MAKO – Modular Aquatic Knowledge Obtaining (Unit)

PIONEER Class: MATE ROV 2025 World Championship

Embry-Riddle Aeronautical University

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Team Members

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Nicolas Chamberlain ('26)
Justin Yocum ('26)
Sirio Jansen-Sanchez ('26)
Gabby Aguino ('28)
Madison Warner ('27)

John "Jack" McSwiggin ('26)
Emily Coello ('26)
Robert Thibodeau ('26)
Bethany Wyman ('28)

Over the past year, our team of students has worked hard to design, build, and improve an ROV to perform the tasks set forth by the MATE competition. We wanted to improve upon our previous ROV by increasing its controllability, ease of maintenance, and robustness. Through countless hours of research and hard work, we are confident that we have achieved this goal. We look forward to this year's MATE competition, and we cannot wait to prove what we can do.

Contents

Project Management:

Meet the Team:

Mark Thompson
Position: CEO
Major: *Aerospace Engineering*
Fish Counterpart: *Porcupine Pufferfish*

Justin Yocum
Position: *Safety Officer*
Major: *Aerospace Engineering*
Fish Counterpart: *Peacock Mantis Shrimp*

Sirio Jansen-Sanchez
Position: *Software Lead*
Major: *Electrical Engineering*
Fish Counterpart: *Clownfish*

Emily Coello
Position: *Marketing Lead*
Major: *Mechanical Engineering*
Fish Counterpart: *Parrotfish*

Garrett Lynn
Position: *Team Member*
Major: *Space Operations*
Fish Counterpart: *Barracuda*

Garrison Ottolini
Position*: Team Member*
Major*: Mechanical Engineering*
Fish Counterpart: *Catfish*

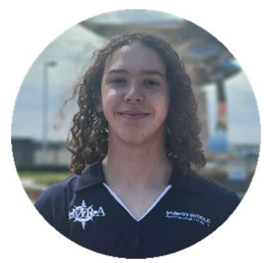
John "Jack" McSwiggin
Position: Pilot
Major: *Aerospace Engineering*
Fish Counterpart: *Bluegill*

Robert Thibodeau
Position: *Team Member*
Major: *Aerospace Engineering*
Fish Counterpart: *Longnose Butterflyfish*

Nicolas Chamberlain
Position: *Team Member*
Major: *Aerospace Engineering*
Fish Counterpart: *Atlantic Salmon*

Braden "B" Ballard
Position: *Team Member*
Major: *Computer Engineering*
Fish Counterpart: *Grouper*

Gabby Anguino
Position: *Team Member*
Major: *Aerospace Engineering*
Fish Counterpart: *Betta Fish*

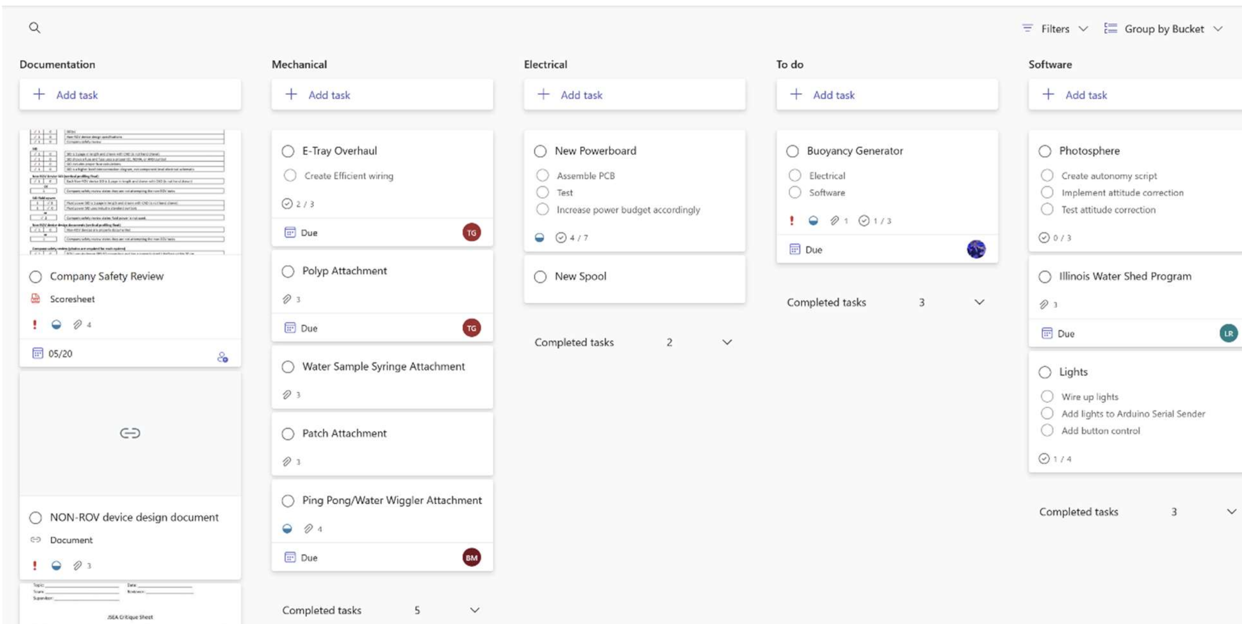


Bethany Wyman
Position*: Team Member*
Major*: Computer Science*
Fish Counterpart: *Moon Jellyfish*

Madison Warner
Position: *Team Member*
Major: *Aerospace Engineering*
Fish Counterpart: *Fire Goby*

