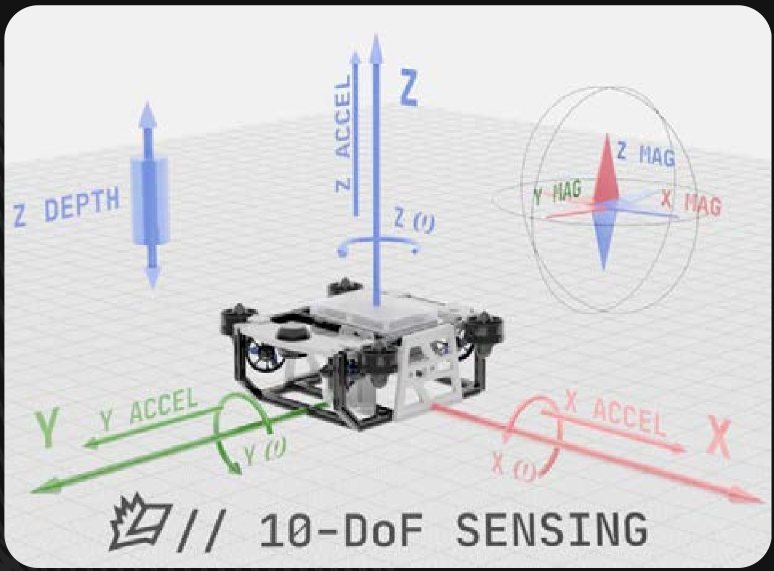
CONTROL/ELECTRICAL SYSTEM

MUREX Integration Diagram. Diagram: B. Huang, M. Liu



> 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 V3.5 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 V3.5 to glide through water and reliably carry out tasks such as placing brain coral, enabling irrigation systems, and deploy subsea cabling.



3D Render Demonstration. Render: B. Huang

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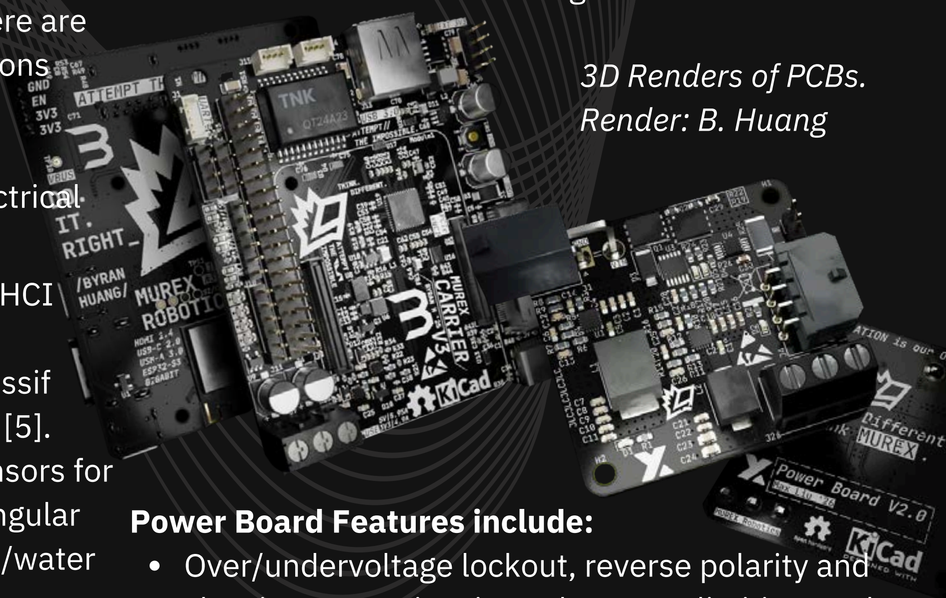
> OVERVIEW CONT.

The system communicates through MASCP to the MUREX ANYESCs, which house commercial ESCs and drive T200 and T100 thrusters. The ANYESCs slot into the ESC Carrier for modular storage. Finally, a Murata 12V-5V buck converter provides up to 20A for powering external servos for the arm/manipulators, which receives PWM from a dedicated Raspberry Pi Pico. Video is streamed from IP and USB cameras through the Ethernet switch, the mrxPLC system, then decoded into Ethernet in the topside.
In total, the MUREX ROV V3.5 has over 13 custom PCBs, enabling various functionality at costs <12% of existing commercial options [2]. MUREX will now provide further descriptions and functionalities for custom boards and methodologies in use.

> CARRIER BOARD

The MUREX Carrier Board V3 is 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.** USB3.0’s 5Gbps speed is currently used for video input but can expand to networking, AI acceleration, storage, and high-speed DAQ systems. The board costs ~7% of alternative commercial options, with our prototyping run costing around 30 dollars per board, and offers a suite of features previously inaccessible at this price point. Although there are more powerful System on a Chip (SoCs) options from Rockchip and Allwinner, we chose to continue development in the Raspberry Pi ecosystem for the software support and electrical reference material [3]. **Features include:**

- A controller supporting the USB 3.0 and xHCI specifications with the uPD720202 [4].
- A dual-chip design with an onboard Espressif ESP32-S3 wireless and GPIO capabilities [5].
- BMI088, LIS3MDL, BME680, MS5837 sensors for 10-DoF sensing (XYZ acceleration, XYZ angular velocity, XYZ spatial orientation, pressure/water column depth).
- 2 TPS259474LRPWR eFuses offer independent input protection and monitoring of the 5V and 3.3V power inputs.



