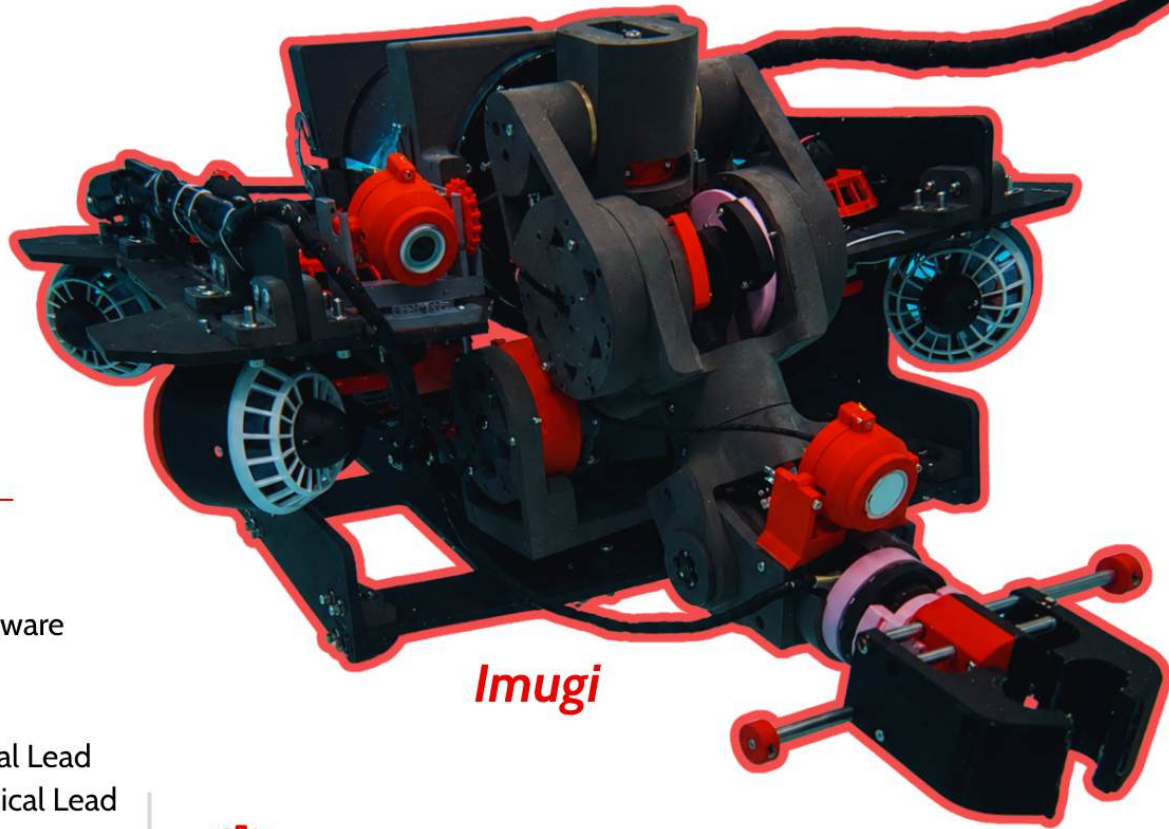




NUWave 2026

Technical Documentation

Northeastern University
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Table of Contents

Teamwork.....	3	Safety.....	17
Company Profile.....	3	Safety Rationale.....	17
Project Management.....	3	Safety Features.....	17
Design Rationale.....	4	Safety Procedures.....	18
Design Process.....	4	Critical Analysis.....	18
Design Overview.....	5	Testing and Troubleshooting.....	18
Systems Approach.....	5	Prototyping.....	19
Vehicle Structure.....	6	Accounting.....	20
Vehicle Systems.....	6	Budget and Cost Accounting.....	20
Electrical System.....	10	Build vs. Buy, New vs. Used.....	20
Control System.....	13		
Propulsion.....	14		
Buoyancy and Ballast.....	15		
Payload and Tools.....	15		

Abstract

Climate change is damaging marine ecosystems at an unprecedented pace that demands equally rapid advances in marine technology. Designed to meet that challenge and the call of the MATE Request for Proposals (RFP), NUWave proudly presents Imugi, an underwater Remotely Operated Vehicle (ROV). Imugi is designed to withstand adverse conditions while replacing eDNA sensors, capturing 3D models, carefully collecting coral species, and installing power connectors. With four years of experience engineering marine robots, from ROVs and Buoyancy-Controlled Floats (BCFs), to electric-powered Unmanned Surface Vehicles (USVs), NUWave is an interdisciplinary team of 30 undergraduate marine scientists, software developers, and engineers working to deliver high-quality products to tackle complex marine challenges.

Imugi is NUWave's fourth-generation ROV features a brand new frame, 5-DOF arm, new PCB, and full software stack migration. The following document explains the engineering process behind Imugi, from our team philosophy to design decisions, testing, and more.

Teamwork

Company Profile

NUWave is a marine robotics company based at Northeastern University in Boston, MA. With 30 employees, including 10 new ones, NUWave continues to grow, taking on ambitious projects such as autonomous surface vehicles and remote deployment systems, all while educating the next generation of great marine roboticists.



Figure 1: NUWave's secondary surface vehicle project

However, NUWave's main focus has been on our fourth-generation ROV, Imugi.

In order to facilitate the design and construction of this ROV, NUWave has a leadership team, which can be seen below in Figure 2.