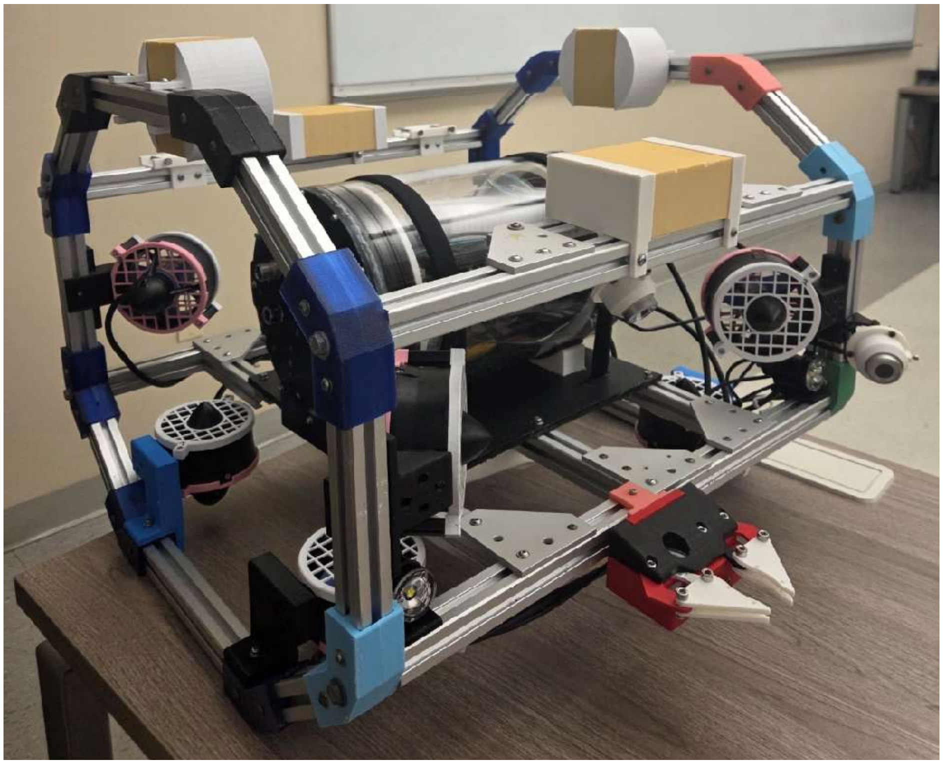
Schedule

For this year, Wave Co. implemented Microsoft Planner into the team dynamic. This addition aided greatly in management of the project, allowing for the team's weekly technical meeting time to be maximized. The function of Planner for Wave Co. focused on ensuring each team member had access to the technical resources and goals for individual sub-projects. This process team members to increase the amount of progress made on their individual projects within the allotted time for each weekly meeting.



Screenshot of Wave Co. Microsoft Planner

Design Rationale



MAKO Unit

Mechanical

Overview

Our goal with this ROV was to produce a simple, modular, expandable, serviceable, robust, and cost-effective platform for ocean exploration

The Modular Aquatic Knowledge Obtaining Unit, or MAKO Unit for short, delivers a reasonably priced submersible built with versatility in mind. MAKO features an acrylic cylindrical control housing encased in an aluminum exoskeleton for protection. This design allows for all MAKO's electronics and tools to be safe from impact, and the T-slotted extrusions allow for easy equipment mounting. This base design opens the door to endless opportunities, making the Unit adaptable to any situation.

Frame

This year, the first decision our team needed to make was whether or not to make changes to the frame. After a lot of discussion, we opted to retain but upgrade the existing structure from last year. We chose this route because we valued the flexibility that the original frame provided, and this allowed us to focus our efforts on other components that required more immediate improvements.

The frame is an octagonal prism with a width of 24 inches, a length of 21.5 inches, and a height of 18 inches. We originally decided on these dimensions as they provided the largest frame possible while keeping a symmetrical design and an unobstructed path for exhaust water from our thrusters. We used T-slot aluminum extrusions, which are crucial to the MAKO Unit's modularity as they allow us to mount tools easily to the frame and move them if necessary. The frame pieces are connected using 3D printed brackets. These brackets, originally printed out of PLA, were beginning to show signs of wear, so we reprinted the brackets out of polycarbonate. This change improves the MAKO Unit's rigidity and impact resistance.

Making the frame an exoskeleton resulted in the MAKO Unit being both larger and heavier than most ROVs in the MATE ROV Competition. However, the additional protection the exoskeleton adds more than makes up for the added size and weight.

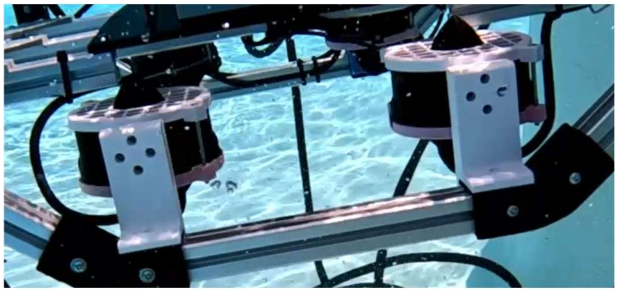
Propulsion

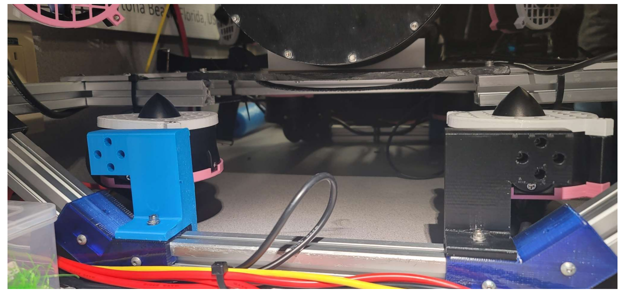
MAKO features eight Blue Robotics T200 thrusters, four vertical and four horizontal. By using eight thrusters, the MAKO Unit is able to match the maneuverability and responsiveness of a smaller ROV. Unfortunately, this results in higher power consumption, but this increase in amperage has not been a problem.

The vertical thrusters are mounted to the bottom of the frame and the horizontal thrusters are mounted to the vertical extrusions at a 45° angle, both thruster variations are mounted using 3D printed mounts within the exoskeleton to avoid any damage from potential collisions. This mounting configuration, along with the fact that we use eight thrusters, gives MAKO the ability to maintain six-axis control and symmetric thrust in the event a thruster becomes damaged.

We chose to reuse the thrusters from last year because they have proven to be extremely reliable. Blue Robotics also provides a great amount of technical documentation and support so that we can diagnose any issues that may arise.

We were pleased with our thruster performance last year, particularly when the ESC controlling one of the horizontal thrusters failed. By disabling its opposing thruster and adjusting the power to the remaining seven, we were able to maintain control without any major issues. As a result we decided to retain our original thruster configuration with one small change. In order to increase the ROV's pitching moment, we offset each vertical thruster 1.25 inches, which resulted in a 28% increase in pitching moment.

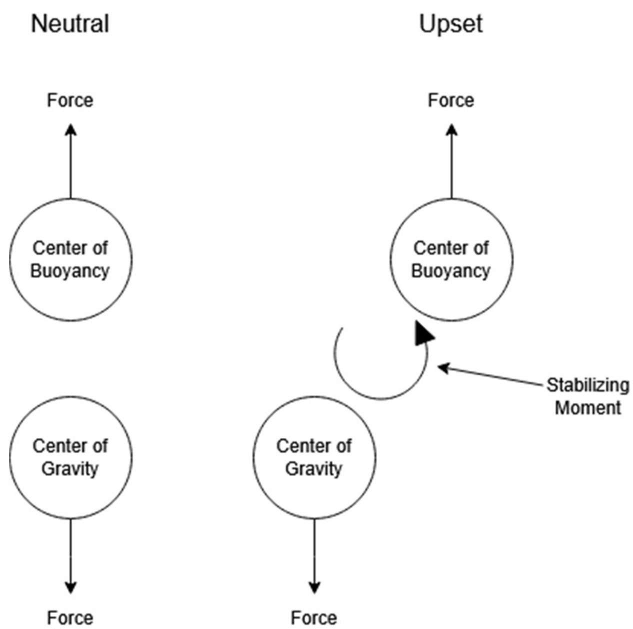

Last Year's Vertical Thruster Spacing


Revised Vertical Thruster Spacing

While it is not shown in the above figure, all of the motor mounts were reprinted out of polycarbonate in order to strengthen the parts and prevent the catastrophic failures that were possible when printed out of PLA.