3D Renders of PCBs. Render: B. Huang

> POWER BOARD

The MUREX Power Board V2 is the **world's smallest open-source dual-output, high-power module designed for 12V/5V/3.3V DC systems and ROV applications**. Measuring 44mm x 46mm, the board supports 500W continuous power and is 95% efficient at DC-DC conversion. This is used as our power input and DC-DC converting system, providing safe voltage levels to every part of the system.

Power Board Features include:

- Over/undervoltage lockout, reverse polarity and shorting protection, in-rush current limiting, and transient spike protection with the LTC4352 Ideal Diode Controller.
- Current and voltage monitoring with the INA226 Power Monitoring IC.
- Beat-frequency correction, high-power, and efficient dual DC-DC conversion with the TPS568230 Synchronous Buck Converter [6].

Notes: [2] Please see build/buy section. [3] We are experimenting with embedded Linux and becoming the one of the first people to accomplish hardware H.264 encoding on Allwinner systems as opposed to simpler but less performant software encoding. [4] See the world’s only active and purchasable USB3.0 controller IC. [5] See this. [6] Referenced ***TI white papers*** SLVAED3, SLVAEG8, SLVA882B and more.

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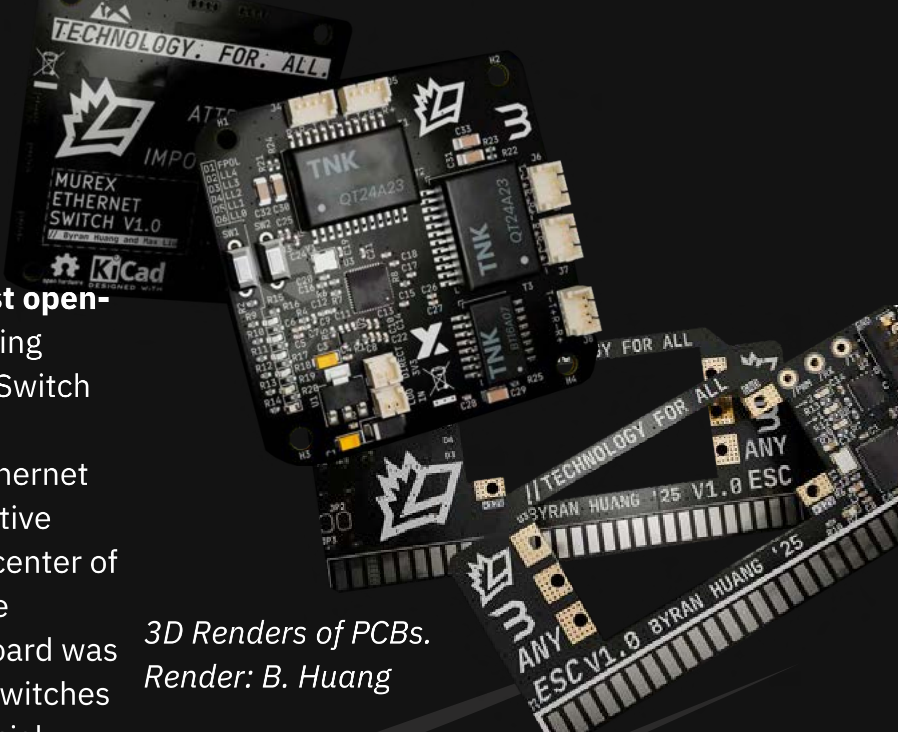


3D Renders of PCBs.
Render: B. Huang

> ETHERNET SWITCH

The MUREX Ethernet Switch V1 is the world's **first open-source 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 costs 5% of alternative options and acts as the central communications center of the MUREX ROV, combining the 2 IP cameras, the LX200V20, and the MUREX Carrier Board. 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.

Features include:

- 5 802.3u compliant Ethernet ports with the IC Plus IP175G [7].
- 4.5 - 15V protected input through the LM1117MP-3.3 800mA LDO.
- Direct 3.3V power input for high efficiency.

> *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).

Notes: [7] See this. [8] See this. [9] See this.

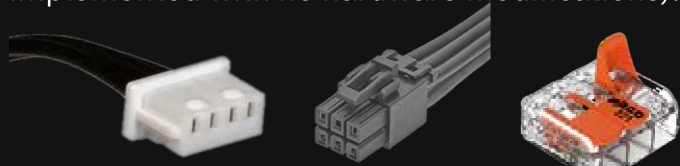
> *ANYESC + ESC CARRIER*

The MUREX ANYESC V1 is the **world's first modular serial single ESC** and our first prototype ESC for the MUREX Motion System. The ANYESC integrates commercial ESCs into a flexible RP2040 board in a card-edge form factor (hence the name "ANY"). The RP2040 was chosen for its balance between optimal price, performance, power consumption, and more. It acts as an extremely powerful translator, supporting UART and PWM communication to any ESC mounted [8]. Adaptable length for any commercial single-sized ESC is also supported. MUREX has also conducted testing with field-oriented control of our thrusters with our concept MUREX DRVESC V1 design. The MUREX ESC Carrier V2 integrates the world's first open-source serially connected motion system.

In-rush current limiting with an NTC thermistor

Standard high-power Molex connectors for fast replacements

ANYESCs can slot into the MUREX ESC Carrier, with the RP2040 ensuring full compatibility no matter what ESC is slotted (allowing for future custom high-power or FOC ESCs to be implemented with no hardware modifications).



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

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: [10] See ArduPilot EKF explanation + theory.
[11] Understanding altitude.

ARDUSUB

../ 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 [10].** 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 [11]. 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.