Figure 2: The leadership team of NUWave

The Chief Executive Officers oversee the Software, Mechanical, Electrical, and Float Leads, ensuring that each of the disciplines stays on track and managing these interdisciplinary teams to create a cohesive and effective product. The Software, Mechanical, Electrical, and Float Leads each manage the employees on their subteams, delegating tasks to ensure that desired outcomes are achieved efficiently and meet or exceed our quality standards. Finally, the Chief Safety Officer ensures that everyone follows safety protocols at

all times. Each subteam meets separately once a week and attends a company-wide meeting once a week. The company-wide meetings start with each of the leads sharing their subteam's updates to ensure the whole company can effectively collaborate. This interdisciplinary coordination allows for the creation of an ROV and float that excel at the tasks outlined by the MATE organization.

Project Management

Schedule

NUWave begins each season with a six-week onboarding program for new members where employees are split into three teams, composed of new and existing members. Each team is then tasked with creating a small-scale ROV called a WavePerch using PVC, propellers, motors, and any static devices they want to create or 3D print. Each week, a small lesson is taught on important skills, including part specification, waterproofing, and soldering. This aligns with NUWave's "teach first, do second" mentality, where we believe in making slightly slower progress for the benefit of building our members up to be stronger engineers for the future.



Figure 3: A team working on a WavePerch

During these six weeks, the company also works on the planning stage of development, where we decide on what we believe will make the ROV most successful, taking into account the specific tasks the vehicle will be designed to accomplish and researching the best materials and practices for each aspect of the robot. While

it is more work to run the onboarding and planning phases at the same time, it's worth it to get our new members interested and up to speed so we can be more efficient during the iteration phase, as this is often where we learn the most. It also gives our new members the chance to immediately start applying the skills they learn once they complete the WavePerch program. Throughout the iteration phase, the company improves on our designs by testing different ideas from the design phase and building on what is learned from each prototype. After many iterations of our subsystems, an ROV design is finalized, at which point we begin to practice in the pool. The exact timeline of these phases can be seen in Figure 4 below.

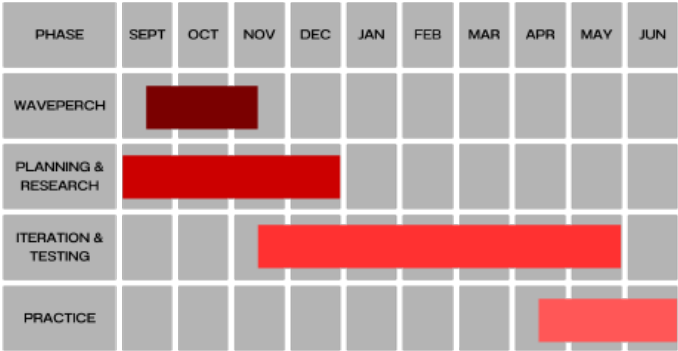


Figure 4: The timeline of phases for NUWave

Resources

NUWave utilizes shared resources to ensure that information from previous years remains accessible. We use Google Drive to store and share team files, Outlook for external communication, and Discord for internal communication. Our Discord includes channels for each subteam, as well as a channel for company-wide updates and questions. Before each subteam and general meeting, an agenda with specific tasks is sent by the corresponding lead so everyone enters with goals in mind.

SolidWorks is utilized for our computer aided design (CAD), alongside Product Data Management (PDM), which allows for easy sharing of and collaboration on CAD designs. KiCAD is used for electrical PCB design. NUWave’s

software is developed and hosted in an open-source Github repository, where GitHub Issues track bugs and feature requests.

Design Rationale

Design Process

Since our founding in 2021, we have continued to hold ourselves to our core design pillars of extensibility, serviceability, and precision. With our ambition to learn, innovate, and explore, we strive to create a world-class ROV that pushes technical boundaries while being competitively successful.

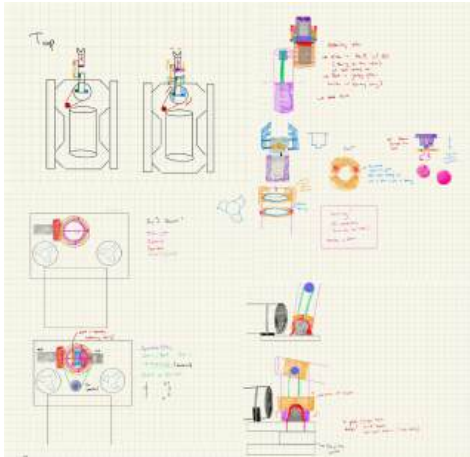


Figure 5: Initial Brainstorming for the 2026 Season

Ideation for the 2026 season started days after the 2025 World Championship. Starting with sketches, a collaborative brainstorm, and a stroke of inspiration, we began conceptualizing an arm and an overhaul of the ROV. Due to the complexity and interdisciplinary aspects of the project, all subteam leads, project leads, and employees discussed the power requirements, software constraints, and mechanical designs from the beginning. This unity systematically and effectively ensured proper integration.

Simultaneously, we enacted our ideology of MVP (Minimal Viable Product) first for rapid iteration and testing. Having made extensive ROV changes each year since our founding, we consistently push to have a minimal working prototype as soon as possible in the design cycle.

Design Overview

Imugi is NUWave's most ambitious ROV yet. Building on knowledge from previous years, Imugi features a durable frame, easily accessible electronics tube, and a 5-DOF robotic arm. The vehicle's eight Blue Robotics thrusters allow for roll, pitch, and yaw control, as well as strafing and movement forward, backward, up, and down. This range of motion allows us to position the vehicle in any way needed to accomplish a task and will be particularly helpful at this year's competition, where we will need to fight against waves and currents.

Meanwhile, the 5-DOF arm provides greater control, ideal for tasks like collecting coral by the substrate only (1.1), attaching a recovery line to the buoy anchor (2.4), connecting the new eDNA sensor to the Holyrood subsea observatory (2.5), and installing the power connector into the oil platform port (3.2). These tasks involve grabbing or interacting with a small target, making the precise movement of our arm ideal.