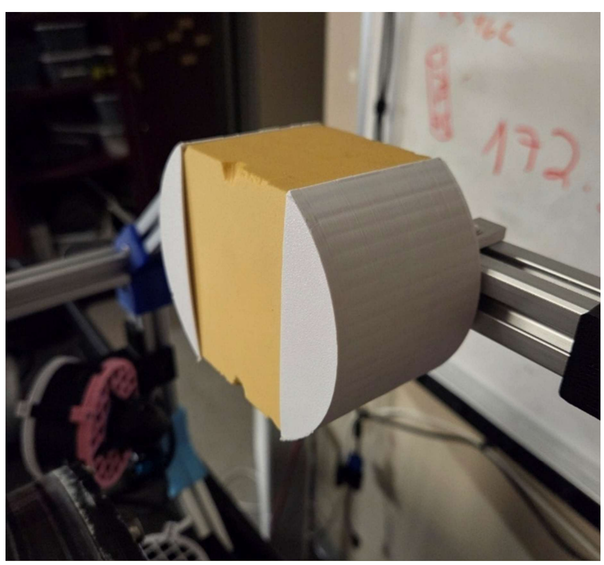
Buoyancy and Ballast

The initial design of the MAKO Unit focused on providing a neutrally buoyant ROV for ease of vertical movement. In addition, we attempted to provide a neutrally stable system in the pitch and roll axis by placing the component with the largest concentrated volume, the electronics enclosure, in the center of the ROV. However, once a PID-based active stabilization system was implemented on the ROV, we encountered significant issues with the ROV entering periods of uncontrolled, random motion in the stabilized axes. Following a consultation with a senior member of our club, we learned that a PID controlled system must first be statically stable for the PID control loop to work properly. To achieve a statically stable system, buoyancy foam was added to the highest point of the ROV, and ballast to the lowest. By making this change, the center of buoyancy was raised, and the center of gravity lowered. Below is a diagram showing the forces and moments that cause a watercraft, such as the MAKO Unit, to experience static stability.



Buoyancy and Gravity Forces on Watercraft

By increasing the vertical distance between the center of buoyancy and center of gravity, the horizontal distance between the two points increases as the angle of rotation increases. This results in a proportional increase in the corrective moment. This change allowed for an active stabilization system to be implemented on MAKO.

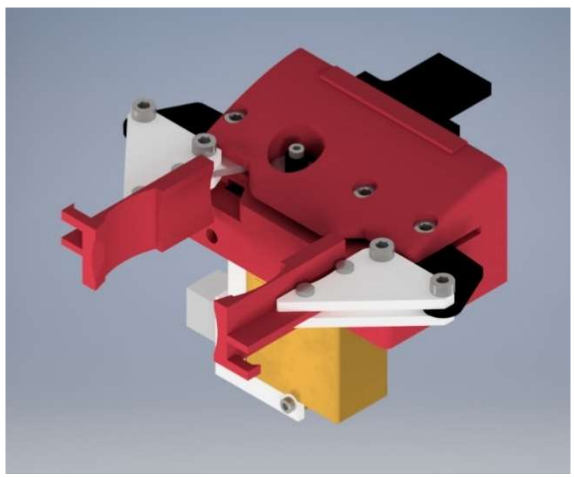


Buoyancy Foam Installed on MAKO Unit

Tools

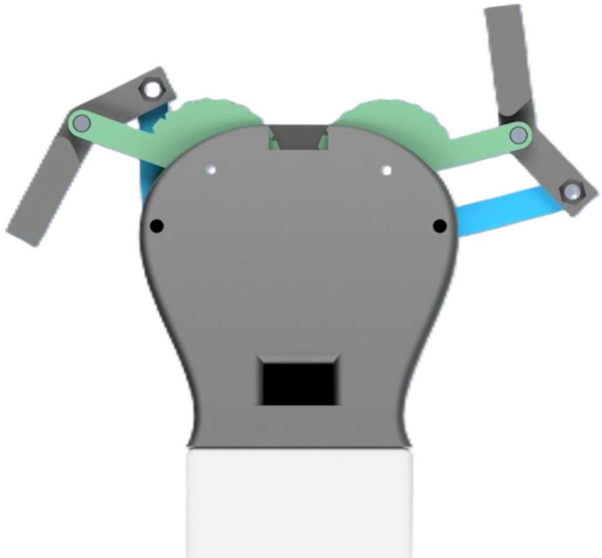
Gripper

The MAKO Unit utilizes a custom gripper which was designed and built in house, dubbed "Gripper Mk II". The finalized version of this gripper uses a Volz DA 22-SUB Servo which is rated for a depth of 100 meters. The gripper opens to 7.24 centimeters and has a grip strength of approximately 90 Newtons. The claws of the gripper feature two mounting holes which allowing various tools and paddles to be mounted to the gripper using pins. The gripper, along with a variety of attachments will allow us to complete a multitude of tasks including Task 1.1, 1.2, 2.1, and 2.2. By reusing the gripper for multiple tasks, we were able to reduce complexity along with the number of failure points. This decision also had the added benefit of allowing us to save on money when it came to tooling.



Gripper Mk II with Paddle Attachment Render

It was decided that the entire gripper needed to be redesigned for this year's competition. There were a few reasons for this. The first was that the stepper motor used to drive Mk I suffered from water intrusion and seized. It also suffered from relatively low grip strength and would experience a condition we dubbed "crossed-linkage" if it did not grip an object squarely. This condition is shown in the following image.



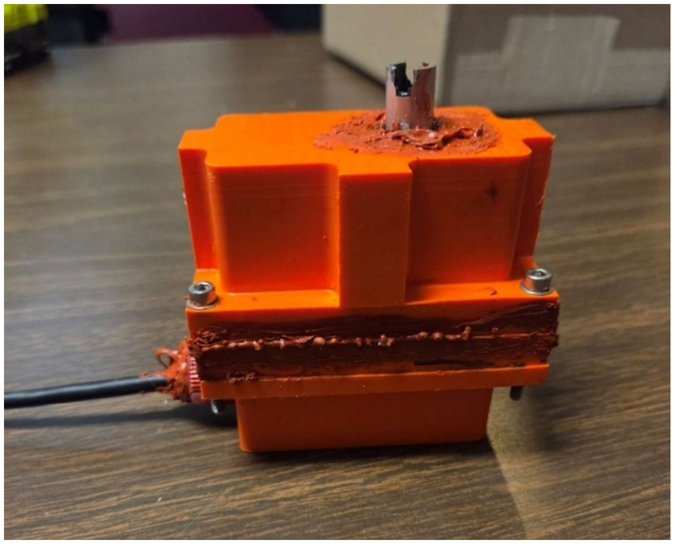
Render of Gripper Mk 1 in Crossed-Linkage State

The first step in designing the new gripper was deciding to use a servo instead of a stepper motor to increase the grip strength. The next step was to decide how we would go about waterproofing the servo. To do this, a decision matrix was created as shown below. The three options were to create a housing for the servo, fill the servo with oil, or to use the Volz servo (The problem with which was that we would need to make our own cable since the cable designed for the Volz DA 22-SUB servo was outside of our budget).