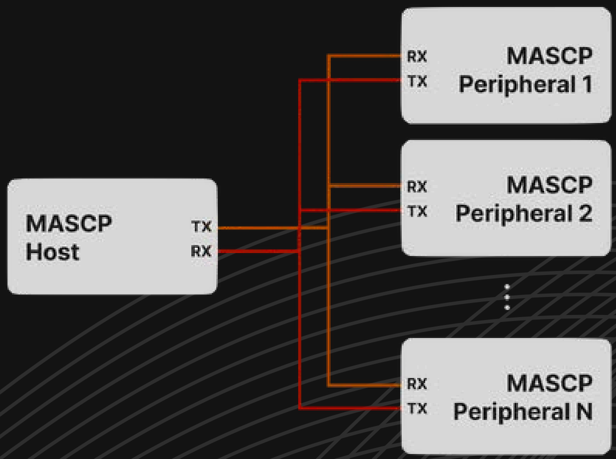
Our driver interface/ground control system is also part of the ArduPilot software suite. MUREX uses a custom version of QGroundControl (QGC) compiled specifically for our topside computer to **aggregate telemetry and communicate instructions** from the driver to the ROV. QGC greatly simplifies the testing 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 [13], 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 [12].** ArduPilot exposes a Lua Scripting API that supports reading and modifying the execution of ArduPilot.

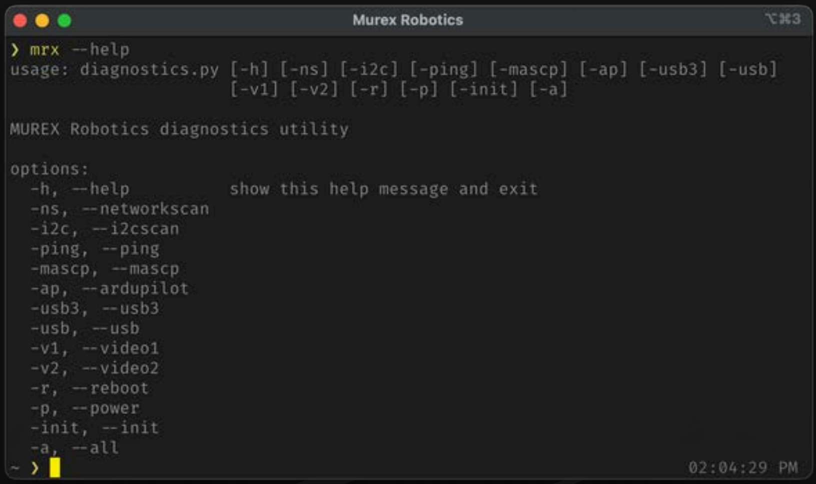
/ COMPONENT TESTING SCRIPTS

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: [12] See Lua Scripting. [13] 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

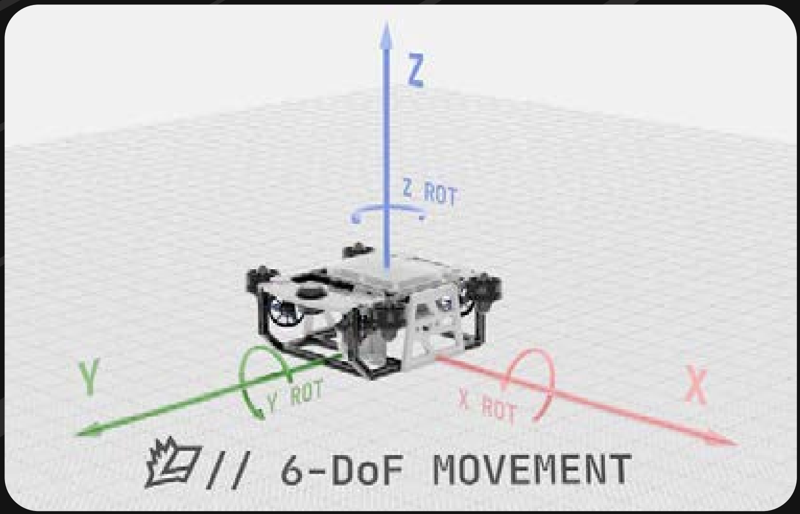
// ANYESC FIRMWARE

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

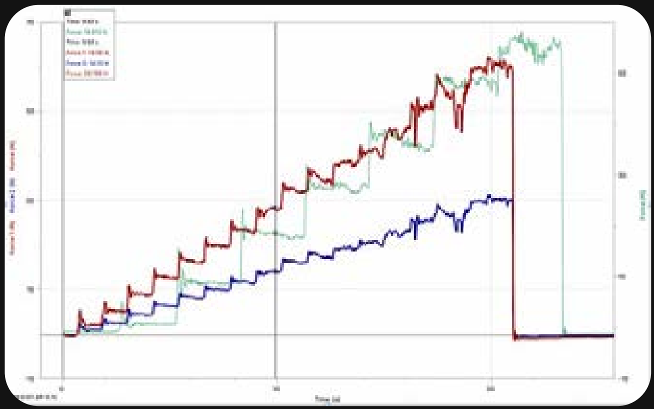
The MUREX propulsion system consists of 8 Blue Robotics T200 thrusters driven by MUREX ANYESCs. The MUREX ROV has 8 thrusters in a vectored configuration, allowing movement in all 6 DoFs. This is a standard thrust vectoring configuration, allowing for rapid electrical and software expansion. **Using 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 [14]:

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. The mechanical design used CAD software such as Fusion 360 to determine the center of gravity and the density of the robot. The use of Fusion 360's in-built dimensional analysis helped approximate placements of all ROV elements to maintain a neutrally buoyant and stable ROV. With the addition of well-placed foam pool noodles, the **MUREX ROV V3.5 has a specific gravity of 1.002**. The most buoyant part of the system, the Main Enclosure, is placed at the center and above all other components to heighten the center of mass which aids in the stability and safety in case of unwanted rams of the outermost ROV sections such as the thruster guards against oceanic facets.