Imugi is equipped with four cameras: two front-facing cameras, a claw camera at the end of the arm, and a downward-facing camera. These positions allow our pilots to fly Imugi with ease while also assisting in tasks like coral garden ridge modelling (1.2), maintaining position over the coral garden (1.3), and counting European Green crabs (2.1).

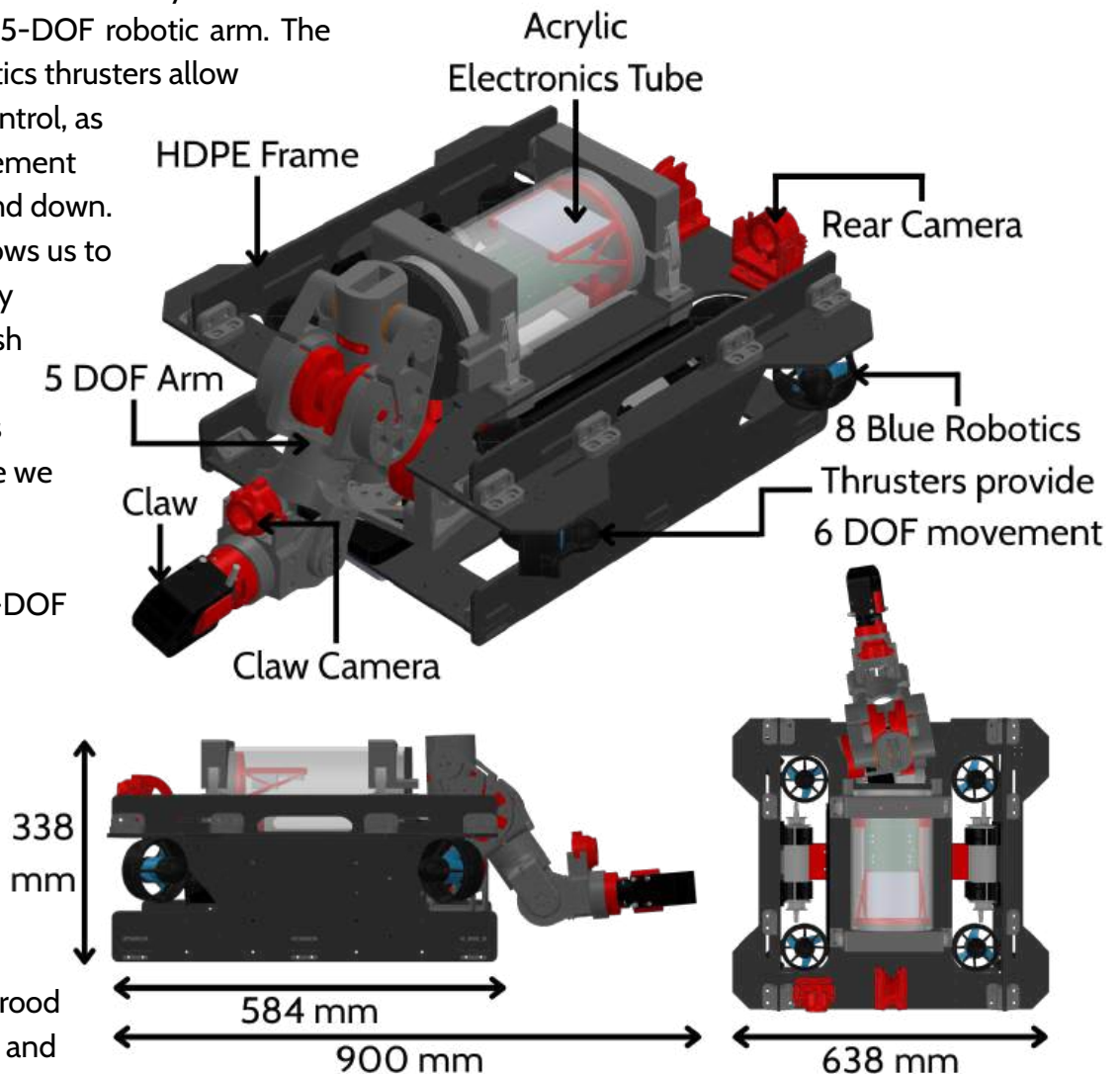


Figure 6: The CAD of the ROV, Imugi

Systems Approach

Every subsystem of this ROV was designed through a collaborative, cross-functional process. Before any decision was finalized, all subteam leads reviewed it together and conducted thorough research to understand its effects on the vehicle as a whole.

A clear example of this integration is the arm. Its power implications were carefully weighed against the ROV's strict overall power budget, and arm controls were developed in close coordination with the software team to ensure

seamless operation. The entire vehicle-level design follows the same philosophy.

On the software side, the team recognized that last year's Python threading was insufficient for the application's demands and transitioned to ROS 2, a framework built specifically for robotic systems. This change drove a parallel decision on the electrical side to integrate a more capable bottomside computer to support four simultaneous camera streams for the pilots. Mechanical, meanwhile, undertook a full frame redesign that required them to plan and integrate all necessary external wiring into their design from the start, as well as take ownership of the arm.

The result is a vehicle where no subsystem was designed in isolation. Each team's constraints and requirements shaped the others, producing a cohesive, well-integrated system.

Vehicle Structure

Our ROV prioritizes robustness, modularity, and precision, all while remaining cost-effective and environmentally conscious. Imugi is designed to withstand the physical demands of underwater environments. Tasked with a current tank and a wave pool, the ROV needs to be strong enough to resist external forces while minimizing the need for manual pilot correction. Additionally, the 5-DOF arm adds size and weight that had to be carefully managed and balanced across the frame. With the performance benefits of adding a fully electric arm and gripper outweighing the added complexity, Imugi is designed to be as compact as possible while maintaining stability and reliability at all times, regardless of the environment. While the arm adds weight, the ROV is still able to be lifted in and out of the pool by two poolside operators without any assistance from deployment devices.

