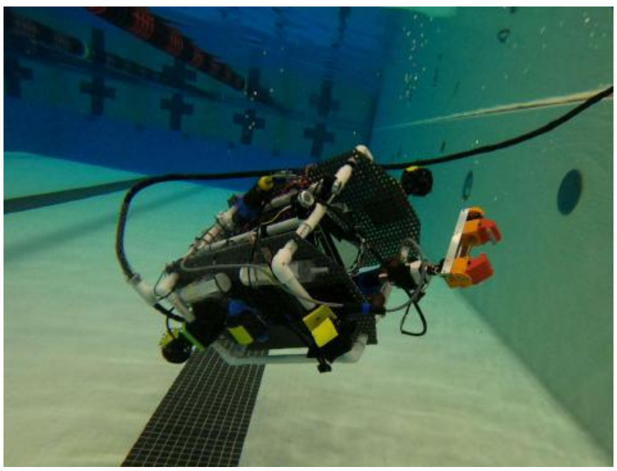
NUWAVE

Northeastern University
Boston, MA, USA
2024 MATE ROV Competition

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Abstract

NUWave is a marine robotics company with a focus on designing and manufacturing solutions for the wide range of challenges presented by our world's oceans. With experience in building both underwater Remotely Operated Vehicles (ROVs) and electric-powered Unmanned Surface Vehicles (USVs), NUWave's team of 28 talented engineers has the background needed to produce top-notch products.

Figure 1: NUWave's USV: Epoxy I

Figure 2: Testing NUWave's ROV Calypso

NUWave's design philosophy hinges on three pillars: extensibility, serviceability, and precision. Being extensible allows us to adapt to any challenge that comes our way, being serviceable allows us to rapidly deal with the harsh realities of working in such an unforgiving climate, and being precise allows us to efficiently operate our vehicles. With those principles in mind, we designed our newest ROV: Calypso.

Calypso is NUWave's second generation of ROV and features an arm with three degrees of freedom, an automatically stabilizing control system, and NUWave's signature adjustable buoyancy syringes. It is a drastic improvement on NUWave's previous product Mariana, with the most significant advancements coming in the ROV's newfound compactness and increased modularity. Calypso is designed to install and activate probiotic irrigation systems, deploy and power a wide variety of sensor arrays, and transplant coral species to restoration areas.

This document will detail NUWave's meticulous engineering design process, commitment to safety, and the entirety of the team's effort to prepare for the 2024 MATE ROV competition.

Teamwork

Company Profile

NUWave is a company based out of Boston, MA in its third year of operation. The company has once again seen an over 50% spike in team size this year and has harnessed this to offer a wider range of marine solutions, with the introduction of a new surface vehicle and even testing underwater LiFi (Light Fidelity) communication. The main focus though, has been in honing the company's ROV, offering a compact and serviceable model designed to more efficiently aid in observing our world's oceans.

NUWave is split up into three major engineering subteams, electrical, mechanical, and software. The core leadership team is made up of the CEO, the team's two mechanical leads (static and dynamic), an electrical lead, a software lead, and a CSO. There is also a second tier of leadership to help with the rapidly growing team, employing a float lead, an integrations lead to help everything come together and propmasters to manage building the MATE competition's wide array of tasks. This establishes a clear chain of command and gives engineers clear responsibilities to handle.

At NUWave, our philosophy is to build not just great robots, but also great roboticists. As such, we emphasize a "teach first, do second" mentality among all of our team's leaders. While it may be slower in terms of short-term progress, we believe that building people up into great engineers will pay dividends down the line.

Project Management

In keeping with our philosophy of building great roboticists, we started the year with our newly introduced Waveperch program. Our team was broken up into three different teams to build small-scale ROVs to complete a series of tasks, with this year the theme being item retrieval. Each team was given a base set of items including thrusters, controllers, and a PVC frame, in addition to a $50 budget to make unique improvements to their ROVs. Each week started with a 25-minute lesson on a topic important to marine robotics. Lessons covered parts specification, mechanical design, waterproofing and more. After the lesson, teams would then work on their ROVs for the remainder of the meeting, typically employing the skills they just learned. At the end of six weeks, we tested the Waveperches in a pool at MIT Sea Grant. While no single robot completed all of the tasks, the lessons learned were invaluable, from the heartbreak of faulty waterproofing, to the most compact robot winning. Ultimately, everyone left with many new ideas on how to improve our primary ROV.

Figure 3: Waveperch team discussing their design

Figure 4: Waveperch's first time flying in the pool

In developing a schedule from here, our team used Notion to organize all the parts of our ROV we wanted to work on. Each task is given a size, difficulty, and priority, as well as being assigned to one or more subteams. From there, the leads determine an initial deadline and who will be assigned to the task based on people's skill sets and interests.

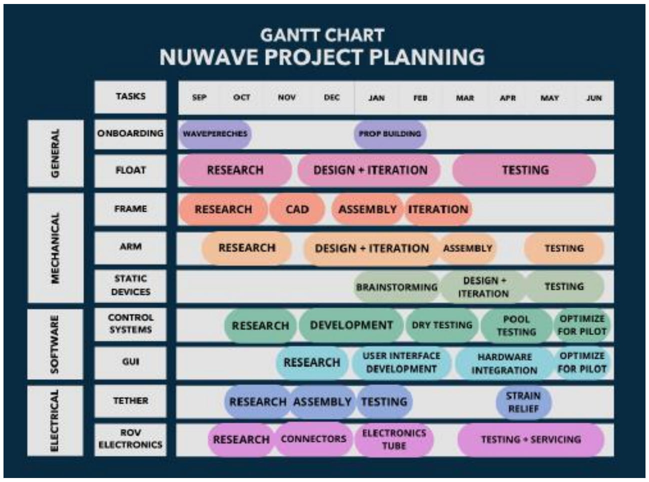

Figure 5: NUWave project planning, with each subsection split into designated time blocks.

It can be difficult to accurately predict exactly how much work a given task may be, so having information determined about each task also allows us to flexibly adjust the deadlines to tasks without ever sacrificing the priority order of what needs to be done. Our schedule is broken up into four total phases: onboarding/research, design, assembly, and testing. Each phase is designed to increase in specificity, with the design phase prioritizing a widely applicable ROV in line with our core design tenants, while the refinement phase focuses on MATE task-specific attachments and modification.

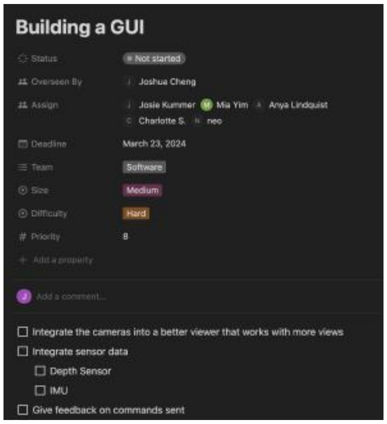

Figure 6: A Task in Notion

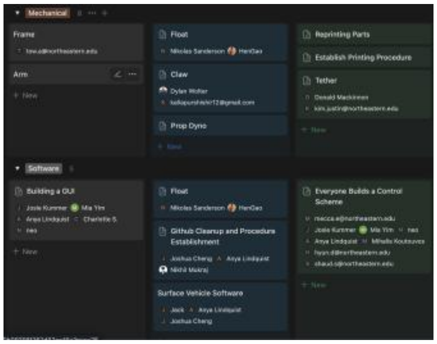

Figure 7: An excerpt from the NUWave Notion

The tasks are organized in a Kanban Board to allow members to change the status of their part of the ROV. We also further divide them into two different boards, one for large overarching tasks and one for smaller subtasks. This allows people who aren't entirely sure what to do to independently find unclaimed subtasks and begin making progress. People can be sure they're taking on the appropriate subtasks since everything has a predetermined scale and priority.