The combination of recycled HDPE and aluminum extrusions allows the chassis to be nearly neutrally buoyant. This is due to HDPE's density of around 0.97g/cm^3. The aluminum's density (2.7 g/cm^3) compensates for the electronics' density (~0.8 g/cm^3). The decision to use 2020 aluminum allowed for easy mounting and testing of various ballasts and buoyancy materials. After further CAD and physical corrections, the MUREX ROV is **almost exactly neutrally buoyant.** In combination with 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

The initial mass of the mrxFloat rests at 3407 g, but once 100g of water is intaked through the syringes, the mass increases to 3507g while the volume of the float stays constant at 3463 cm^3. Thus, the intake of water changes density from 0.984 to 1.02 resulting in descension. The inverse is repeated for ascension.

Notes: [14] Decisions made with reference to Texas Instruments' SLVAES1A whitepaper

BUOYANCY MODULE (mrxFloat)

The vertical profiling float, mrxFloat, is constructed with a 4” acrylic tube and operated with a **buoyancy engine of a continuous rotation servo and lead screws**. The mrxFloat is 31.4cm in height. The top section of the float holds the electronics, which consist of 4 AA batteries, an inline 7.5A fuse, an on/off switch, a 6V to 3.3V buck converter, and an ESP32 LoRa V3. The actuator is screwed through a nut and can extend 10cm vertically. Another ESP32 LoRa V3 transmits and receives signals, consisting of the local time, ROV team number, and pressure information. The LoRa radio protocol was selected for its long-range, reliability, and ease of use. MUREX considered options like Wi-Fi and Bluetooth but preferred the simplicity and long range of LoRa 915 MHz.

mrxFloat. Photo: Y. Shah

Following safety specification ELEC-NDR-005, a 7.5A fuse is attached within 5cm of the power wire of the battery. 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 which disengages from the acrylic tube in the event of high pressure, which is also paired with a standard blue robotics pressure cap rated to 12 psi. The depth sensor collects data in 5-second intervals throughout the ascension and descension period.

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. 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 the added complexity.

Our thruster mounts are custom CNC’ed aluminum brackets which far exceed the strength and rigidity of our previous 3D-printed mounts. Our 3D-printed parts are produced at a low cost and provide mounting angles that would not be possible with off-the-shelf parts. The CNC-cut HDPE plates used to mount the electrical enclosure, thruster and camera help simplify mounting configurations. They were produced at a low cost, using previously owned material and our school theatre’s CNC.

To conserve cost, we have re-used the ROV’s controller, thrusters, various miscellaneous hardware, and re-implemented our old ROV electronics enclosure as an effective solution for the mrxFloat. The latter in particular saved us over $300 in cost in comparison to purchasing a new product. In pivoting to our newest ROV design, nearly all aspects of the system have been reconsidered, thus very few parts have been re-used in the MUREX ROV V3.5.

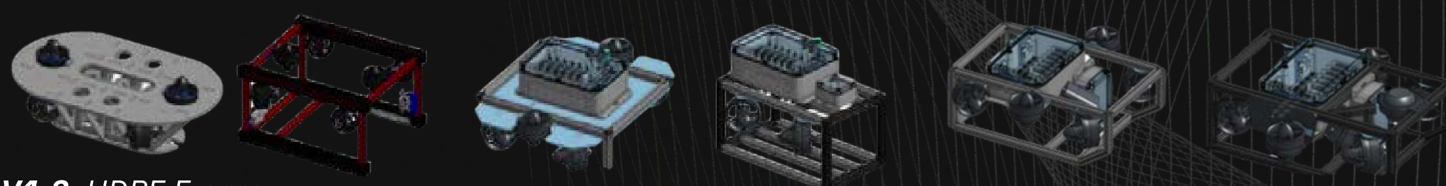
BUILD/BUY,NEW/USED CONT.

System	Function	Prototype Price (ea) [15]	Commercial Option Price (ea) [16] [17]	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%**

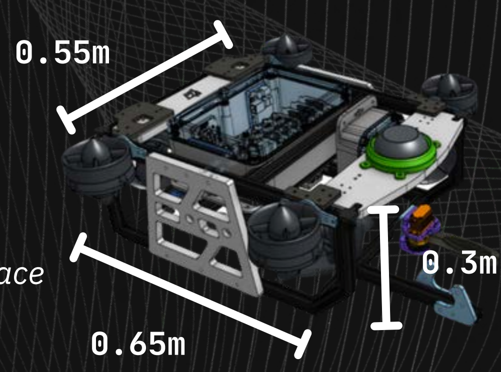
CRITICAL ANALYSIS AND TESTING

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 mechanical has produced over *5 chassis designs* to achieve the *MUREX ROV V3.5 design*. **Each design has been run through extensive fluid simulations in Autodesk CFD** providing the necessary insight to isolate places of excess water resistance that helped us relocate the positions of electrical enclosures, HDPE plates, and thrusters. Each new design tailors more towards the RFP's tasks requirements by adding, and changing placement of mission sensors and manipulators.



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



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

Notes: [15] Price based on JLCPCB production cost, tax and shipping included. [16] Tax and shipping not included. [17] Most commercial options lack features and power protection compared to MUREX systems. Please see Control/Electrical System.