Servo Waterproofing Decision Matrix

Method	Simplicity	Implementation	Cost	Effectiveness	Size	Total
Housing	6	2	8	8	8	32
Oil	8	6	7	2	9	32
Volz Servo	4	6	5	10	4	29

Since the housing and oil methods of waterproofing tied in our decision matrix, we decided to attempt the housing method first since it scored higher when it came to effectiveness. After several iterations and attempts at both 3D printing and machining the housing, water intrusion continued to be a problem. We believe this to be due to misalignment between the shaft seal and the output shaft. It was also during this testing that we found that the 3D printed servo linkage was not strong enough to handle the torque provided by the servo. To remedy this, we machined a linkage in-house out of aluminum.

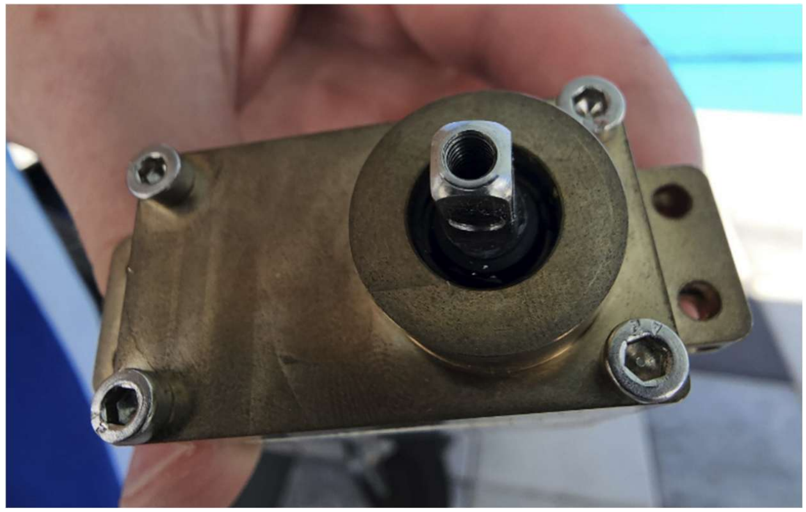


In-House Manufactured Servo Housing

Aluminum Gripper Linkage During Machining Process

Since we were running out of time to produce an effective waterproof housing, we decided to attempt to use the Volz servo since it should have been the most effective option. During our first in-water test of the Volz servo, we lost control of the servo. We suspected that this was due to an issue with our homemade cable. After determining that the cable was fine, we found that the mounting hole in the output shaft of the servo went straight through into the internals of the servo and was not waterproof. We were surprised by this as the servo is rated to 100 meters in depth and there was no mention of the through hole in any of the technical documentation. We are currently waiting to hear back from Volz on this issue so that we can come up with a solution.

Volz DA 22-SUB Servo



Volz DA 22-SUB Output Shaft

Magnet

To complete remove the pipe cleaners "jellyfish polyps" in TASK 2.2, we are using a permanent magnet which is affixed to the frame of the ROV. Since the pipe cleaners have a ferrous wire core, the magnet has proven a sufficient means of pulling and retrieving the polyps from the PVC. If this method were to fail for some reason, we have the ability to use the gripper instead, but it would take additional time.

Measuring

To measure the shipwreck in Task 1.1, we are using a flexible measuring tape which has been attached to our tether. We use the ROV to drag the tether alongside the shipwreck. We then circle around with the ROV to read the measurement. This method is simple and inexpensive, yet highly effective.

Velcro

To carry the epoxy patch to the corroded area of the base, we have two small Velcro patches on the right vertical frame piece. These pieces of Velcro are small enough to ensure that the patch will be detached from the ROV when placed against the Velcro on the structure's base.

Cameras

The MAKO Unit is equipped with two ExploreHD 3.0 cameras which are made by DeepWater Exploration. Though they are far more expensive, we decided to use externally mounted waterproof cameras instead of mounting a standard camera inside of our electronics enclosure. This is because the curve of the acrylic tub causes ocular distortion which was very disorienting to the pilot when this method was tested.

To aid the pilot in completing tasks, we moved the forward-facing camera, reused from last year, to the top crossbeam of the ROV. We also added a second camera to the MAKO Unit. This camera was donated to us by Team Unsinkable, a sister project within our larger robotics club. The camera is mounted to the front left vertical beam to provide a side view of the gripper. This position in particular was selected because we discovered that depth perception is extremely difficult with only one camera. Placing the second camera perpendicular to the forward-facing camera allows the pilot to have a reference for depth perception.

These cameras are used for every task, but they are invaluable when it comes to identifying objects, as required in Tasks 1.1 and 2.2.

Software

The MAKO Unit utilizes ROS2 Humble for its control system, with C++ nodes and Python launch files.

One of the biggest improvements this year was the complete overhaul of the control system. Our new system provides significant pilot aids, including active stabilization, a new interface, and coordinate frame compensation.

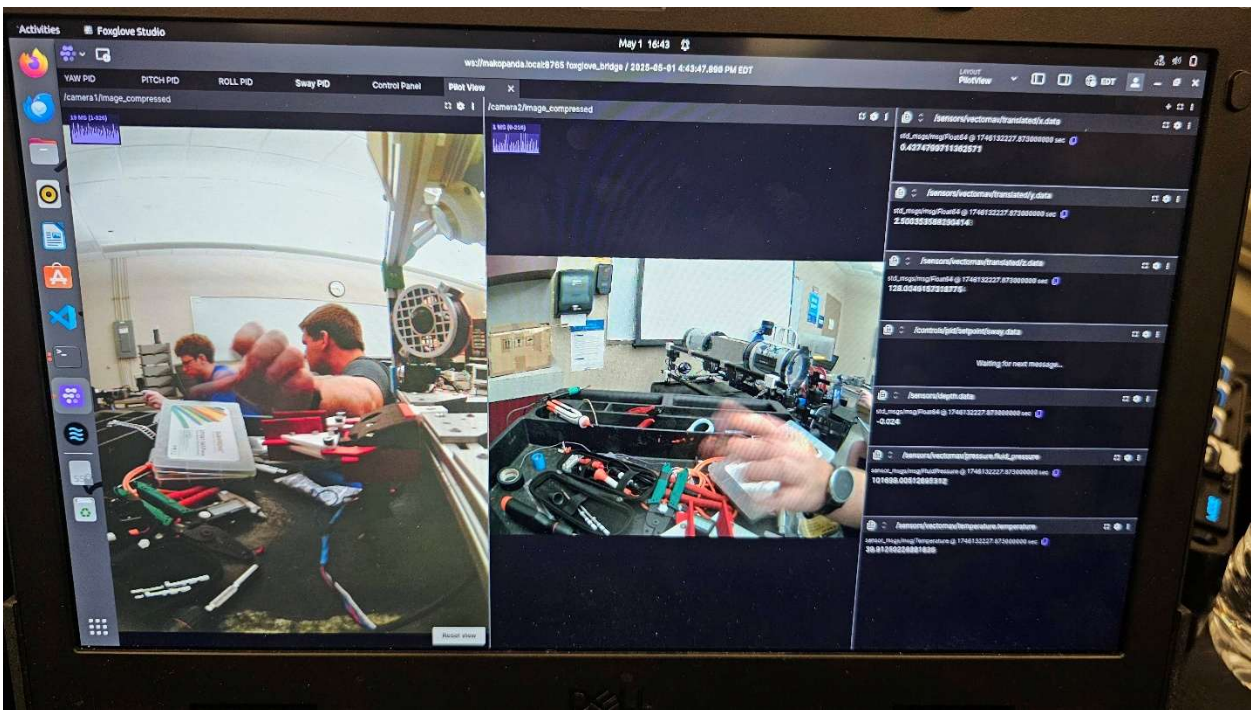
Active Stabilization

The active stabilization system uses our in-house developed ROS2 Humble PID library for stabilization on all three rotational axes and depth. One of the issues we encountered with using PIDs was how to allow the Pilot and the active stabilization system to work together. The initial approach involved incrementing the setpoint, based on how much control input was provided. This system suffered from latency issues.