Our team meets three times a week, with a general meeting on Wednesdays, an electrical/software subteam meeting on Sundays, and a mechanical subteam meeting on Tuesdays. We use Discord as our central communications hub, and for each general meeting, an announcement is put out detailing the plan for the day so that everyone comes in on the same page. We start each meeting by giving progress updates, and then we discuss and break out into work groups. Subteam leads spend most of their time at meetings offering support to those facing challenges in their respective tasks, building the team to be stronger and more resilient down the line.

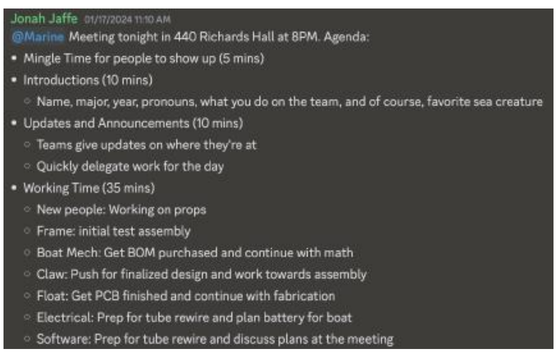

Figure 8: An Agenda for an Upcoming Meeting

As a company, we utilize Google Drive for file storage and information management. We use SolidWorks as our Computer-Aided Design (CAD) software and adhere to a self-developed style guideline designed to support newer members in designing robust parts. For code management we use GitHub, and in order to merge code into our central codebase it must be rigorously reviewed by two other members.

Design Rationale

Design Philosophy

NUWave aims to set itself apart from the rest in its sheer applicability to all situations, and ability to rapidly make adjustments to approach any challenge. Our goal is to design solutions that can be applied to multiple challenges at once. This philosophy allows us to spend a lot of time optimizing a few designs rather than working on multiple smaller systems to deal with our large set of problems. In designing, extensibility is also a priority. We tend to think of it similarly to a large software project, if the person setting up the architecture hard codes every step, it becomes difficult for future developers to make changes and update the system.

Our process of solving a particular challenge always starts with defining what needs to be accomplished. We then brainstorm a series of solutions and determine which of them is the most in line with our design principles. Next, we select one or two solutions to proceed with the design and manufacturing phase, utilizing rapid prototyping solutions like readily available boards like Arduinos and 3D printing in the cheap yet efficient polylactic acid (PLA). Finally, we evaluate the results and move to perhaps the most important phase of our design process: iteration. We firmly believe that one of the best ways to learn is by doing, and by consistently improving solutions through iteration, not only does our product become stronger, but so does our team.

NUWave also exists within a unique set of circumstances that inform our design decisions toward affordability and compactness. While building an affordable ROV is generally good, NUWave, unfortunately, had its incoming yearly funding cut by the university.

Figure 9: Spare Thruster Core Used for Claw Motor

Instead of buying new components, the team has leaned towards the creative reuse of parts that it already had. Our new arm is made almost entirely of parts from existing materials. The claw open and close motor is made out of the core of a spare thruster (Figure 9), the wrist rotation is a repurposed stepper motor from last year's failed actuating screw design, and the linear actuator for extension is the elbow joint linear actuator from last year. Out-of-the-box solutions like these not only minimize the cost of the ROV but allow NUWave to adapt to the ever-changing world of Northeastern's club sphere.

NUWave exists with Northeastern's larger robotics club: NURobotics. The club has eight other projects and shares a space with both a measurements lab and a mechatronics lab. As such, the team has limited space for both storage and fabrication, so compact solutions are often the only feasible ones.

Frame

In evaluating the successes and failures of Mariana, the company's previous offering, there was one clear consensus: the ROV was too large. Among other issues, in completing our final task of 2023, we managed to get full points for manually docking the ROV, but we needed diver assistance to escape the docking station.

Rank	Meaning
1	Strong Negative Impact
2	Slight Negative Impact
3	No Impact
4	Slight Positive Impact
5	Strong Positive Impact

Category	Remove Elbow Actuation	Remove Extension	Acrylic Frame	Keep PVC Frame	PVC + Perf Board Frame	Perf Board + Remove Elbow
Ease of Assembly	4	4	2	3	4	5
Affect on Ability to Complete Tasks	2	1	3	3	3	3
Compactness Improvement	4	4	4	3	4	5
Ease of Mounting	3	3	4	3	5	5
Cost Improvement	4	4	1	3	2	2
Weight Improvement	4	4	2	3	2	3
Totals	21	20	16	18	20	23

Figure 10: Evaluating Possible Frame Design Changes

The team discussed a series of ideas landing on two possible ways of becoming more compact: removing different axes of actuation from the ROV's arm and rebuilding the frame out of new materials for a new design. We then evaluated each solution on ease of assembly, how they impacted our ability to complete tasks, how much they improved our compactness, the ease of mounting in the given scenario, and cost (Figure 10). While it always feels strange to reduce functionality, after a detailed analysis of the tasks the team concluded that removing it would only make a few tasks like triggering the release of the multi-function node slightly harder due to not having as good of an angle, but it would also simplify tasks like activating the irrigation system as the previous design was unable to get close enough for the claw to be parallel to the bottom pool and grab the knob for rotation.

Propulsion

The four thrusters for yaw and lateral movement are powered by 12V and the two larger thrusters for vertical movement are powered by 24V. These thrusters sourced from Diamond Dynamics were chosen over the industry standard BlueRobotics thrusters for three main reasons. Firstly, they are cheaper. Secondly, they have built-in waterproof ESCs with high-voltage power conversion outside of our airtight electronics cylinder. This mitigates the potential of heat building up in the tube, which was a concern because of the inherent increase in pressure. Lastly, the up-and-down thrusters from Diamond Dynamics have better overall specifications. Off of 20V, the BlueRobotics thrusters have 5.05kg of thrust, while the Diamond Dynamics ones have 6.7kg. Additionally, 20V is not a common voltage to output, so an additional in-tube voltage converter would be required, adding heat and clutter to the system.

	Blue Robotics T200 +ESC	Diamond Dynamics TD7	Diamond Dynamics TD1.2
Price	$238.00	$159.99	$64.00
Max Thrust	5.05kg	6.7kg	1.2kg
Max Power Draw	640W	720W	360W
In-Water ESC	No	Yes	Yes

Figure 11: Evaluating Thruster Options

We decided to use four thrusters instead of two because balancing the forces off of each other gives us access to lateral movement. This equips Calypso with more dynamic movement, which is necessary for our ability to encircle the coral structure to make a 3D model of it. We decided on using smaller thrusters because for horizontal movement we value precision over speed, as there are no tasks that require significant horizontal pushing.

Figure 12: A top view of our TD1.2 Thruster

Additionally, the thrusters using 12V have significantly less current power than the 24V thrusters, allowing us to budget our major power draw to efficiently traverse up and down. Conversely, we determined that budgeting the power and price point for our vertical thrusters was completely worth it, as tasks like the irrigation system require us to carry fairly heavy objects down to the bottom of the pool. Furthermore, a large amount of traversal time is spent covering the distance from the bottom of the 15 ft-deep mission area to the surface, and speeding that up increases the time when the ROV is actually completing tasks. Lastly, we decided to place the two vertical thrusters on the side of our ROV because it made us more compact, and kept them closer to our center of mass for more effect.

Buoyancy

Given our central design principle of extensibility, we needed a buoyancy system that accounts for the rapid testing of different attachments and configurations. This led us back to our signature buoyancy solution of syringes. By filling the syringes with air and capping them before submersion, the syringes acted as adjustable buoyancy tanks that could be changed quickly and precisely. In placing a syringe in each of the four corners of the ROV, we can adjust the volumes of air to ensure both neutral buoyancy and tilt. We do this before every test in a new configuration.