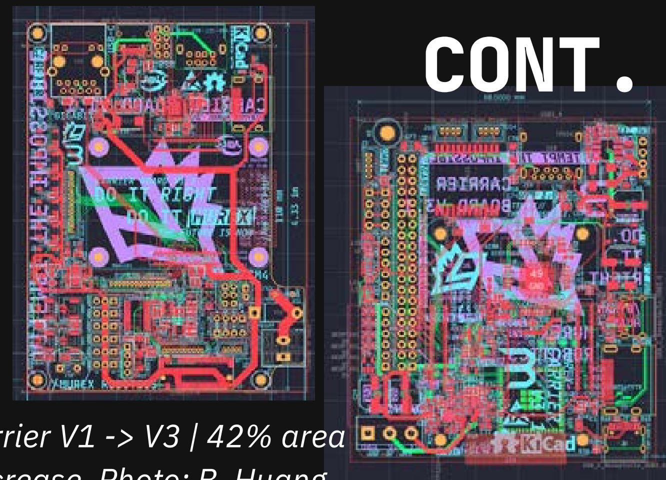
MUREX ROBOTICS

ATTEMPT THE IMPOSSIBLE

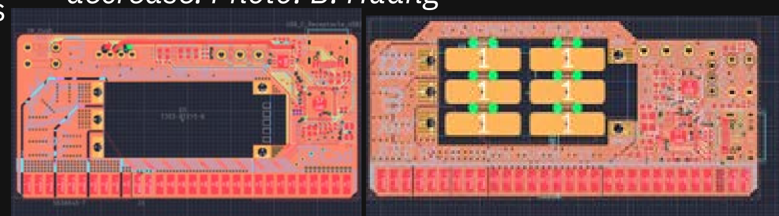
CRITICAL ANALYSIS CONT.

> ELECTRICAL R&D

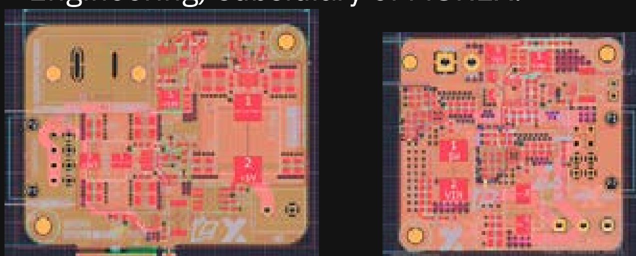
Much of the beginning of the year was invested in conducting research and development of the electrical system. Our initial designs lacked EDS, transient, and other circuit protection systems. The PCBs were also routed inefficiently, resulting in unnecessarily dangerous and large boards. **After multiple 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 [18] (MUREX Experimental Engineering) subsidiary of MUREX.



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



STESC -> ANYESC | Generalized ESC design. Photo: B. Huang



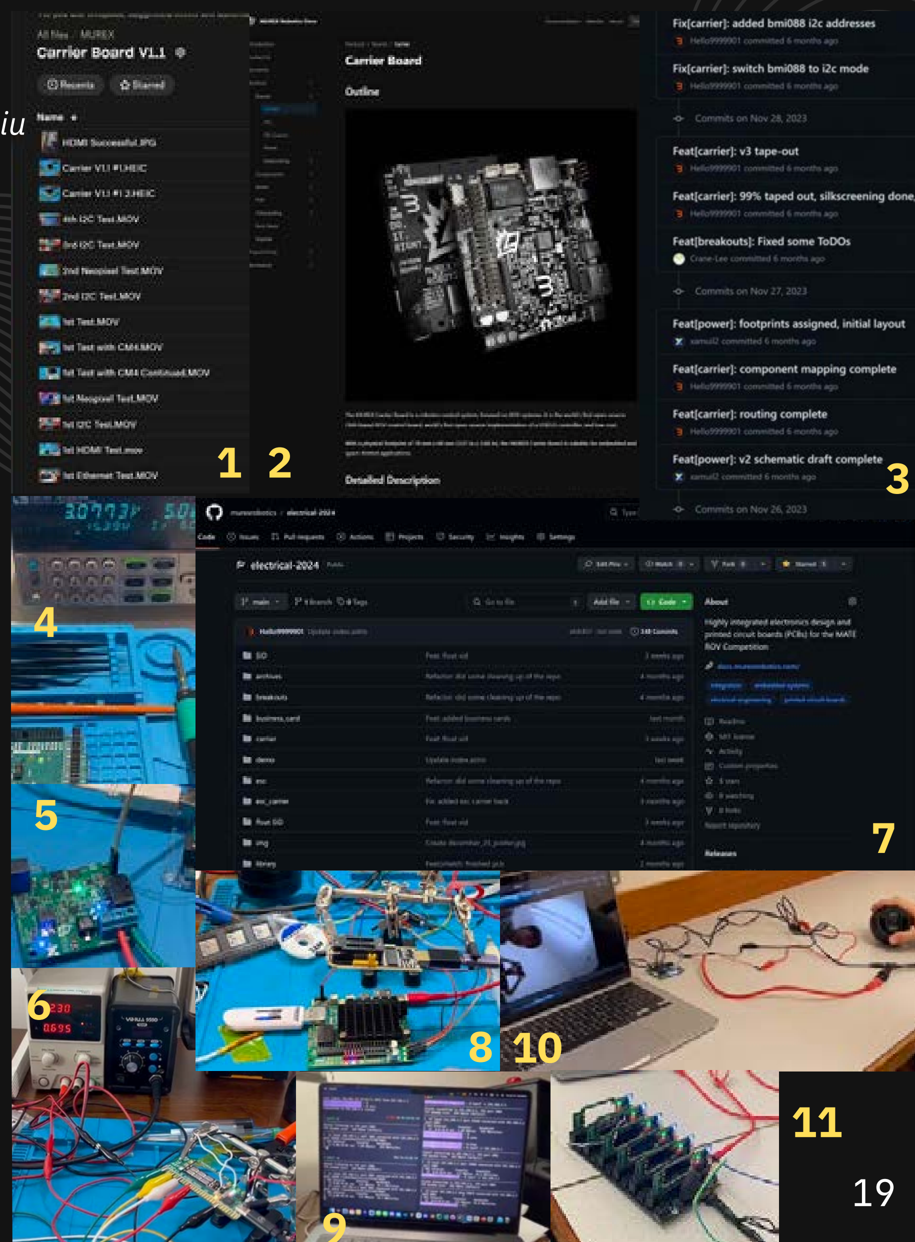
Power V1 -> V2 | 20% area decrease. Photo: M. Liu