After a brainstorming session with the entire team, our pilot came up with an idea based on one of his favorite games, Kerbal Space Program. With the new system, once a non-zero value for control input is received, stabilization is disabled for that axis, the control input value is scaled and directly published to the motors. Once another input value of zero is received, the stabilization is reenabled, and the current attitude of the ROV is set as the setpoint. In other words, when pilot input is received for a given axis, the PIDs for that axis are disabled until the pilot stops providing an input, at which point the PIDs are set to maintain the ROV's new heading. This system allows fast responses, while allowing for the stabilization system to maintain the pilot's desired attitude.

Pilot Interface

The new interface outputs the ROV's current attitude in roll, pitch, and yaw values in degrees, as well as the depth reading, the depth setpoint, and the ROV's internal conditions such as pressure and temperature. The interface also outputs the view of both cameras. This new system is able to be expanded to include additional information such as visualization of the ROV's current attitude, and the display of task specific measurements, such as pH.



Pilot Control Interface

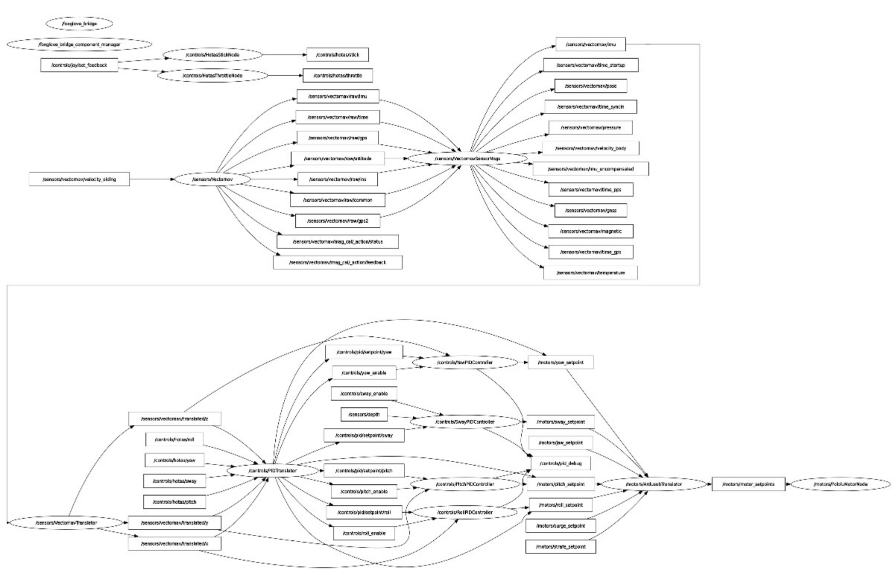
Coordinate Compensation

The most complicated change for this competition year was the coordinate frame compensation. This system operates by receiving orientation data from our Inertial Measurement Unit (IMU) in the form of quaternions relative to the ROV's reference frame. It then transforms this data into the appropriate output coefficients needed to convert a control input into the global (inertial) reference frame.

This system allows the ROV to be placed at extreme attitudes in order to complete mission tasks, while still maintaining depth hold, which is the only stabilized axis that is tied to the inertial reference frame. Taking this system further and transforming the inputs for forward/backward, and side to side to the inertial frame will allow the pilot to make control inputs that will not change the current depth of the ROV, despite the fact that the front of the sub may be facing straight down for example. For the completion of certain tasks, it may be easier for the pilot to have forward/backward and side to side control stay in the ROV's reference frame. Fortunately, our implementation allows for the switching of coordinate reference frames on the fly.

The primary reason for the addition of coordinate frame compensation was to complete Task 2.1 - Sacrificial Anode. The plan to complete this task is to pitch the ROV down 90° and align it with the sacrificial anode handle using the ROV's forward/reverse axis while it is in the inertial frame. Once this alignment is completed, the forward/reverse axis will be switched to the ROV's reference frame, allowing for the pilot to more easily maneuver the anode out of its connector. We decided on completing this task using coordinate frame compensation because performing this task easily would require an additional camera or a change of the current camera setup. With the ROV rotated downwards 90°, the hole for the anode is much more visible for the pilot.

ROS 2



ROS 2 Stack

All of these changes were made possible by the modular approach taken with our ROS2 stack, depicted above. Each node, depicted as a circular object, has a specific function, which allows it to be decoupled from the other nearby nodes. The 'VectornavTranslaor' allows us to feed each PID its own setpoint message by splitting the Twist Message with 6 degrees of freedom (DoF), to simply a number under a specific topic. This leads to ease of development and integration for any new systems into our project. Each node is also written with modularity in mind, allowing us to easily add additional button integrations on our control interface, for instance, without needing to rewrite the entire node. The same can be said for the frame compensation. When we need to compensate for the rotated frame, we can simply apply rotation to our fix frame thrust vector and feed these rotated results to our motor controller.