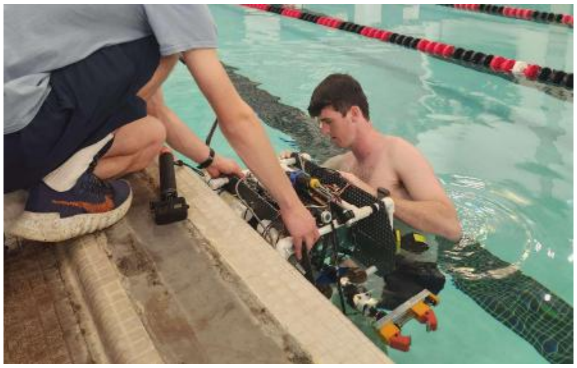

Figure 13: A Team Member Adjusting Buoyancy

After removing one of the two linear actuators from our previous design, Calypso was now positively buoyant. To achieve neutral buoyancy, the team now needed a solution for adjustable ballast. Our solution was inspired by an adjustable dumbbell used for home weightlifting. A nut and bolt coupled with marine washers are used to make the ROV negatively buoyant, and the number of weights on each nut and bolt could be changed if necessary. One of these was placed in each corner, just like our syringes. Calypso also uses smaller 150ml syringes, making it more compact than Mariana's 350ml syringes.

Figure 14: Adjustable Ballast System

Our syringes' adjustability also allows for increased functionality during the mission. When a task requires the ROV to carry something heavy, the poolside employee can increase the buoyancy on the front two syringes to counteract the force. This does present a challenge for the return trip, as the ROV will naturally pitch backward without the heavy object. To account for this, we can extend our arm, pitching the ROV forward and leveling the ROV.

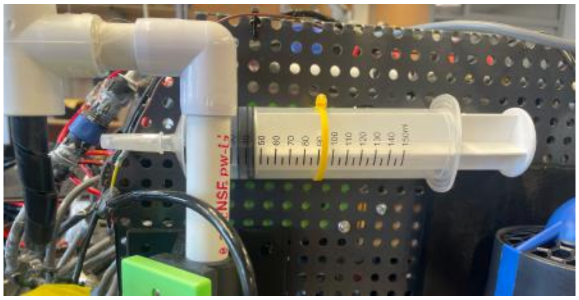

Figure 15: A Syringe Mounted on the Side of the ROV

Electrical Systems

Component Selection

Many electrical components that performed well in last year's design were also incorporated in this year's design. Given their proven dependability and budget considerations, the choice was clear. Each new electronic component for Calypso was selected based on its purpose, power consumption, footprint, and waterproofness when applicable. With limited space inside the electronics enclosure, it was important to select components that fit on the acrylic mounting plate. Given pressure considerations, we selected components with minimal heating of the air inside the tube.

Electronics Housing

To house our electronics, we used a 6-inch cylinder from Blue Robotics, positioned in the center of the frame in parallel with the forward range of motion to ensure optimal hydrodynamics.

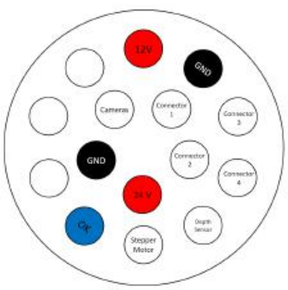

Figure 16: Pass-Through Map of Main Tube

Redesign and Rewire

To improve the layout inside of the electronics housing, we changed the design of the acrylic baseplate used to mount the components inside of the tube. The locations of the parts were changed to optimize wiring, and holes were added along the sides of the plate to allow wires to pass from the top of the plate to the bottom of the plate. This eliminated previous cable clutter near the end cap and made powering components on the bottom side of the plate much easier. During this reorganization, all parts inside the tube were rewired.

Previously, jumper wires were used to plug into the Arduino's standard socket headers, but these connections were loose, and could not be relied upon to stay in place. To remedy this, we desoldered the socket headers and replaced them with screw terminals, creating strong connections for all signals.

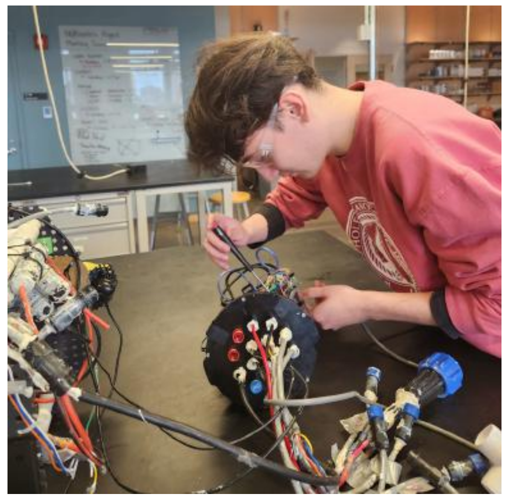

Figure 17: Teammate Nik Working on the Screw Terminals on the Arduino Mega

Connectors

To make the electronics system more modular, we incorporated connectors outside of the tube so parts could be replaced or added. This idea makes the design scalable and allows different sensors and thrusters to be added based on the demands of the mission. It also protects the design from long repair processes if a thruster or sensor fails.

Four 8-pin connectors from Bulgin were used to route signal and power wires to the thrusters and linear actuator used by the claw. The power wires were also routed via a large

4-pin connector from Bulgin so that the tether could be easily disconnected from the ROV. This connector was rated for 32A to accommodate all power being passed through it.

These connectors were an advantage in development and testing, providing accessible test points for voltage outside of the tube, where most connections would usually be waterproofed.

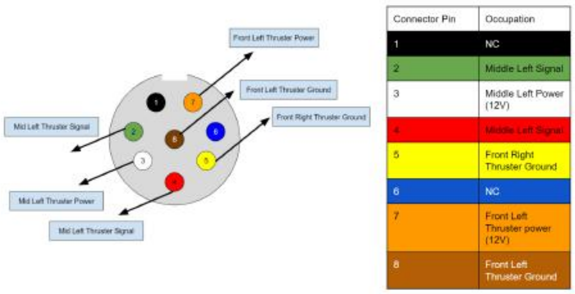

Figure 18: Example of Connector Pinout Documentation

Power Management

A 48V 1500W power supply from Mean Well was used to supply power to Calypso, and managed by a 30A fuse and an emergency switch. The single power line was split using waterproof T-Splice connectors, then converted to 12V and 24V by two waterproof buck converters outside the electronics tube, each rated for 30A, attached to the frame of the robot.

Inside the tube, 24V power was connected to an in-line terminal block, while 12V power was connected to a large, mounted terminal block. 12V power was then stepped down to sensor via I2C. The Pi is also connected to a USB hub used to receive visual data from two cameras mounted on the frame.

5V, and another terminal block was added for 5V power. All ground wires were routed via the 12V power terminal block, to create a common ground.

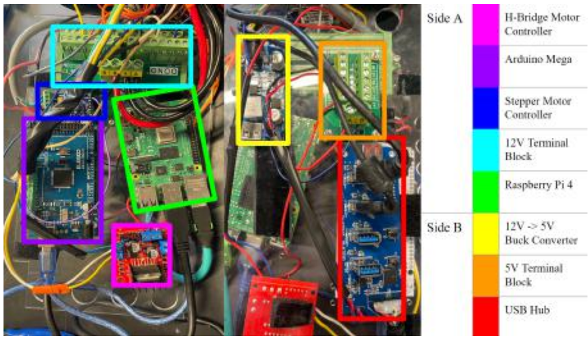

Figure 19: Inside of the Tube: Electronics

Voltage Level Input	Components
48V	24V buck converter 12V buck converter
24V	2x Up/Down Thrusters
12V	4x Directional Thrusters DC Brushless Motor Stepper Motor Linear Actuator Arduino Mega H-bridge Motor Controller
5V	Raspberry Pi 2x Cameras
3.3V	Depth Sensor

Figure 20: Voltage Input of Different Components

Electronics Enclosure Control Flow

Ethernet is used to communicate with the Raspberry Pi 4, which in turn communicates with the Arduino via USB, and with the Depth The Arduino Mega sends PWM signals to the DC Brushless Motor, the Stepper Motor via a stepper controller board, and to each of the six thrusters: four for directional (left/right) control and two for up/down control. The Arduino is also connected to an H-Bridge motor controller to control the analog signals sent to the linear actuator, and a USB Hub to receive signals from the two cameras mounted on the frame.