> ELECTRICAL TESTING

As MUREX continues to push the boundaries of underwater robotics, we began to need 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]

There are a total of four 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 HDPE crossbeam is an Amcrest IP5M-T1277EW-AI. It provides a frontal and slightly downward view of the claw and its surroundings. There is one Logitech Brio 101 camera and one Logitech C270 camera, one facing the front in a mini enclosure (ML-31F) and one facing upwards in the main enclosure. This watertight placement allowed us to remove the outer covers of both cameras and save space. The Brio 101 camera inside the mini enclosure provides a front view of the claw and looks directly ahead. The C270 camera, facing upwards in the main enclosure, helps the driver position the ROV in the deployment area as it returns to the surface while also giving the driver a rough idea of ROV's depth.

The last 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 faces the front and gives the driver an overview of the pool floor and a wider view of the ROV's surroundings. This camera is used for creating an photogammetric model of oceanic ecosystems and corals. The camera mount, while sturdy, allows movement of camera so as to fit the driver's needs. These four cameras allows the driver to operate the ROV, track its movements, and approximate its location remotely. The front facing Logitech and the downwards facing Amcrest focus on the two claws and target various objects, while the other two cameras provide upward and downward facing angles to give the driver an approximate idea of the ROV depth.

Left to Right: Logitech Brio 101 in Mini Enclosure. Front Amcrest. Back Amcrest. Photo: O. Chang

The two manipulators, denoted as active and carrier claw, on the front of the ROV perform all the tasks outlined in the MATE RFP. **The active arm is a two-part geared claw mechanism that extends out of the ROV for easy access into remote areas.** This claw is used to perform smaller tasks requiring more accuracy including the relocation of ocean observing assets, retrieving and installing power connectors, and transplanting the brain and branching corals. The main innovation within the active arm includes the custom water-proof servo, and the herringbone gears. The oil-filled and waterproof enclosed servo in the active arm is positioned downwards to use gravity to prevent water from entering and damaging the servo. The use of custom designed herringbone gears in contrast to traditional gears gives the active-arm an increased grip and reduced chance of wear and tear. The carrier claw, located in the bottom, provides a far sturdier base to transport heavier freight including the deployment of the probiotic irrigation system.

Carrier Arm and Active Arm. Photo: O. Chang

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. Both 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. There is additionally 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.***

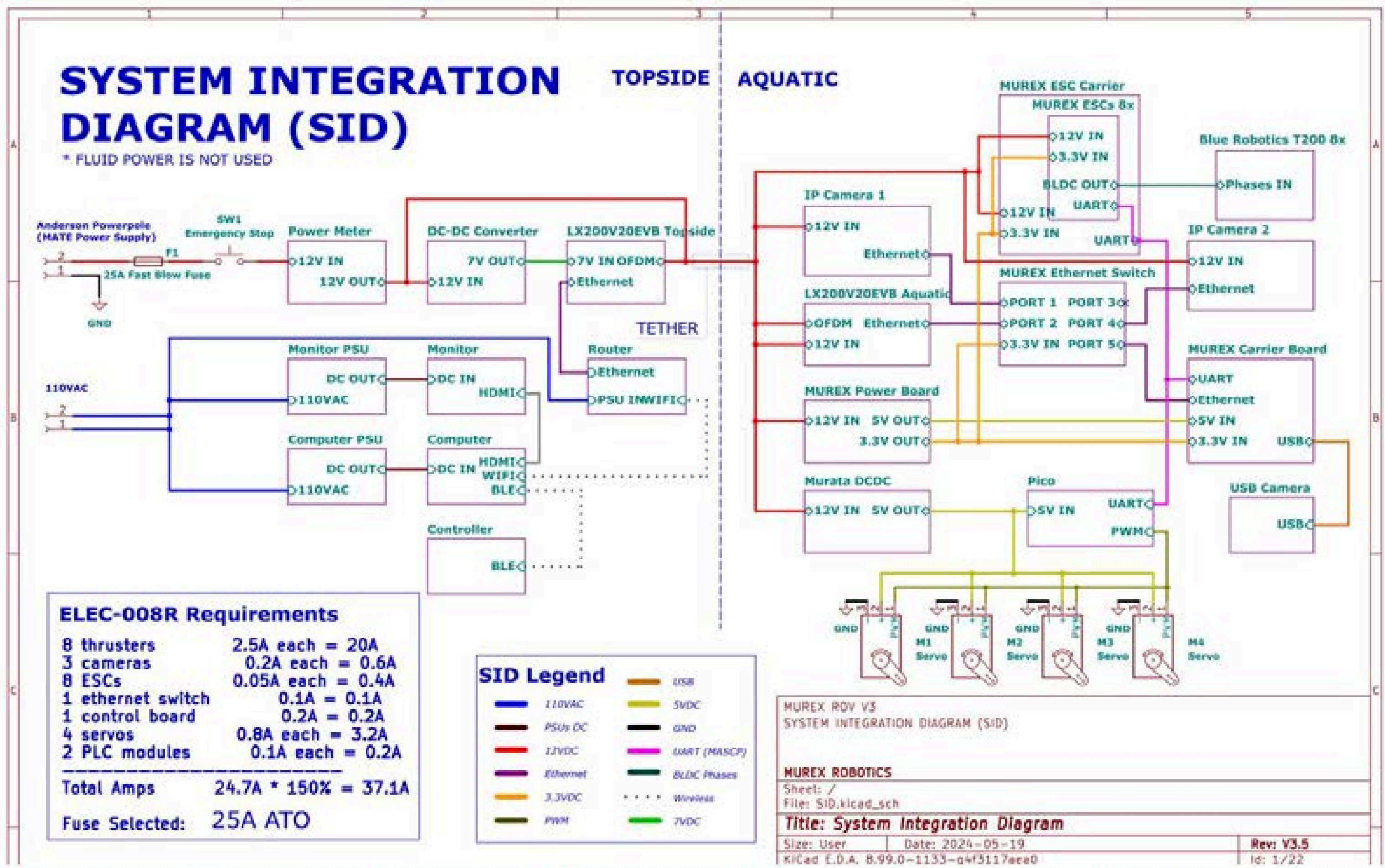
- Chassis supports at least 600N force applied. **"CHASSIS CLEARED"**
- Thrusters attached securely + cannot move over ±2mm in any direction. **"THRUSTERS CLEARED"**
- All propellers, servos, and any other motors are free spinning. **"MOTION CLEARED"**
- All manipulation devices attached securely and 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".**