Material	Acrylic (previous year)	Recycled HDPE (selected)
Bouyancy	Negative	Positive
Toughness	Low	Medium
Manufacturing	Laser Cut	Waterjet or Router
Relative cost	\$\$	\$
Sustainability	Low	High- Fully recycled
Additional buoyancy needed	High	Minimal

Figure 7: Frame Material Comparison Analysis

Vehicle Systems

Most of our structural 3D prints are SLS nylon, donated and fabricated by Formlabs. As shown in Figure 8, SLS was selected over FDM and SLA for its high water ingress resistance, isotropic strength, and ability to produce complex geometry without support structures. Compared to SLA, SLS provides similar strength at a reduced weight, and unlike FDM, it is not susceptible to significant water absorption, which can disrupt buoyancy and balance over time.

Property	FDM	SLA	SLS (Selected)
Water ingress resistance	Poor	Excellent	Excellent
Weight	Light	Moderate	Moderate
Isotropic strength	No	Yes	Yes
Support structures needed	Yes	Yes	No
Complex geometry	Limited	Moderate	Excellent

Figure 8: 3D printing process comparison

All frame mounting is standardized to common hardware across the ROV to maximize serviceability and allow components to be replaced quickly at poolside if necessary.

The main electronics enclosure is a six-inch diameter Blue Robotics acrylic tube, selected for its proven sealing performance, clear appearance for easy electronics inspection, and compatibility with the Blue Robotics passthrough and endcap ecosystem. Electronics are supported on 3D-printed standoffs to derisk any potential water ingress. The enclosure is capped with two aluminum endcaps with passthroughs on either end to maximize wire routing and minimize excess cabling, as well as providing a thermal pathway for additional cooling. The tube is mounted in the center of the ROV on the upper side, as it acts as the primary source of ballast. The mounting location provides stability by moving the center of buoyancy above the center of gravity to prevent any unintentional roll.

Two two-inch Blue Robotics aluminum enclosures are also used for additional electronics housing, storing the motor controllers for each arm actuator. They are placed parallel to the main enclosure on both the port and starboard sides to maintain stability and symmetry. These add additional ballast, offsetting the weight of the arm, and declutter the main electronics tube. Being completely aluminum, they act as large thermal pathways for cooling and eliminate the fear of overpressurizing the o-rings internally.

Frame

This year, our frame is made of marine-grade recycled HDPE, rather than the acrylic used in previous years. Found to be more resilient to loading and positively buoyant, HDPE provides increased stability, structural strength, and reduced reliance on supplemental buoyancy devices. The decision to pivot to recycled HDPE also highlights NUWave's commitment to sustainable materials, all without sacrificing

performance. Furthermore, HDPE was one of the more cost-effective options available, with recycled stock being significantly cheaper than brand-new acrylic or aluminum alternatives.



Figure 9: ROV Assembly

To accommodate the size and weight of our new 5DOF arm, the frame has increased in size from previous years. While our dimensions have changed, we have retained our plate-based design. The frame consists of four plates (Top, Bottom, Port, and Starboard). The port and starboard plates are identical and mounted vertically, reducing manufacturing complexity and increasing serviceability. These plates also house the vertical thrusters and buoyancy syringes. The top and bottom plates are mounted horizontally. The top plate houses the lateral thrusters and the electronics tube, strain relief, and wiring, while the bottom plate adds structural reinforcement and mounting for the arm.

To secure the plates together, we utilize SLS printed gussets, tabs, and slot joints. The Port and Starboard plates also exhibit a slotting feature, allowing them to be placed into the top plate without the need for additional cuts or fasteners and increasing overall strength.

With the increased size, we also added enlarged cutouts to minimize drag. The frame is intentionally cut to allow for proper flow.

Ultimately, the frame is designed to maximize performance while minimizing cost, weight, and environmental impact.

Arm

The arm represents the largest mechanical design change from last year. Inspired by Alvin and the push to innovate, the ROV is equipped

with a complete 5 DOF (Degree of Freedom) electric arm. While most work-grade ROVs utilize hydraulic and fluid power for control, NUWave has opted to be fully electric to chase novel ideas and simplify topside requirements.



Figure 10: Initial Assembly of the Arm

With the addition of five degrees of freedom, the ROV has a significantly larger work space and more precise control of props. The arm removes reliance on the main ROV pilot by allowing the arm operator to perform fine control while the ROV pilot focuses on macro control.

Each DOF of the arm is driven by a custom cycloidal actuator. A cycloidal actuator works by driving an eccentric input shaft that causes the cycloidal disk to rotate by one lobe (similar to a large gear tooth) per input rotation, allowing for large and customizable ratios in a small footprint.

These actuators are known for their low backlash and nonbackdrivability. This allows the arm to hold position even without power and have precise control without slop and lost degrees of motion. Compared to other gear trains, a cycloidal actuator had the best packaging, reduction ratio, non-backdrivability, and ease of manufacturing. While a harmonic has similar performance, it is harder to manufacture due to the wave generator. Planetary gears also need multiple stages to achieve a similar reduction, can be back-driven, and their footprint can't be customized.

The cycloidal gearbox has the outrunner motor itself as the input shaft, making the actuator wider but greatly decreasing the total height of the gearbox. As a result, we have a compact pancake-like actuator with a built-in motor. We experimented with a two-stage 11:1 per stage reduction as well as a three-stage 9:1 per stage reduction (totaling in 121:1 or 729:1). The high gear ratio within a very small footprint is ideal for our low-torque motor constrained to a small form factor arm.