Signal Type	Components
USB	2x Cameras
Ethernet	Raspberry Pi
PWM	4x Directional Thrusters (yaw) 2x Up/Down Thrusters (roll) Stepper Motors DC Brushless Motor
Analog	Linear Actuator
I2C	Depth Sensor

Figure 21: Signal Type of Different Components

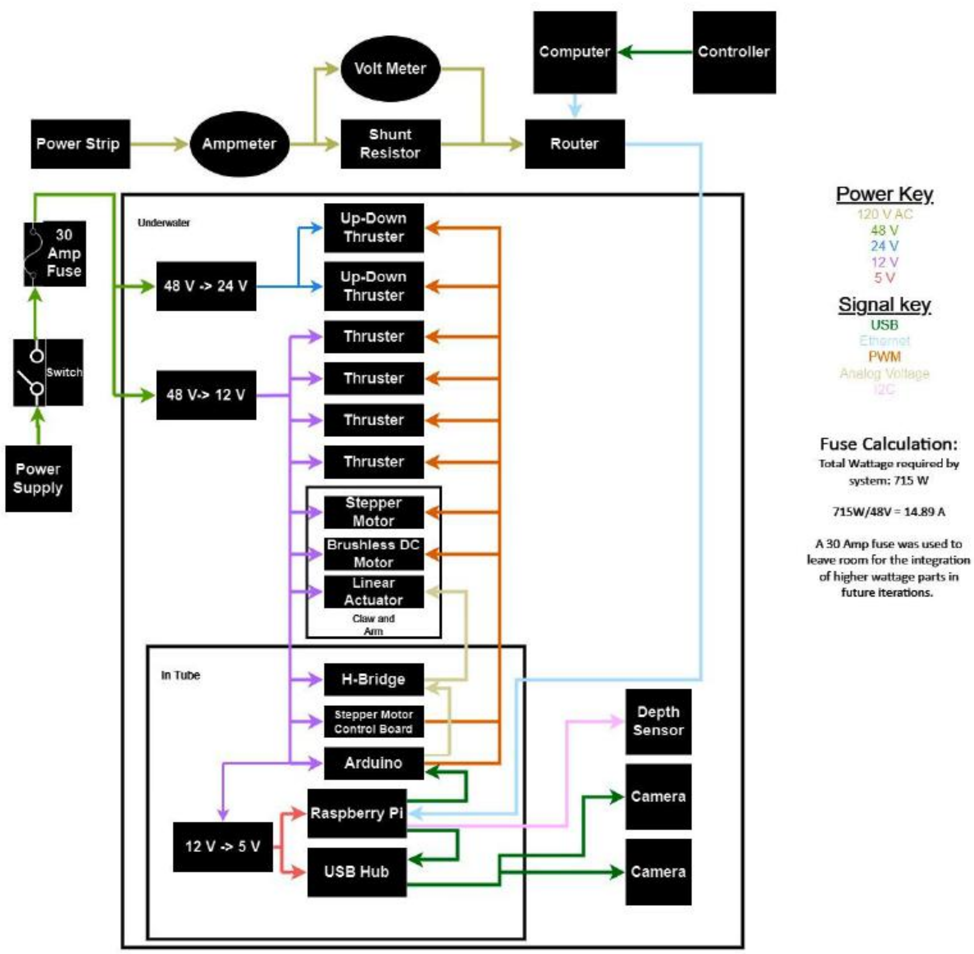

Figure 22: Full System Integration Diagram (SID)

Tether

When designing the tether, our team wanted to be as flexible as possible while being both neutrally buoyant and neat to have minimal impact on flying the ROV. To achieve flexibility, our first step was to minimize the number of wires being sent down through the tether, ending up only needing a single 48V power and ground pair and a single Ethernet cable for signal.

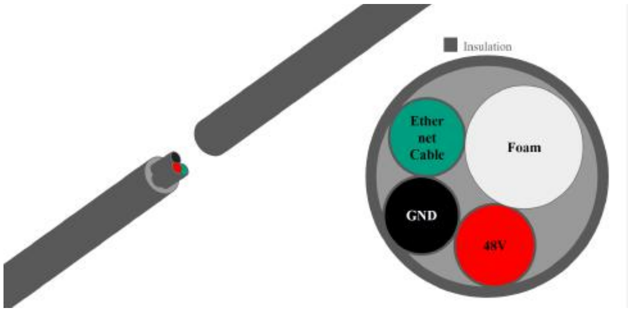

Figure 23: Tether Cross-Section

From there, we wanted to ensure that our wires were as flexible as possible, doing extensive research on the bend radius of Ethernet options and ended up with a cable from our sponsor Automation Direct that beat out all of the competition available. We similarly chose BNTCHGO silicone-jacketed wire for our power and ground wire, which was so flexible that, despite it being a much higher gauge of wire than the Ethernet, it could bend enough that the Ethernet cable was the rate-limiting factor in bend radius. In order to have neutral buoyancy along the length of the tether, we found ¼'' caulk saver foam. It was long enough that it could be fed along the entire length of the tether, offsetting the weight of the wires, and was still extremely flexible.

The tether is relied on to relay all power and communication from the topside controls to the ROV, so minimizing the opportunities for it to be tangled, snagged, or strained was a high priority. To keep everything neat, we used 3/8'' hose sheathing to wrap the entire tether into one easy-to-handle bundle. For topside strain relief, we used a carabiner that clips into our topside control box. For bottom-side strain relief, we use a mesh wire gripper that screws into our ROV's frame to secure the wires and ensure all strain from tether tug is distributed through the more rugged frame. To manage the length of the tether in the pool, a Bayco cable storage reel was used, and the tether was wrapped around it. The handle in the middle and knob on the reel allows it to be held and the cable to be wound or unwound easily.


Figure 24: Tether Strain Relief

Our tether management protocol involves a specially trained employee handling the tether at all times to ensure it is kept in a proper state. Clear communication between the pilot and the tether manager is kept paramount for safety. We also implement a post-use maintenance routine for our tether to ensure its health.

Software

Control System Flow

The software for our control system is implemented using Python3 and utilizes the Pygame package. Pygame allows us to check for activity on either of our two Xbox controllers (framework shown below) using an infinite loop.

Figure 25: ROV Control Scheme

Figure 26: Claw Control Scheme

On the controllers, each of the inputs are categorized as either buttons, axes, or toggles. Axes are used for granular control on things like thrusters. Toggles act as binary variables that enable us to switch between states like an on-off switch. In contrast, buttons can trigger momentary actions until the button is no longer being pressed. If either controller is receiving input on a button, axis, or toggle, a predefined Python dictionary is updated with a corresponding numerical value.

Our control system utilizes a precision variable that controls whether the ROV's speed is multiplied by one of two values: a lower (0.2) or greater factor (1). The lower precision value allows Calypso to move at slower speeds and complete tasks with higher accuracy, while the higher factor supports speed for movements over greater distances.