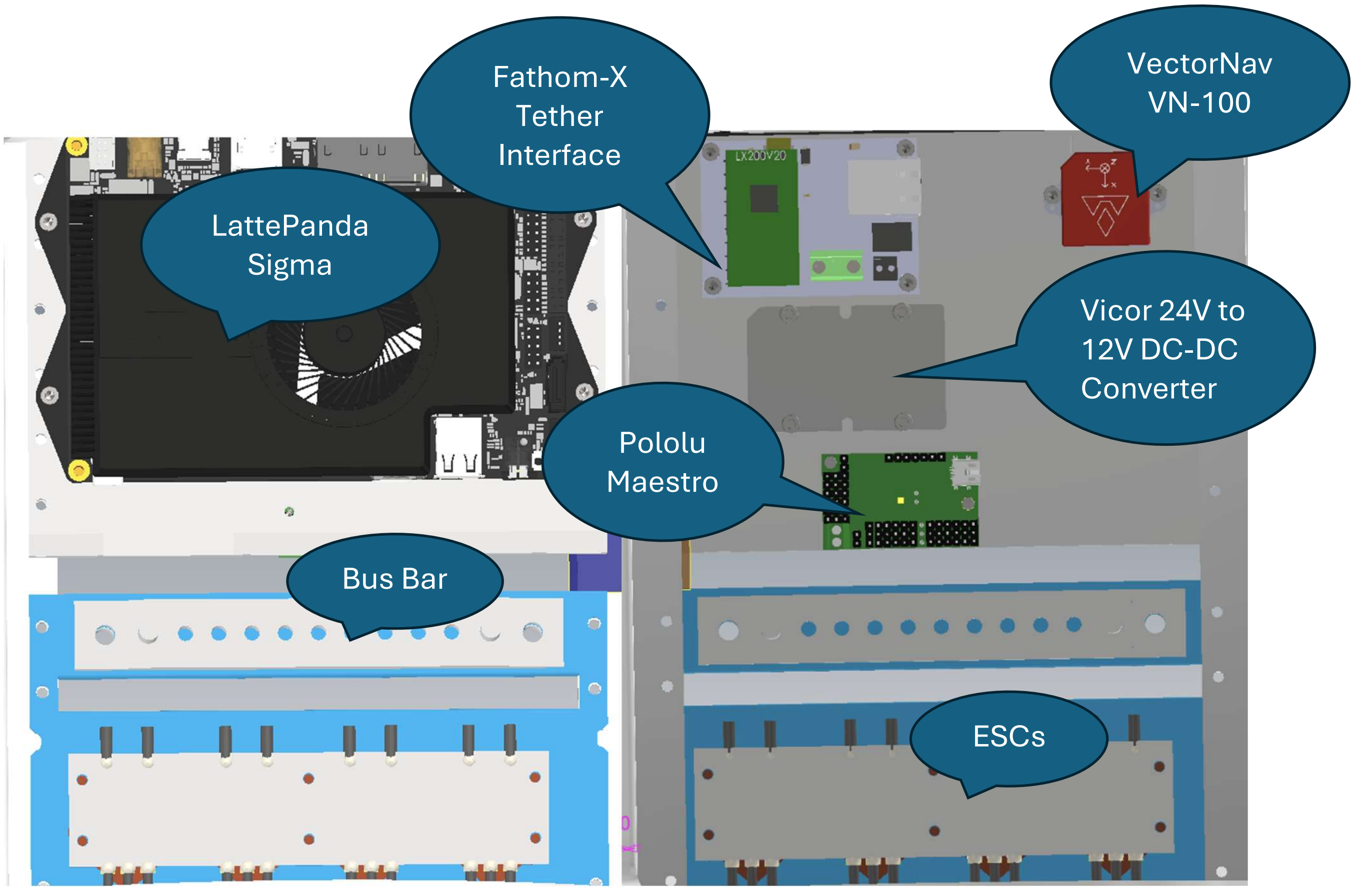
Emergency Shutdown

One last change that has been paramount to increasing safety during our pool tests has been the change in implementation of our emergency-stop system. The software emergency stop system now works on an interrupt basis. Essentially, when the emergency stop message is received, it forces the motor control program to halt execution and perform the emergency shutdown procedure. The only issue that was discovered during testing of this system is that there were occasional messages that would get in after the interruption was executed. This issue is unavoidable due to how ROS2 processes messages. There are two main components to the message reception mechanism in ROS2. One of these components lives at the firmware level, the other at the operating system level. When an interrupt is called the portion of the reception handler that resides in the firmware continues to receive messages and places them in a queue for the operating system level component. Upon interrupt completion, the operating system continues its loop to clear all messages from the queue even if the emergency stop function had been called. Resulting in the actuation of thrusters after the emergency-stop. This was easily solved by closing the handle to the motor controller, ensuring that nothing in the process could talk to the controller after shutdown. The motor controller is reenable after arming again.

Electrical

Wiring

The MAKO Unit takes an input of 48V DC from the shore, which is reduced to 24V DC by a DC-DC converter. This voltage is then sent to the bus bars, shown in the images below, for distribution to the Blue Robotics Basic ESCs and both Vicor DC-DC converters. The first converter, a 24V to 12V converter powers the LattePanda Sigma, our main computer, and the Fathom-X tether interface which allows the ROV to communicate with the shore over the tether. The LattePanda's USB interface steps down power to 5V to power the VectorNav VN-100, which is our IMU, and the Pololu Maestro, which is used to control our thrusters and gripper. The second DC-DC converter is effectively used as an isolator for our DA-22 SUB from Volz Servos. It is rated for an input voltage ranging from 20-30V DC but our 24V rail suffers from inductive voltage spikes exceeding 30V. Therefore, in an abundance of caution we added a high-quality isolated converter inline.

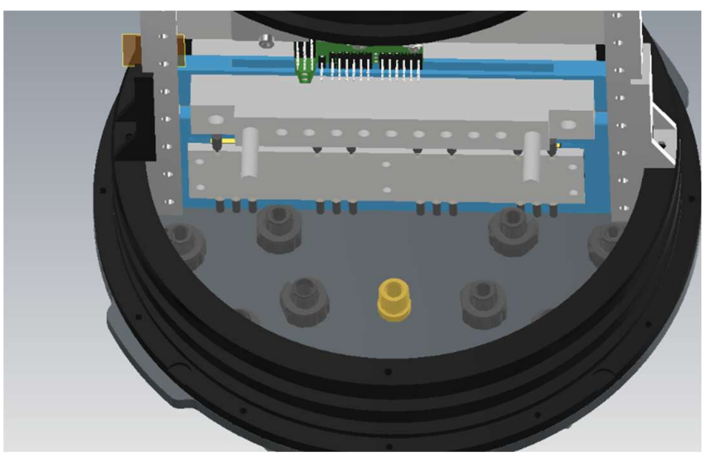


Top of Electrical Board (Left) and Bottom of Electrical Board (Right)

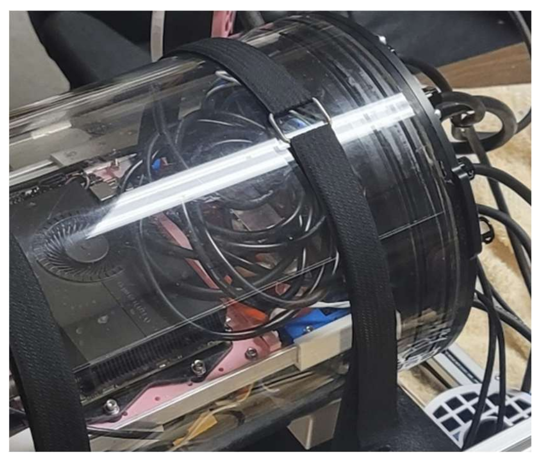
Electronics Tray

New Electronics Tray Design

One of the most significant challenges discovered during last year's World Championships was the lack of accessibility and difficulty in removing the electronics tray. Specifically, the tight fit and necessity to remove two fasteners which were in a cramped location made removal of the e-tray a task that was avoided as much as possible. The removal issue compounded with the lack of accessibility to the penetrators and the wire density near the penetrators shown in the following figures. These two issues made the removal and installation of penetrators and ESCs challenging while leading to poolside troubleshooting difficulties.