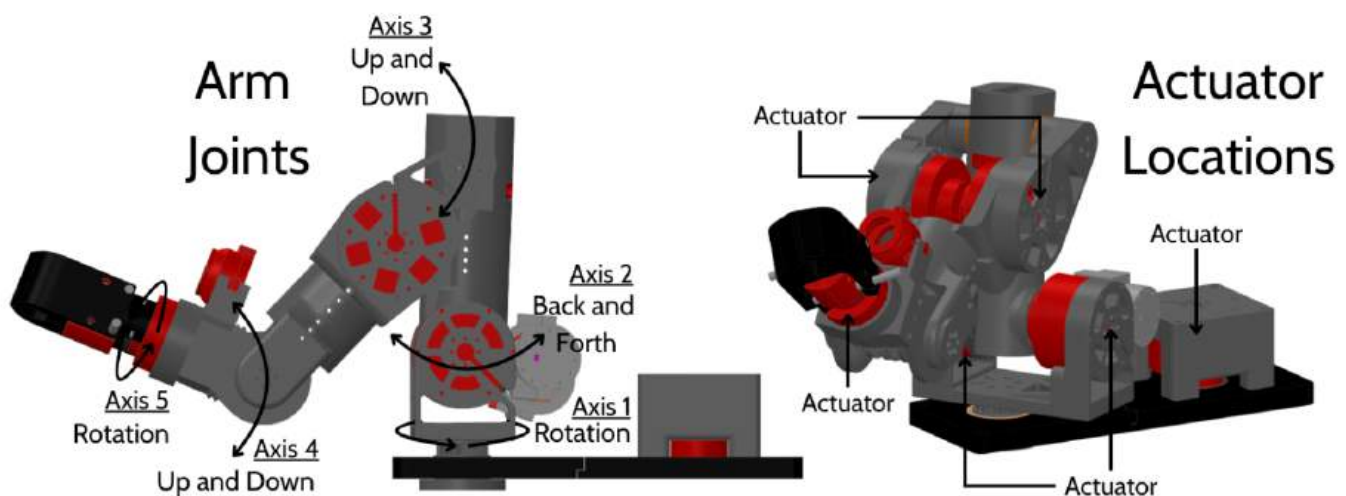


Figure 11: Full Arm Assembly

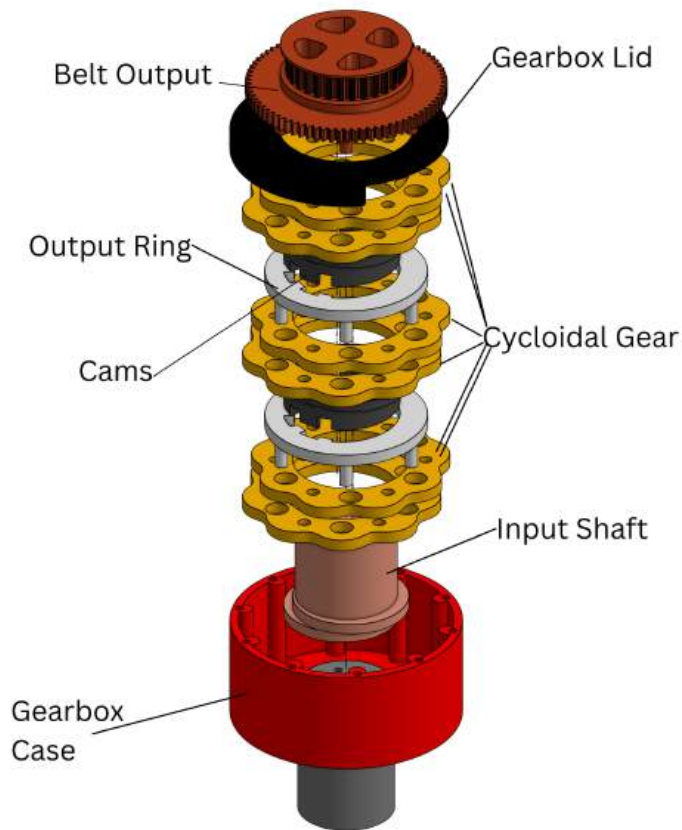


Figure 12: Cycloidal Gearbox Exploded View

Each cycloidal actuator is driven by a Diamond Dynamics DD3130 motor, selected for low KV (high torque per amp), compact form factor, low cost, and native IP68 waterproofing that eliminates the need for custom sealed housings. Additionally, the actuators have their own magnetic encoders. The use of sensorless control is perfect for an ROV thruster application due to the low load at start-up and the lack of



Figure 13: Front View of Arm in Use

position control needed. For an actuator, low-speed commutation and position control are required, especially under load, so magnetic encoders paired with VESC motor controllers make up this need for control.

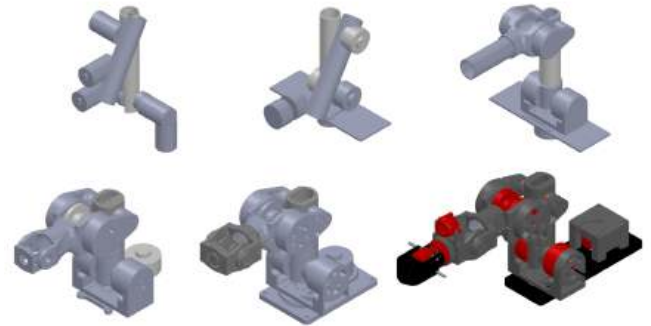


Figure 14: 5 DOF Arm Development

The location and driving method of each actuator are specifically chosen. The turret (Ax1) is belt-driven with the motor pushed toward the aft end of the ROV, giving it further range of motion without self-intersection while also shifting weight away from the fore end, which is already heavier due to the location of the arm. The shoulder (Ax2) and elbow (Ax3) are placed next to each other at the base, eliminating strain on the arm and other joints by removing the need to lift their own actuators during operation. The shoulder is directly driven while the elbow uses a remote transmission virtual four-bar linkage, allowing the load to sit on a smaller moment arm and therefore achieve higher lifting capacity and decrease power consumption. Axes four and five are coupled in a differential to provide pitch and roll control in a condensed form factor. They are also belt-driven to limit strain by keeping the actuators closer to the base. The differential allows both motors to sit closer together, away from the end of the arm, while enabling more complete movement and control.