Last year, control messages from the joystick were used to directly command the ROV's motion. This resulted in overly sensitive motion. We updated our control flow this year to utilize a proportional-integral-derivative (PID) controller which continuously calculates an error value as the difference between the desired velocity received from the joystick state and the computed current velocity and applies a correction function. An infinite PID loop running on a bottom side async server allows for smoother motion and avoids overshooting the desired position, as it ensures that we will not oscillate around, but rather converge to the desired value.

We also utilized a PID controller to implement automatic depth stabilization. Similar to the way it calculates the minor discrepancies between desired and current velocity, the PID controller for our depth sensor calculates these disparities for the desired and current depth and applies them to find a target velocity to correct for these marginal errors in position. This enables Calypso to maintain a set depth, which provides both stability and accuracy. Such functionality is especially relevant when considering that the ROV may not always be perfectly neutrally buoyant. At any point, Calypso is subject to changes in buoyancy caused by the varied porosity of materials on the ROV and in picking up mission items such as the SMART cable repeater. Furthermore, these design choices make Calypso prepared to handle disturbances and waves that would be present in real bodies of water and significantly improve stability in the pool.

This system functions similarly to what you may find in a typical flight controller like ArduRover. These common flight controllers often have years of development behind them, but we decided to implement our own from scratch. Doing so allowed us to tailor it to our own specific needs because it's important to understand the code driving our ROV for debugging and team member skill development.

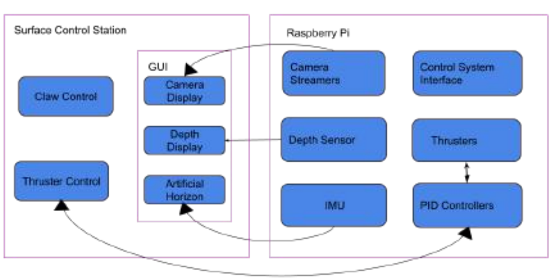

Figure 27: Software Information Flow Diagram

Graphical User Interface (GUI)

Last year, our ROV was equipped with two cameras, which were displayed on two separate web pages. This design required toggling back and forth between the pages and did not display valuable data such as depth, position, velocity, and acceleration. To address these shortcomings, we accounted for two additional cameras on our ROV and updated our GUI (Graphical User Interface) to support all four camera views as well as IMU and depth sensor data. The grid design of our GUI allows us to see every camera view in one place. We also implemented the ability to click on a grid square to toggle a single view to full screen. Additionally, we implemented an artificial horizon utilizing HTML and JavaScript to efficiently and effectively understand the position of our ROV in the pool. The combination of added camera views and position data (including yaw, pitch, and roll) has given us a higher level of precision when maneuvering Calypso from the surface. Our GUI is displayed on a webpage created using Flask, which provides a more accessible framework for us to send data from backend to frontend seamlessly.

Figure 28: Our Graphical User Interface (GUI)

Cameras

Our camera system relays signals through the USB hub to the Raspberry Pi. We chose a slim USB hub model to decrease the footprint within our electronics tube. Additionally, the USB hub allows us to take in and power more cameras than would be possible through only the Raspberry Pi due to its limited ports and power output constraints. This year we are reusing the ExploreHD 3.0 cameras from Deepwater Exploration (a company started by a former MATE competitor). The cameras are rated to 1,300 feet underwater and have preprocessing color correction for underwater environments onboard. They also come with a custom streaming system that helps reduce bandwidth issues. All of these features justified their price tag last year, and continue to pay dividends on Calypso.

Currently, Calypso is equipped with two cameras located on the front of the frame. The first of the two points downwards, giving us a direct view of our claw from above. The second camera points forward, capturing a front-facing view that allows us to see the path ahead clearly. In addition to these two cameras, Calypso is designed to support four cameras, both electrically and in software, and we considered adding another angle. A rearview would display a direct path behind us, or a bottom view would see directly below the ROV to help us perceive depth and aid in tasks that require placing and retrieving mission items from a designated area. However, after carefully considering the level of necessity and tradeoffs mounting more cameras would add, we decided to limit our ROV to two cameras for this year's competition. This choice was made in an effort to mitigate bandwidth and power issues and maximize video streaming quality and efficiency. Valuing consistency and avoiding over-complicating our cameras has allowed us to come away with a design that is both scalable and reliable.

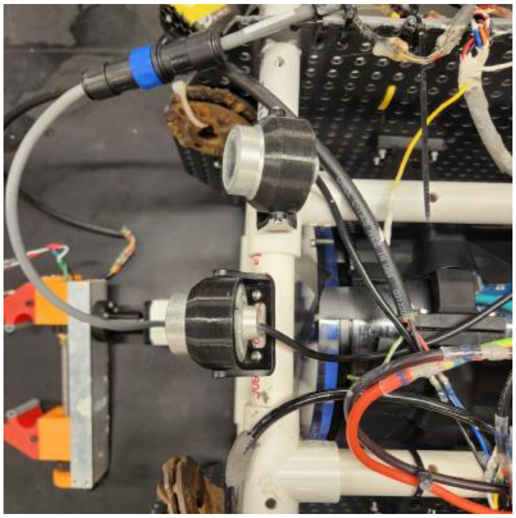

Figure 29: Two Cameras: Forward View on Top, Claw View on Bottom

Payload

Bale Connector

In order to connect to the bale on the multi-function node, the company wanted a solution that required less force than a carabiner. While secure, carabiners require a significant amount of force to open and often slip to either side of the U-Bolt when flying the ROV downwards to connect. To solve this, we built a connector with an inverted V-shape designed to guide the connector onto the U-Bolt. Once attached, it creates a 360° seal that cannot be tugged off, as the U-Bolt has no easy way to force itself back through. For removal, one must open the connector from the bottom and slide off the connector. The structural part of the connector is made out of PVC for easy adjustment, and the flexible part is made from corrugated plastic for the right mixture of strength and bend. The material cost is even cheaper than a carabiner.

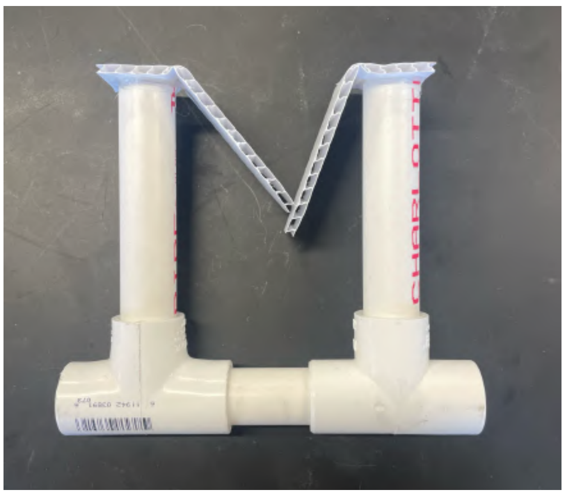

Figure 30: Custom Bale Connector

Arm

In further evaluating the successes and failures of the company's previous design Mariana, issues such as pilot accuracy and reliability were the main focus points in making a new gripper for Calypso. Mariana was equipped with a parallelogram gripper driven by screw gears. While successful, it was difficult for the pilot to gauge where to grab props, as the claw would extend further out when closed. At the same time, the screw gears would often skip, resulting in incomplete closure. To address these issues, Calypso is equipped with a new lead screw parallel gripper to succeed in this year’s tasks. Inspired by the Northeastern Mars Rover Team, a lead screw was chosen to actuate the claw for Calypso due to its small form factor, torque, and precision.

The gripper was designed in Solidworks and consists of two claws: static and dynamic. The static claw, shown on the left, houses the 12V DC driving motor, lead screw coupling, and stainless steel guide rod. It is secured to the U-channel frame with laser-cut panels. The dynamic claw, depicted on the right, has a lead screw nut and negative cut out of the motor, allowing it to go flush when completely closed. These are then housed in a U-channel frame, increasing the structural integrity and strength of the entire gripper. The lead screw and guide rod are constrained in a 3D-printed coupling with radial bearings and shaft collars to maintain concentricity and alignment.