Penetrator Location Relative to Electronics Tray

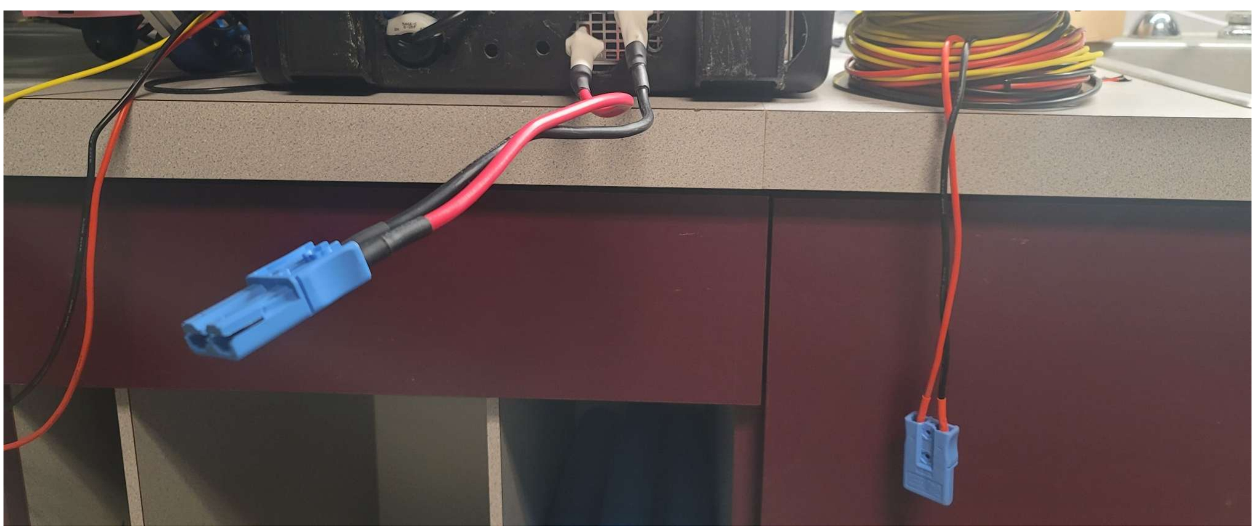


Wire Density Near Penetrators

To fix this problem, we decided to redesign the e-tray mounting mechanism. We determined that our modular tray-based system had minimal faults and did not need to be changed, therefore it was carried over to the new design. The primary goals for the new design were toolless removal of the electronics from the housing, and the ability to remove the interface endcap without needing to disconnect any electronics. The new design incorporated a fixed mounting system for the e-tray, with the ability to slide the electronics out on a sled. This allows us to more easily service the previously hard to reach components, like the penetrators and ESCs.

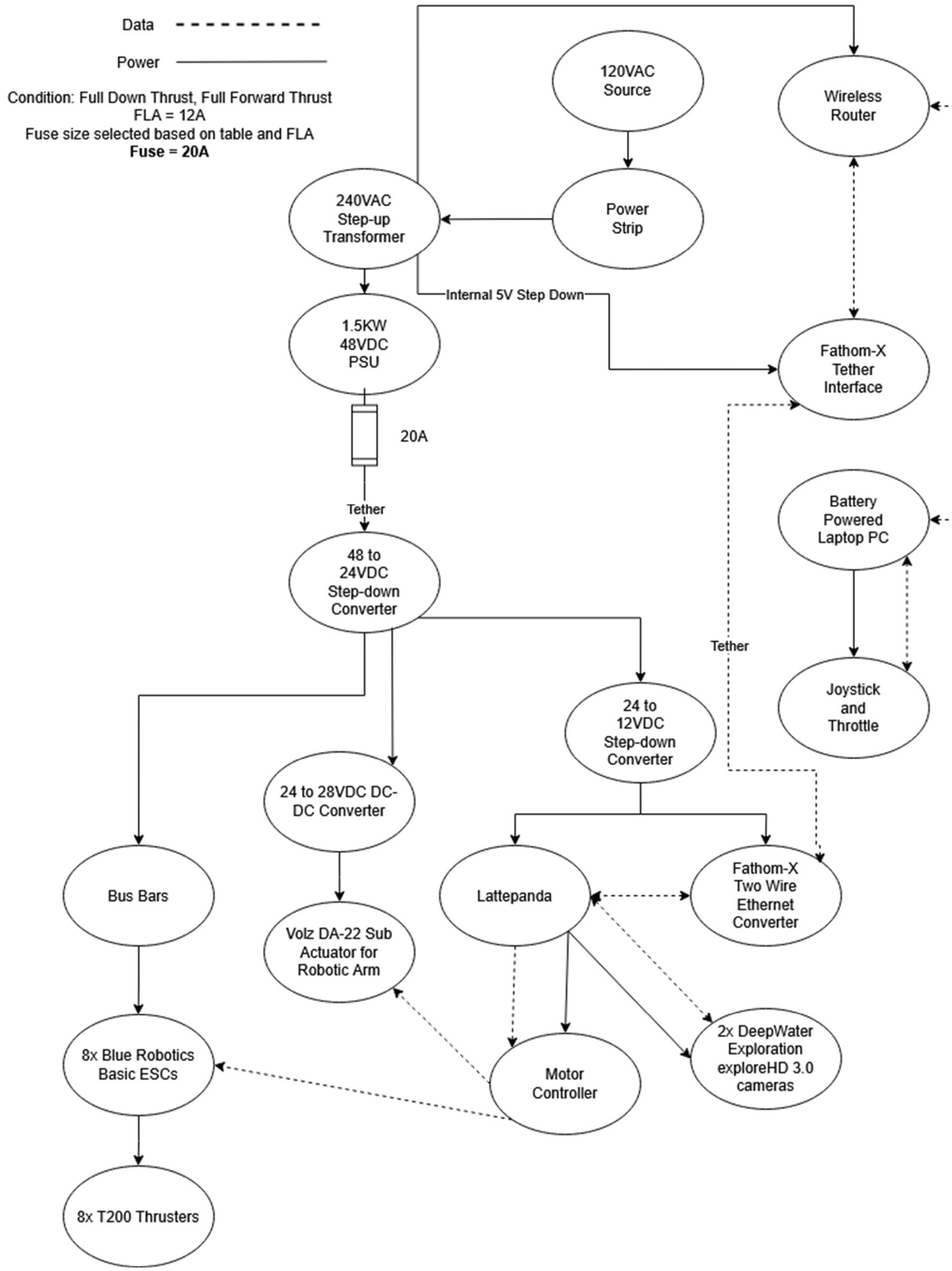
Tether

One of the biggest problems with the previous version of the tether was how bulky and rigid it was. This led to maneuverability issues, from the tether resisting movement, especially pitching moment, causing trouble during certain tasks. The original tether used 8-gauge power wire with thick, stiff insulation, along with a 4-pair Fathom Standard communication wire. We swapped these out for slimmer 12-gauge power wire with softer insulation and a single-pair Fathom Slim communication wire. Both of the new wires still met the system's power and communication needs while reducing the bending radius of the tether by 83%. To properly manage the tether, we have a dedicated team member to give and take slack for the ROV. During setup and takedown, a second member's job is to plug in and unplug all elements of the tether. Since the tether is close to neutrally buoyant, we can aim to keep enough extra slack in the tether to prevent any issues with resistance. Due to the neutral buoyancy and PIDs, the tether does not significantly weight down, or pull up on the ROV.