Claw

This year, we opted for a parallel gripper design that differs from our previous design. Last year, we chose a design that kept one claw static

while the other was dynamic, creating an offset design. This year, both sides are dynamic and move symmetrically. This design is beneficial as it significantly minimizes the footprint of the gripper and keeps forces balanced.

The gripper is attached to the differential on the arm, providing a significant range of motion in both pitch and roll control. The base of the differential is a helical gear, which is then attached to the coupler with an M4 bolt. This wrist coupler mounts both the gripper motor and cycloidal gearbox. This gearbox functions identically to the previously mentioned cycloidal gearboxes; this one is smaller and is only a 10:1 reduction. Despite the size, the reducer still provides ample torque amplification, allowing for high grip strength for prop control.

The smaller gearbox is being driven by a smaller Diamond Dynamics Motor (DD2838), as compared to our arm motors, which are successful from previous end effector designs.

The motor controllers used for the arm actuators are VESC VI EDU. Due to board complexity and additional control ports, these are housed in separate enclosures for thermal management and waterproofing complexity.

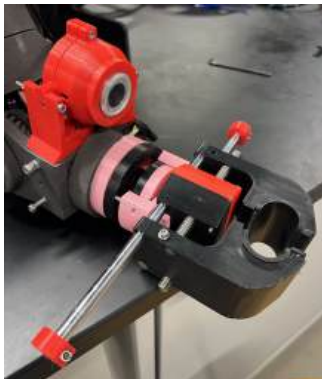


Figure 15: Assembled Claw

At the output of the cycloidal is a helical gear adapter that couples to a set of cross helical gears. With the use of helical gears, the geartrain transmits the direction of motion axially from the gripper perpendicularly to the gears. Nested with the gears are lead screw nuts. As opposed to normal lead screw operation, in which the screw is

driven, the nuts are driven, which then move the lead screws translationally. These lead screws are coupled to the ends of the claw, resulting in the opening and closing motion of the gripper. To assist this motion and further constrain the claws to only move translationally, below the lead screws are aluminum linear rods mounted in a similar fashion.

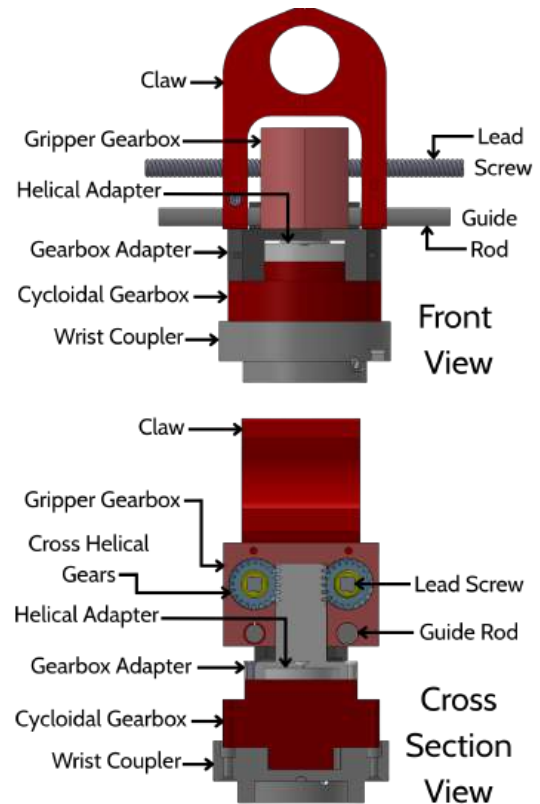


Figure 16: Front and Cross-Section of the Claw

Electrical System

Tether

This year, we utilized the same tether as last year, as we similarly found that it was the best fit for our ROV. In last year's technical documentation, we stated that "Our tether contains 48V power, ground, and Ethernet lines that run from our topside control box and power supply to the ROV. We use 12-gauge wire for power due to the high current demands of our robot and a CAT5e Ethernet cable from Automation Direct for fast and reliable data communication. These cables were chosen not just for their electrical properties, but their

mechanical ones as well. The silicone-jacketed wire and the Ethernet cable have the best bend radius at that gauge and price point on the market. Having a flexible cable ensures that turns and tether snags won't tug on the ROV or lead to cable snapping, and our reasons have not changed this year.

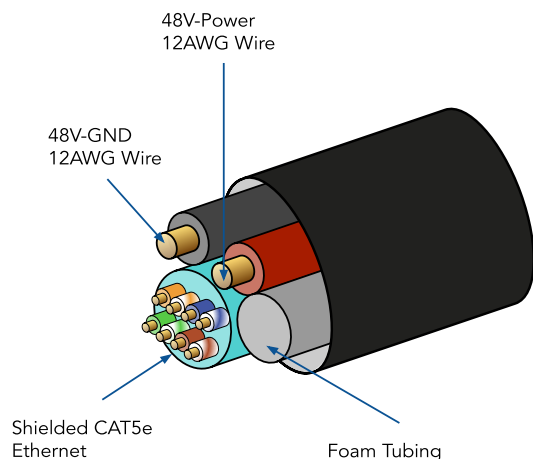


Figure 17: Inside view of the tether

To achieve neutral buoyancy, we use foam tubing and pool noodles to offset the negatively buoyant wires. The wires, foam tubing, and pool noodles are contained by marine-grade spiral cable wrap and wound around a standard wire spool to make it easy to give and remove slack in the line.