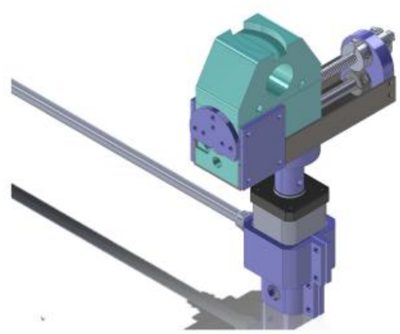

Figure 31: CAD of Claw Design

In order to drive the system the lead screw is coupled to the driving motor by a custom 3D printed part. When actuated, the lead screw nut housed in the dynamic claw threads back and forth opening and closing the claws to a total of four inches. The dynamic claw also houses a linear bearing that runs down the guide rod, constraining the claw and smoothing out lateral motion.

With the new system, fixing one of the claws and switching to a parallel-style gripper, allows the pilot to intuitively interact with objects, as they no longer have to estimate where the claw would grab, and can align with a fixed position. The lead screw is also highly reliable and doesn't skip, resulting in ease of operation and consistent opening and closing at a fast rate. These changes have been very helpful for a wide variety of tasks, as the gripper can now easily take on a wide variety of objects.

Calypso's gripper has also been equipped with its redesigned arm which features 2 additional points of actuation consisting of extension and rotation which each provide key functionality for completing a wide array of tasks.

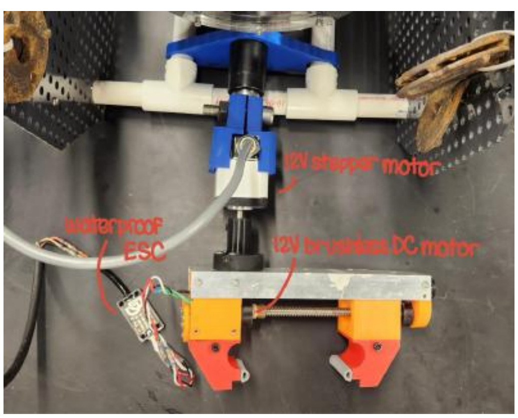

Figure 32: Final Claw

The extension is driven by a linear actuator and allows Calypso to extend the gripper beyond the frame and interact with props not as directly accessible with the ROV. This is especially useful when it comes to the pin for the recovery float, as Calypso can interact from afar and pull it out without needing to fly.

The rotation is driven by a stepper motor and allows for Calypso to rotate the gripper >360° allowing for various ways to interact with props. Depending on the orientation of the handle or PVC, Calypso doesn't have to be as precise in flying, as the gripper can be moved to a more favorable position. The rotation is also needed to activate the irrigation system, and the larger degrees of freedom allow Calypso to freely rotate the knob without fear of tangling.

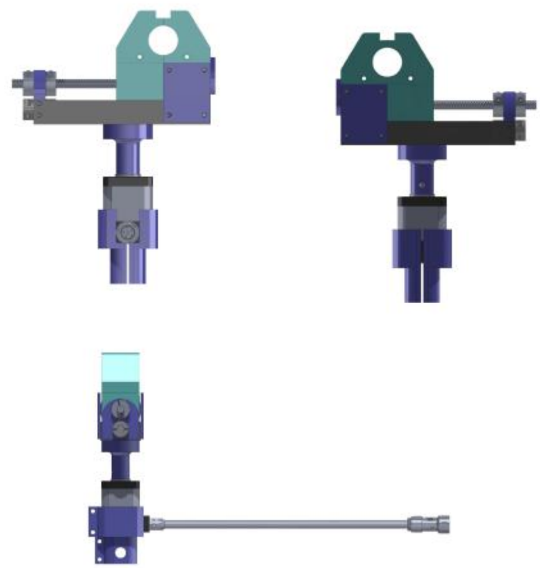

Figure 33: Three Angles of the Claw in CAD

For parts selection, the team needed reliable motors that could continuously rotate, but it initially proved difficult to find affordable waterproof motors that fit the needed specifications. Instead of focusing outwards on the lackluster or pricey options available, the team found ways to cut costs by repurposing what it already had into viable solutions. For the wrist rotation, the team needed a high-torque motor with the ability to turn the whole claw assembly. We found our solution in an IP65 weatherproof stepper motor that the team had used last year in testing an actuating screw design for the arm. IP65 would not be sufficient for pool missions, though, so the team used Loctite Marine Epoxy to seal all the seams on the stepper motor. The wrist rotation motor needed to be lightweight and able to quickly close the claw. The team found a solution when looking at a spare 12V Diamond Dynamics thruster.

Figure 34: Repurposed 12V Diamond Dynamics Thruster

Inside it was a waterproof DC brushless motor that was designed specifically to rotate quickly in water. The linear actuator for extension was the incredibly reliable IP67 model we repurposed from Mariana's elbow rotation to make a vastly improved arm from only re-used motors.

Swappable Claw Heads

Further adding to the applicability of our claw is its modular claw tip changer. With the changing of a single screw per side, Calypso's claw can change between a smaller opening, a larger opening, and a completely flat option. The smaller opening is designed to fit perfectly around the very common ½" PVC pipe props. The larger one is best for picking up things that require a larger margin of error, like the rope for the brain coral and larger PVC props. The flat claw is especially powerful in getting a strong grip on hooks, as it provides a maximum surface area to contact the hook. While it may seem intuitive to hook the claw around a hole in another design, the flat claw has a significantly more reliable release as other hole designs can get caught on the hook, leading to catastrophic consequences.


Figure 35: Swappable Claw Heads

Sensors

The team uses a Blue Robotics Bar02 sensor for both depth and pressure. The sensor was chosen because of its incredibly high resolution of 0.16mm enabling precise automatic depth stabilization. Additionally, it provides a temperature reading that allows us to back Calypso into the zone to validate the

SMART cable sensor readings. Moreover, the team is experimenting with the use of a 9-degree-of-freedom IMU. It can be used to get both speed and acceleration, helping to improve the accuracy of the team's PID loop system. Furthermore, it has roll, pitch, and yaw to give pilots a better understanding of the orientation of the ROV.

Safety

Safety is always NUWave's top priority. In order to ensure that all team members stay safe while working on the ROV, we have numerous safety features implemented on Calypso, as well as for the surrounding environment. Whenever working with any kind of tools or a dangerous substance, such as power tools, epoxy, or solder, proper protective equipment, including goggles, gloves, and masks must be worn. All of our thrusters are properly shrouded in order to ensure that they cannot be touched. Whenever the ROV is powered on, it is vocalized to all present that the ROV is being powered, the fuse is checked to ensure the electronics are protected if anything goes wrong, and the circuit is examined to verify it is set up correctly.

When the ROV is live, there are various safeguards in place to protect team members, the first being waterproofing. All of our wire connections have at least two layers of waterproofing, including waterproof solder sleeves, marine epoxy, and duct seal. There is also a 30A Littelfuse installed within 30 centimeters of our Anderson Powerpole connectors as an additional safety precaution.

When adding a new feature to the robot, we work to test it in stages and go through multiple iterations as a team to find the safest and most effective way to implement that feature. We start by testing functionality dry, then power off the ROV and put it in water to ensure it is watertight. After inspecting it for signs of water, we will test functionality one more time before powering the ROV in the water and testing it in the pool.