Old Tether (Left) Versus New Tether (Right)

System Integration Diagram



Safety

At WaveCo, our top priority is safety. In our lab, we make certain that everybody follows a simple set of rules. First, and most important, is common sense. If something feels like it has the potential to be unsafe, we don't do it. Second, when working with power tools and soldering irons, safety glasses are required, and long hair must be tied back. Third, when working with any materials that create airborne particles, everybody in the lab must wear a mask. Fourth, close-toed shoes are required whenever in the lab or working with the MAKO Unit.

For pool testing, we had several safety precautions in place. We would not put the sub into the water without having at least one person with it in the water. This diver was required to have passed our swim test which consisted of multiple tasks including recovering a brick from the bottom of the pool and treading water for five minutes. We did this for several reasons. For starters, it made it a lot easier to get the ROV in and out of the water. Second, and more importantly, the diver provided a set of eyes that could observe if the ROV was behaving abnormally.

As an additional layer of safety, one of our team members is trained as a paramedic. Their medical expertise adds a crucial level of emergency readiness when working in the lab and at the pool. While we work hard to avoid accidents, having someone on-site who is trained to respond to medical emergencies ensures we are equipped to act quickly and effectively if something were to happen.

For our customers, our submersible comes equipped with multiple safety features. For starters, each of the thrusters has a guard on both the front and the back, which eliminates the possibility of somebody's finger getting caught. MAKO also comes with an onshore emergency stop switch which cuts power to the sub if something happens that could result in injury to a diver or damage to the sub. The sub also comes equipped with a switch to arm and disarm the thrusters. This means that there is no chance of the thrusters spinning before the pilot is ready. The thrusters are never to be armed when working on or handling the MAKO Unit, this adds an extra level of safety on top of the thruster guards.

When working on the MAKO Unit the following guidelines need to be followed.

1. Closed-toed shoes required at all times (except for safety diver).
2. Hair longer that shoulder length must be tied back.
3. Safety glasses are required whenever using power tools and soldering iron.
4. Masks must be worn whenever working with materials that may produce harmful airborne particles.

5. Two people are required to move the ROV and the power box.
6. If not testing an electrical or software system, the ROV should remain powered off and unplugged.
7. Thrusters should only be armed when testing the thrusters or operating the ROV. Nobody should be within six inches of the thrusters when armed.
8. The emergency stop must be tested before each deployment.
9. The workspace must be dry whenever working with electronics.
10. A first aid kit must be on-site during all work in the lab and at the pool.
11. In the event of a malfunction, the ROV must be shut down and inspected before further use.

Testing and Troubleshooting

Wave Co's testing strategy involves creating an agenda for every pool test on the day before and presenting that agenda to the team at the club's general meeting. The agenda includes the goals for the pool test, the role of each individual at the pool test, and the time that it will start. The main roles are the Diver, Test Director, Pilot, Tether Manager, and Scribe. Having the Diver means that we can have a set of eyes on the ROV while it is in the water. The Test Director's task is to provide technical support and keep the ROV and Diver safe throughout the pool test. The Pilot's job is to control the ROV and relay information to the Test Director on how the ROV was behaving. The Tether Manager is responsible for making sure that the tether did not form a tripping hazard and does not become tangled. The Scribe's job is to note down any important information, such as bugs that need to be fixed, or changes to the control system that the Pilot requests. This information will be then placed in a Microsoft Planner bucket and dated for easy access.

Wave Co. conducts pool tests every Saturday of the school year that is not on a holiday weekend or near final exams. The most impactful pool tests of the year were conducted on January 18th, February 1st, and February 8th. During the January 18th pool test we discovered the stability issue which was discussed previously. Before the solution was identified, troubleshooting was conducted in the form of both in-water and out of water testing.

One of the biggest benefits of ROS2 is the ability to inspect the flow of data between different scripts very easily. This aspect was fully utilized to troubleshoot our PID issue. We verified that our IMU had its axes mapped correctly, that the PIDs were changing the output effort correctly depending on error, etc.

During the February 1st pool test, all software related issues were ruled out or resolved. Between pool tests, buoyancy foam was added to the highest portion of the ROV, and ballast was added to the lowest. Both systems were initially attached using zip-ties for prototyping. 3D printed PLA brackets were used and installed once the solution was verified to be effective during the February 8th pool test.

Accounting

Funding for this project is provided through ERAU's College of Engineering for a total of 4,500 USD for the school year. Purchases made with this funding may be reimbursed through ERAU's Student Government Association up to 5,800 USD per semester. However, these reimbursements are shared between two projects. Equipment donations were made by the following companies:

- VectorNav Technologies
- Volz Servos GmbH & Co. KG

We would like to thank these companies for their vital donations to the operation of the MAKO Unit.

In terms of monetary contributions

- Daniel G. Penny III for covering three rooms, six nights each, at the Wyndam Hotel in Alpena, Michigan.

The budget for ERAU's MATE ROV team is provided on a per school year basis. The MAKO Unit has been in development for three years, with each funding period focusing on the purchase of components that are either required for the operation of the ROV or would provide the largest increase in capability per cost. For this funding period specifically, ERAU's MATE ROV team was provided 1500 USD for upgrades and possible spare parts. The total value of the MAKO Unit and all of the supporting equipment is $14,773.25. The breakdown of the cost for the ROV and directly supporting equipment is shown in the tables below.

Reused Components

Section	Component Examples	Cost
Frame	Aluminum Extrusion, Electronics Tube, Fasteners	$880.63
Computer/ Electronics	LattePanda Sigma, Polulu Maestro, Sensors	$2,440
Tools/Mechanisms	Camera, Headlights	$731.76
Propulsion	BlueRobotics T200 Thrusters	$1,600
Onshore Equipment	Power Supply, Fathom Interface, Dell Laptop, Logitech HOTAS	$4,274.36
Connections	Tether, Data Cable, Penetrators	$622.99
	Total Cost of Reused Components	$10,549.46

Purchased Components

Section	Component Examples	Cost
Frame	Fasteners	$ 67.34
Computer/ Electronics	Pololu Maestros, Depth Sensor, Fuses	$ 178.35
Tools/Mechanisms	Servos, Measuring Tape, Water Pump, Magnet	$ 130.87
Onshore Equipment	Travel Router, Miscilaneous Cables, Cart	$ 223.67
Connections	Penetrators, Tether Wire	$ 93.56
Miscellaneous	Experimental components, Props	$ 776.12
	Total Cost of Purchased Components	$1469.91

Donated Components

Donor	Component	Cost
VectorNav Technologies	VN-100 IMU/AHRS	$ 1,200.00
Volz Servos GmbH & Co. KG	DA 22-SUB Servo	$ 2,000.00
Team Unsinkable	DeepWater Exploration ExploreHD 3.0 Camera	$ 330.00
	Total Value of Donated Components	$ 3,530.00

This left us with a remaining operational budget of $30.09. We left this budget for incidental expenses, such as 3D printer filament, or fuses.

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