Where the tether connects to our ROV, we use a custom 3D print to provide strain relief and protect our tether, as well as the critical data and power it delivers. By distributing the force over a continuous curve, pulling tension is transferred away from the cables and pass-through fittings, distributing it throughout the structural surroundings of the tether. The strain relief also serves to keep the tether centered, eliminating any potential yaw introduced.

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, concise communication between the pilot and the tether manager is paramount for safety.

We also implement a post-use maintenance routine for our tether to ensure its health.



Figure 18: Bottomside strain relief

PCB Design

Central to Imugi's electrical system is a single four-layer PCB. The board hosts two 48V to 12V converter modules and interfaces with the external 12V to 19V and 12V to 5V converters, with a 3.3V rail sourced directly from the Jetson. On the control side, the Jetson communicates with the PWM driver that generates signals for the thrusters and arm. Sensing and monitoring utilize two I2C buses shared between the power monitors, IMU, depth sensor, and ADC. Power and signal exit the board through WAGO connectors out to the ESCs, thrusters, and arm. The primary goal of the PCB is to reduce wiring, make the power and signal system easier to repair and debug, and increase the reliability of the whole system, following two of NUWave's core design values: extensibility and serviceability.

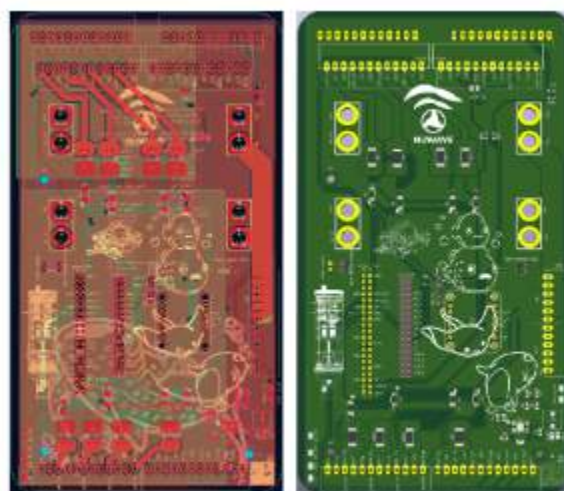


Figure 19: PCB Layout Design in KiCAD

A major design choice involved keeping the high-current 48V to 12V conversion modular

instead of fully integrating it into the PCB. Each 12V rail is produced by a replaceable Flex BMR492 converter module rated for 67.5A continuous, 90A burst. In the event of converter failure, it is easy to service and replace the module rather than desoldering or making a new main board. Since these converters handle the highest power in the system, making them replaceable reduces repair cost, repair time, and electrical risk during testing. Similarly, both the 12V to 19V and 12V to 5V converters are external to the main board, with easily removable connectors for serviceability. The only non-modular voltage level is 3.3V.

Traces were designed to balance safe current carrying with board area. Each thruster branch was designed to handle nine amps, and two ounce copper was selected over one ounce copper to double each trace's current capacity.

Moving to a singular board design from last year's dual-board design left less room for both power and signal traces. So, we decided to transition to a four-layer board to ensure proper trace width for power, and allow for optimal routing for signal integrity. The top and bottom layers are used for signal routing, while the inner layers are used for large power and ground planes. These reduce voltage drop, provide cleaner return paths, and help separate high-current thruster paths from lower-voltage I2C and PWM signals.

The Jetson Orin Nano is powered by a 19V boost converter. It can be powered by 12V, but we discovered that the 12V rail tends to dip just below the Jetson's operating range when the thrusters are in use. The present design ensures constant power to the Jetson, so we do not lose connection to the vehicle.

Both I2C and PWM signals are routed through the PCB to maximize modularity and minimize loose wiring. The I2C network supports the IMU, depth sensor, ADC, power monitors, and PWM driver. The ADC and power monitors are soldered directly to the PCB, while the IMU, depth sensor, and PWM driver connect to the board

through pin headers for devices inside the tube and through WAGO connectors for devices outside. PWM is handled by a dedicated driver because the Jetson only exposes three PWM pins, while the driver provides 16 individual channels, which is enough to control all eight Blue Robotics thrusters and six arm thrusters. These PWM signals leave the driver board through pin headers, pass through the PCB, and exit via WAGO connectors to the ESCs.

Overall, this PCB was designed with practical reliability and compactness in mind. The result is a clean, performant electrical system that is easy to debug, less wasteful to repair, and better suited for future development.

Wiring

Similarly to this year's PCB, we aimed to simplify the wiring outside of the electronics tube to improve the accessibility of our electrical components. Last year, we battled overheating and noise due to overcrowding in the electronics enclosure, so this year we emphasized noise-conscious wire management by moving the ESCs from inside the tube to outside. Before this change, the ESCs produced significant heat inside the tube, so by epoxying them and mounting them outside the tube, we freed up space and eliminated the heat problem by isolating the ESC heat from the rest of the electronics. This change moves the ESCs' three-phase output lines outside the tube, eliminating 24 high-voltage traces on our PCB and making space for other signals.



Figure 20: WAGO twelve-pin board mount lever nut connectors (left) and XT90s (right)

Inside the tube, we reduced wire clusters by utilizing more board-mounted connectors. We focused on XT90 connectors to deliver power to avoid directly soldering the 48V wires to the

board, which allows for a simple connection of the high voltage line that feeds into our ROV's electrical system. Related to our focus on modularity, we use pin header connectors for our Jetson pins, PWM hat, and buck/boost converters, allowing for easy disconnection/connection and debugging. To facilitate wire management, we created custom ribbon cables to carry our PWM signals to these headers.