While it is extremely important that Calypso is as safe as possible, we also have many safety guidelines that we adhere to in our lab space and by the poolside. Our lab space where we work on the ROV is kept clean, with the walkways clear, especially paths to fire extinguishers and exits. Any objects that end up on the ground, particularly screws and other potentially harmful objects, are immediately picked up and properly disposed of. Whenever tools are being used, such as hot soldering irons, or drills, it is made sure that other people working in that space are aware, and are a safe distance away. When working poolside, we ensure that everyone wears proper footwear to minimize the chance of slipping, and team members move slowly when transporting the ROV.

One of the most important safety tools that NUWave utilizes is communication. While completing any tasks, we talk through each step we are completing, especially when opening and closing the claw. We have also implemented an Observation Program, to make certain all team members know to speak up if they feel uncomfortable, or if they feel something being done could be unsafe. We ensure that team members' concerns are heard and properly addressed. In doing so, we proactively prevent incidents before they occur and find places where our safety can be improved.

1. Ensure that there are no sharp objects on or surrounding the ROV.
2. Make sure there are no conductible objects or fluids in, on, or surrounding the ROV.
3. Check that all wires are properly secured, insulated, and waterproofed.
4. Verify all motor connections, coverings, and mounts are properly secured.
5. Check the tether to ensure it is not knotted, and that there are no issues regarding tether strain.
6. Make sure the robotic arm is safely attached to the robot and fully secured.
7. Ensure that the ROV frame is secure and that there are no loose connections.
8. Communicate with team members operating the vehicle, as well as anyone in proximity, to verify they are attentive and clear of the ROV.
9. Check the fuses to make sure they are not blown.
10. Double-check all pressure vessels on the ROV to ensure they are fully sealed.
11. Verify that all electronics are on and running as expected.
12. Control the tether as the ROV enters the water to make sure it is not a tripping hazard and that no one will step on it.

Critical Analysis

NUWave does significant stress testing to ensure the quality of its parts. In 2023, the team had the claw servo fail during the second mission run and was forced to complete the competition clawless. To solve this, the team took a series of servos waterproof servos and put them through a rigorous testing cycle, testing both repeated high-weight testing and significant periods of time in water (Figure 28).

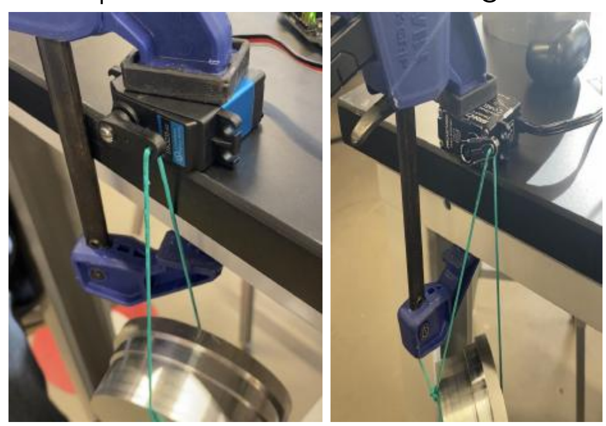

Figure 36: Load Testing a 35kg servo (left) and a 70kg servo (right)

	Hitec HS-646WP	Sincecam	Wishiot	9iMod	Zoskay
Stated Torque (kg/cm)	11.6	70	60	55	35
Initial Rotation	Yes	Yes	Yes	Yes	Yes
Weight Stress Testing	No	Yes	Yes	Yes	No
Sink Pressure Testing	Yes	Yes	Yes	Yes	No
Week Long Submersion	No	Yes	No	No	No
Post-Water Rotation	Yes	Yes	Yes	No	No
Post-Water Weight Stress Testing	No	Yes	No	No	No

Figure 37: Evaluating Servo Testing

When testing Calypso, employees follow a very strict policy to ensure that all facets of the ROV are watertight and operational before beginning a mission after any change. First, we run all systems dry to ensure base functionality. Then the ROV is powered off and placed at the bottom of the pool for 15 minutes to ensure it is watertight. Once it is returned to the surface, all connectors and pass-throughs are thoroughly inspected for any signs of water. A second dry systems test is then performed to ensure that exposure to water didn't cause any damage not visible to employees. Finally, after all of those checks have passed, can a new configuration of Calypso begin attempting its missions for the day.

Following any pool test, initial debriefs are held to discuss initial thoughts on what worked well, and what needs improvement. A deeper debrief is then held at the team's general meeting with a focus on discussing deeper questions about what the results of the test mean for the ROV and how the team should proceed given these results. From there, work is delegated from the COE to subteam leads, and then from subteam leads to individual members for further progress.

All aspects of Calypso are designed with serviceability in mind, and that provides incredible value when troubleshooting. When a problem arises, the team is able to rapidly isolate the problem into a small subsection of the ROV by disconnecting and testing individual subcomponents. Once the location of a problem is found, the team can take that subcomponent and either attempt to fix it, or replace it and continue testing.

The area that has perhaps benefitted the most from this is the connector pipeline. The team decided on 8-pin connectors for the thrusters and motors to minimize the number of connectors that needed to be purchased. While this was good from a budget perspective, it introduces a very difficult-to-decipher issue: noise. In order to fit eight wires into the back of the connector and carry all of the power needed, the team chose a minimally shielded 8-wire cable. Some of those cables carried 24V power and the signal for vertical thrusters. The team noticed issues when trying to fly up from the bottom of the pool, as one thruster would start up much faster than the other, causing the ROV to roll into undesirable positions. While it would make sense for this to be a software issue, an issue with the thruster itself, or a connectivity issue, the team was able to rule out all of those options efficiently by disconnecting the connector and checking all of these possibilities. From there, the team was able to insert a new pass-through with a more shielded cable for the slower vertical thruster and solve the issue. This philosophy of assessing, isolating, and solving is used in all of our troubleshooting.

Accounting

As explained in the Design Philosophy section of this document, this team doesn't have a typical budget provided by the school. Instead, we get all of our funding for parts from research grants. This means before allocating a budget towards the things we need most, we have to prioritize what we need most and secure funding for it. The team has had great success in that regard, bringing in seven grants over the past two years, of which a percentage goes towards ROV-related purchases. While not having a discretionary funding pool to pull from is a drawback in some ways, it's a bonus in others as it requires every subsystem of the ROV that a member wants to improve to have a detailed proposal with a timetable and budget prior to getting approved. After receiving a grant, purchases are requested by each subsystem submitting bimonthly bills of materials (BOMs). Those BOMs are then approved by the CFO and purchased for use. As for travel, the team spent $2,820 on hotels for members and is planning on driving up to Kingsport an estimated 838 miles / 30mpg * 3 cars * $3.5 per gallon = $293.30. To account for potential stops along the way we are setting a $400 budget for gas. All meals will be paid for by employees. As a team, we have received support in the form of parts donations from Automation Direct, Igus, and Dakota Lithium. All in-kind donations are tracked in a spreadsheet and sponsors are regularly given update emails.