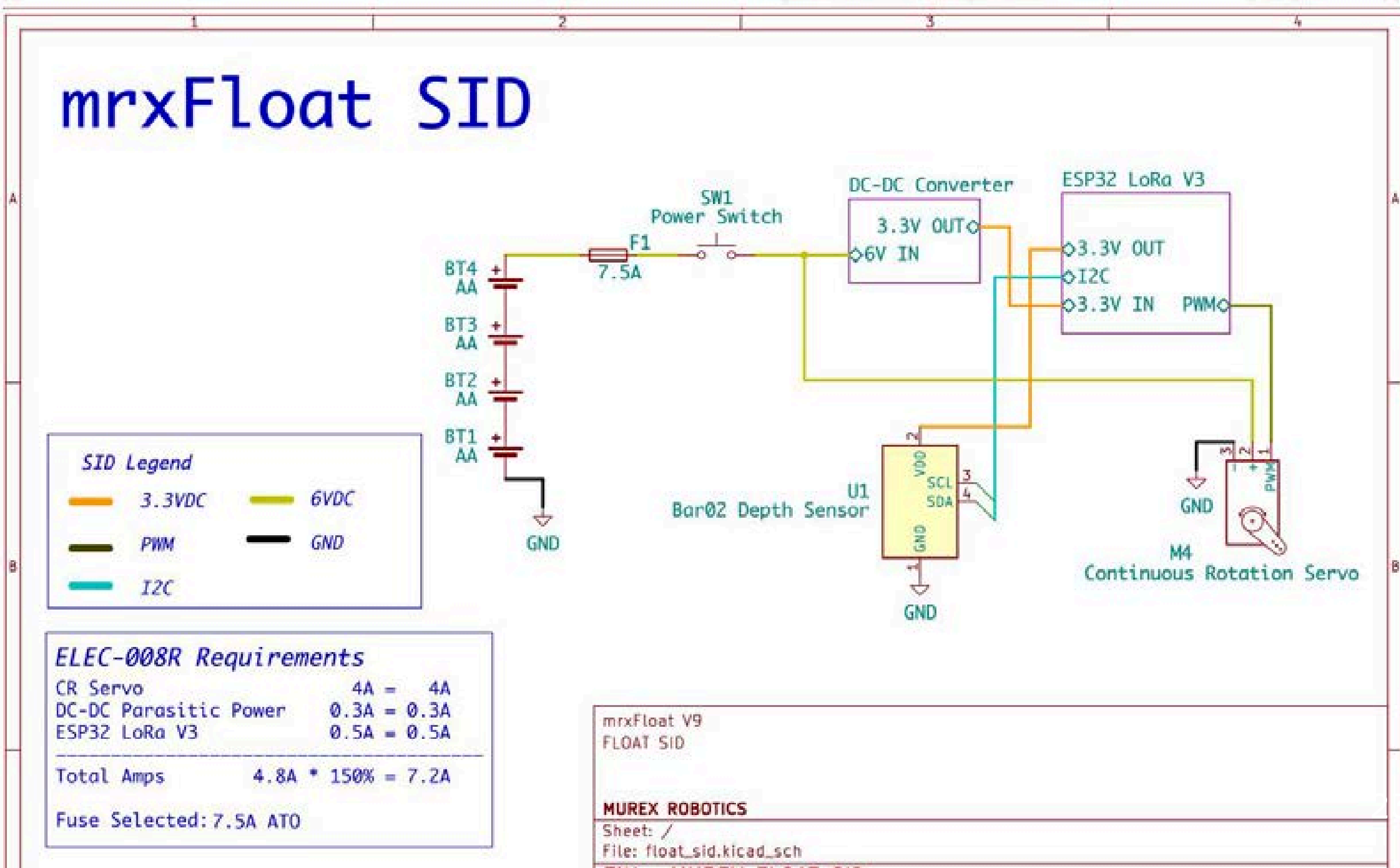
> PRE/POST DEPLOYMENT SAFETY PROTOCOL

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

		Source	Type	Amount
Income	Funds/ Capital	Hessel Fund	Income	$33,500
		MATE NE Regionals	Income	$250
		Alumni Donatation	Donation	$1,000
		Total Available Funds	**Total**	**$34,750**