NUWave Budget 2023-2024				Reporting Period	
School Name:	Northeastern University		Start Date	09/01/2023	
Mentor:	Dr. Tom Consi		End Date	06/30/2024	
Income					
Source		Initial Amount	\mount Allocated to ROV 2024		* = from previous s
PEAK ROV Arm Grant*		$3,000.00	$1,000		
PEAK ROV Frame Grant*		$1,500.00	$500		
PEAK ROV Control System Grant*		$610.00	$610		
PEAK ROV Electronics Tube Grant*		$1,500.00	$300		
PEAK Soft Robotics Gripper		$1,500.00	$500		
PEAK Buoyancy Controlled Float*		$500.00	$500		
PEAK LiFi Communication		$1,311.00	$500		
ANSE PEP Team Support Funding		$2,000.00	$2,000.00		
Schmidt Ocean Coalition 2024 Travel Stipend Award		$2,000.00	$2,000.00		
Total		$13,921.00	$7,910.00		
Expenses					
Category	**Type**	**Description**	Projected Cost	Amount Spent	Flux
Onboarding	Purchased	PVC pipe, electronics for controls and tether, motors and waterproofing and thrusters for our Waveperch onboarding project.	$350.00	$281.55	$68.45
	Donated	Batteries for the Waveperches	$99.00	-	
Internal Electronics	Purchased	Spares for accelerted development and servicability	$500.00	$130.22	$369.78
	Re-Used	All boards from last year were reused	$178.14	-	
External Electronics	Purchased	Connectors and wiring primarily	$500.00	$359.28	$140.72
	Re-Used	Thrusters, motors, actuators and converters	$1,181.94	-	
	Donated	Ethernet Cable Automation Direct	$66.00	-	
Arm	Purchased	U-Channel, Leads Screw + Lead Screw nuts	$500.00	$212.21	$287.79
	Re-Used	Creative re-use of linear actuator, Stepper and thruster	$454.00	-	
Frame	Purchased	PVC and Perf Board	$500.00	$248.52	$251.48
Sensors	Purchased	Depth Sensor + IMU	$200.00	$99.99	$100.01
Travel	Purchased	Hotels, Gas, (not all spent)	$3,500.00	$2,820.00	$680.00
Registration + Fluid Power Quiz	Purchased	Registration + Fluid Power Quiz	$475.00	$475.00	$0.00
Hardware	Purchased	Sealants, 3D Printer Filament and Hardware for ROV	$1,000.00	$599.89	$400.11
	Re-Used	Blue Robotics 6" Tube was reused	$329.14	-	
Buoyancy Controlled Float	Purchased	All materials for our Buoyancy Controlled Float	$500.00	$409.93	$90.07
Total				$5,636.59	$2,388.41

Figure 38: NUWave Budget

NUWave Budget 2023-2024				Reporting Period			
School Name:	Northeastern University		Start Date	09/01/2023			
Mentor:	Dr. Tom Consi		End Date	06/30/2024			
Date	Type	Category	Expense	Description	Notes	Amout	Running Balance
8/30	Income	External Electronics	LiFi Communication Grant	Some funding used for the elctronics tube. Additionally some parts are usable once research is conducted.	This research was presented at an undergraduate poster session this April.	$500.00	-500
9/16	Purchased	Onboarding	Onboarding Materials	PVC, thruster materials and more as a base kit for teams to start with	Used in our Waveperch program	$281.55	-$218.45
9/16	Parts-Donated	Onboarding	Onboarding Batteries	Lightweight 12V batteries form Dakota Lithium	Used in our Waveperch program	$99.00	-$119.45
10/3	Reused	External Electronics	Thrusters	4 TD1.2 12V Thrusters and 2 TD7 24V thrusters	Used for propulsion	$575.98	$456.53
10/3	Reused	External Electronics	DC to DC Converters	IP67 Golf cart converters to 24V and 12V	Used in external electronics	$45.98	$502.51
10/3	Reused	External Electronics	Cameras	2 Deepwater Exploration ExploreHD 3.0 Cameras	Used in external electronics	$559.98	$1,062.49
10/3	Reused	Harware	Blue Robotics 6" Tube	6" Acrylic tube with passthroughs for the ROV	Used to house electronics	$329.14	$1,391.63
10/3	Reused	Internal Electronics	Internal Boards and Terminal Blocks	Raspberry Pi 4 8GB, Arduino Mega, H-Bridge, Stepper motor driver board, 2 terminal blocks + USB Hub	Used inside of electronics tube	$178.14	$1,569.77
10/15	Purchased	Hardware	PLA and PETG Filament	A full supply of 3D printer filament for the year.	Used in Frame, arm and static devices	$300.00	$1,869.77
10/15	Purchased	Arm	Claw + Arm Supplies	Waterproof servos for stress testing	Used for arm	$169.96	$2,039.73
11/1	Purchased	Sensors	Depth Sensor + IMU	Precise sensor for finding depth and IMU for position/orientation information	Used in electronics tube	$99.99	$2,139.72
11/9	Parts-Donated	External Electronics	50ft Ethernet Cable	Flexible ethernet cable	Used in tether	$66.00	$2,205.72
11/9	Purchased	External Electronics	50ft 10AWG cable	Flexible power and ground cable	Used in tether	$71.99	$2,277.71
11/9	Purchased	External Electronics	Bulgin Male Connector	To match our existing connector for power	Used as a connector	$43.11	$2,320.82
11/9	Purchased	Arm	Claw + Arm Supplies	U-Channel, Leads Screw + Lead Screw nuts	Used in Arm	$42.25	$2,363.07
11/9	Reused	Arm	Claw + Arm Reused	Stepper Motors + Linear Actuator + Repurposed Thruster	Used in Arm	$454.00	$2,817.07
11/30	Purchased	Float	Blue Robotics 6" Tube	6" Acrylic tube with passthroughs for the BCF	Used in Float as main structure	$329.14	$3,146.21
11/30	Purchased	External Electronics	Bulgin 8 Pin Connectors + Crimper + Waterproof T-Splices	Used to make waterproof connections for thrusters and motors	Used in ROV Electronics	$244.18	$3,390.39
11/30	Purchased	Internal Electronics	Spare Components and Wire	Spare internal board to allow software to develop while everything is built	Used in the Electronics Tube	$130.22	$3,520.61
12/4	Income	Hardware	Grant for testing Soft Robotics Grippers	The research here went towards deciding on a claw design. $500 went to the ROV.	Used in Arm	$500.00	$3,520.61
12/4	Purchased	Float	Board and hardware for internals	ESP32s, radios, limit switches, and motor drivers	Used in Float	$80.79	$3,601.40
1/14	Purchased	Frame	PVC Perf Board	Perforated PVC sheets of varying porousity	Various levels of perferation in PVC sheets used to tests the optimal balance of weight and structure	$149.99	$3,751.39
1/14	Purchased	Frame	Tools an supporting materials for frame building	Punch tools, PVC, and heat set inserts for the frame	Used in Frame	$98.53	$3,849.92
02/03	Purchased	Hardware	Materials for all props needed to qualify for the competition as well as photogramettry	PVC, the brass fitting for the irrigation system, U-Bolts and Rope.	Used in props	$142.98	$3,992.90
03/23	Purchased	Hardware	Waterproofing supplies	Waterproof solder sleeves, marine grade epoxies, and sealants	Used to seal passthroughs	$82.25	$4,075.15
04/22	Purchased	Registration	Registration + Fluid Power Quiz	Registration + Fluid Power Quiz	-	$475.00	$4,550.15
05/07	Purchased	Hardware	Cleaning Up ROV Manufacturing	Epoxy for further sealant and zip ties for external wire management, smaller syringes for buoyancy, Kapton Tape and Strain relief	Sealing + Securing connectors	$74.66	$4,624.81
05/14	Purchased	Travel	Hotels	4 hotel rooms for the team	Travel	$2,820.00	$7,444.81
05/17	Income	Travel	MATE Scholarship	Schmidt Ocean Coalition 2024 Travel Stipend Award	Thank you so much!	$2,000.00	$5,944.81
					Total Spent	$5,636.59	
					Total Reused	$2,143.22	
					Total Donated Parts	$165.00	
					Total Income	$3,000.00	

Figure 39: NUWave Project Costing

Acknowledgments

Dr. Tom Consi (Mentor/Faculty Advisor): For meeting with our CEO every week and helping to guide the team towards success while letting us learn from our own mistakes.

Paul McGuinness: For inspiring the passion for underwater robotics that made this team possible.

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Igus: For their donation of wire.

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Tawni Gott: For once again supporting us in making the hotel booking process easier.

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Dr. Andrew Bennett: For allowing us to test at MIT Sea Grant and for helping us out when we needed supplies for immediate repairs.

MATE: For hosting the competition and allowing us to compete.

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