		Category	Type	Description	Budgeted Amount	Actual Cost	Net Difference
Expenses	Electrical Costs	Vision	Re-used & Purc...	Cameras	$100.00	$225.56	-$125.56
		Electrical Wires/ Connectors/Com	Purchased	Screw Terminals, Cable Assembly, Connector, Capacitors, Card Edge for ESC Carrier, Micro fit Cable & Header	$600.00	$594.71	$5.29
		Electrical Circuits	Purchased	CM4 Kit, Carrier Board, Power Board, Ethernet Switch, Breakout Boards, Temperature Sensor	$1,000.00	$888.83	$111.17
		Topside	Re-used & Purc...	Suitcase, Router, Monitor (Re-used), Power Monitor (Re-Used)	$150.00	$141.90	$8.10
		Research and Development	Re-used & Purc...	Multimeter, Board Prototypes, Testing Power Supply (Re-used), NanoPi Duo, BananaPi BPI-P2 Zero, Optical Flow Sensor	$1,000.00	$623.02	$376.98
		Total	Re-used & Purc...	Net electrical costs	**$2,850.00**	**$2,474.02**	**$375.98**
	Mechanical Costs	Waterproofing	Re-used & Purc...	Epoxy, Mineral Oil, Vacuum Pump (Re-used), Cable Glands, Polycases, WetLink Penetrators (Re-used), Servo Casings	$380.00	$860.27	-$480.27
		ROV Frame Construction	Purchased	Corrosion Resistant M3 Screws, Corner Bracket, T-Nuts, Steel ball linkage, U-channel, Thruster Mounts, Aluminum Extrusion	$700.00	$487.14	$212.86
		Props	Purchased	Temperature Probe, PVC Pipe, Pebbles, Vinyl Tubing, Spray Paint, Screw Hooks, Milk Crate	$292.20	$292.20	$0.00
		Float	Re-used & Purc...	Acrylic Tube (Re-used), (2) Aluminum End Cap, Depth Sensor, Pressure Relief Valve, Ball Bearings, Syringes, Threaded Rod (Re-used), Imperial Nut (Re-used), goBilda Servo (Re-used)	$400.00	$327.56	$72.44
		Motors	Purchased	AGFRC Brushless HV, Agfrc Mini Servo, AGFRC High Torque Servo	$500.00	$691.98	-$191.98
		Thrusters	Re-used & Purc...	(4) Reused T200, (4) New Blue Robotics T200	340.00	$680.00	-340.00
		Total	Re-used & Purc...	Net mechanical costs	**$2,612.20**	**$3,339.15**	**-$726.95**
	Operational Expenses	Registration Fees	Purchased	Mate ROV Ranger class competiton entrance fee	$500.00	$350.00	$150.00
		Travel (Regional)	Purchased	Travel is paid and provided by Philips Exeter Academy	$0.00	$0.00	$0.00
		Travel (World Championship)	Purchased	Travel accomodations to and from the World Championship.	$10,600.00	$10,571.00	$29.00
		Lodging (World Championship)	Purchased	Lodging/ Housing for Worlds and Pre-Worlds practice	$12,000.00	$11,800.00	$200.00
		Food + Operational Expenses	Purchased	Budget for food and miscleaneaous costs.	$5,000.00	**For Use During Competition**	$0.00
		Merchandise	Purchased	Hats, Polo T-Shirts	$1,000.00	$1,155.44	-$155.44
		Total	Purchased	Total operational expenses	**$29,100**	**$28,876**	**$224**

Summary	Initial Balance	$34,750.00	Predicted Expense	$34,562.20
	Expected Final Balance	$187.80	Actual Expense	$34,689.61
	Actual Final Balance	$60.39		

*All items not explicitly marked as *"Re-used"* were purchased for use in the 2023 - 2024 MATE ROV Competiton

// 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 mrxROV. After qualifying for the World Championship, PEA approved an additional 28000$ for travel accommodations and lodging.

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.

MUREX ROBOTICS

ATTEMPT THE IMPOSSIBLE

ACKNOWLEDGEMENTS AND REFERENCES

THANK YOU TO:

- ***MATE II*** for hosting the MATE ROV Competition
- ***MATE ROV World Championships*** for hosting this 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

> 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

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 GRATITUTE 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.

[4]https://www.renesas.com/us/en/products/interface/usb-switches-hubs/upd720202-usb-30-host-controlle

[5] https://www.espressif.com/sites/default/files/documentation/esp32-s3_datasheet_en.pdf

[6] https://www.ti.com/lit/an/slvaed3a/slvaed3a.pdf, https://www.ti.com/lit/an/slvaeg8/slvaeg8.pdf and https://www.ti.com/lit/an/slva882b/slva882b.pdf

[7] https://www.lcsc.com/datasheet/lcsc_datasheet_2009140933_IC-Plus-IP175G_C80220.pdf

[8] https://datasheets.raspberrypi.com/rp2040/rp2040-datasheet.pdf

[9] https://en.wikipedia.org/wiki/Twisted_pair

[10] https://ardupilot.org/dev/docs/extended-kalman-filter.html

[11] https://ardupilot.org/copter/docs/common-understanding-altitude.html

[12] https://ardupilot.org/copter/docs/common-lua-scripts.html

[13] https://www.analog.com/en/resources/analog-dialogue/articles/uart-a-hardware-communication-protocol.html

[14] https://www.ti.com/lit/an/slvaes1a/slvaes1a.pdf [18] mrxEE's WIP website: https://mrx.ee