Lastly, throughout the system, we use spiral wrap on all of our cable harnesses as opposed to just the tether. This protects our wires from damage and wear. To prevent the cable harnesses from tangling and being pulled downward by the wrap's weight, we use zip ties to tighten the cable harnesses to our ROV frame.

Control System Software

Our control system requirements rest on four main tenets: system performance, extensibility, code maintainability, and ease of integration and use for customers.

We previously implemented a Pythonic server-client architecture on a Raspberry Pi 4. However, as our system and our knowledge grew, we found ourselves pushing up against what it could handle. As a result, we have decided to migrate to ROS (Robot Operating System) 2. This framework represents hardware and software components as “nodes,” self-contained, concurrent processes that communicate by publishing messages to topics that other nodes can subscribe to. The diagram in Appendix B is used by our company to plan, track, and evaluate our design, showing how our system's nodes communicate to collect, process, and deliver data. Additionally, because ROS 2 is not supported on Raspberry Pi OS, we switched to a Jetson Orin Nano onboard the ROV.

At the surface station, we have a ThinkPad E16 with 32GB RAM, new this year, after we found ourselves limited by the poor CPU and RAM capacities of our laptop from last year. We take

input from two Xbox controllers, one for ROV movement and one for the arm.

To streamline deployment, we wrote a bash script that launches all surface-side nodes, then connects to the Jetson via SSH to launch the ROV-side nodes, allowing us to start our whole system with one terminal command.

The topside stack also includes a web-based GUI (graphical user interface) written with HTML, JavaScript, and CSS that runs locally and listens to ROS topics via a bridge node. The grid-based design is modular and interactable, making it customizable for various piloting and data collection scenarios.



Figure 21: GUI in a fun data mocking mode

For this year's tasks, we identified the need for several extra software features. To complete Tasks 1.2 and 2.2, we built and trained a Structure from Motion (SfM) network, a photogrammetric technique that tracks matching features across video frames with computer vision and uses them to calculate the 3D coordinates of an object. For Task 2.1, we trained a YOLOv11 (You Only Look Once) neural network to identify the invasive European Green crabs in the sample. All three of these tasks have associated buttons on the controllers to trigger activation of the relevant systems.

To help pilots complete Task 1.3, we added a brand-new copilot node. Currents and waves provide challenging pilot conditions, destabilizing its gyroscopic orientation and consequently the directionality of its movement. The copilot node

synthesizes sensor data from the IMU and depth sensor and feeds it to Proportional-Integral-Derivative (PID) controllers that lock pitch, roll, and/or depth when desired. This secures vehicle stability while the pilots focus on compensating for the currents while maintaining position over the coral garden. In addition, we have exponential input scaling on ROV movement, giving pilots finer control by allocating more of the control sticks to the slower speeds.

During camera testing, we identified a critical bug: if a camera disconnects temporarily (due to signal integrity issues or power dips), it's assigned a new COM port, rendering it unable to reinitialize. To solve this, we introduced a camera manager node that dynamically handles disconnects, choosing the COM port based on a scan of existing video ports and a list of busy ones, enabling fault recovery without manual intervention.

GitHub is used for version control, and we cut stable releases to ensure reliable performance during rapid development. We have two primary methods of documenting codebase functionality that are both strictly enforced: code comments and a README. For the past four years, we've maintained a running list of known errors and their solutions in our Google Drive. Development happens on branches that are thoroughly tested both with mocks and on real hardware before being merged to the main branch through Pull Requests. All Pull Requests must document changes and testing, verify upkeep of code cleanliness and comments, and be reviewed by another employee before they can be merged.

The primary limitation of our current software design is that, in ROS 2, code objects generally shouldn't be passed between nodes, which prevents nodes from sharing hardware resources directly. This limits them to only representing components directly connected to the Jetson. In the case of our thrusters, ROS 2 prefers that any thruster nodes live on the PWM

board they're wired to. Since it has no microcontroller, this is impossible, and we must represent all thrusters in the PWM board node. However, this is only a code cleanliness issue and does not affect performance or ease of use.

The primary hardware limitation of our control system is a USB throughput bottleneck on the Jetson. The USB hub segregates USB2.0 and USB3.0 traffic into two distinct pipelines, each with its own fixed share of the bandwidth, meaning that all USB2.0 devices share a 480-Mbps maximum despite the bus being capable of significantly higher throughput.

Propulsion

Our ROV uses eight Blue Robotics T200 thrusters for propulsion. Analyzing top ROVs from the past few years, we noticed a clear trend towards the use of four vertical and four lateral thrusters for propulsion. While last year's ROV used eight thrusters, only four were Blue Robotics. Testing over the past two years showcased that while Diamond Dynamics exhibited a lower entry cost per unit and more efficient thrust per amp, Blue Robotics had higher maximum thrust. With a larger ROV, we opted for increased yaw and strafing control; as a result, we chose to invest in Blue Robotics. The more powerful thrusters allow us to maximize our larger ROV movement and make complete use of our arm.



Figure 22: Blue Robotic T200 Thruster

The ROV has four vertical thrusters mounted on the four corners. The four lateral thrusters are mounted on the corners, but are angled laterally in an X-drive configuration to allow for both strafing and propulsion. While an orthogonal thruster layout provides 100% force

for forward movement, it provides 0% for strafing. By opting for a 45° vector, we accept a loss in forward thrust in exchange for omnidirectional maneuverability. By placing the thrusters as far out on the frame as possible, we maximize thrust and stability.

While the thruster configuration handles macro-movements, the robotic arm compensates for any lack of vehicle dexterity by handling the fine adjustments. As long as the ROV is able to maintain vertical positioning and strafe, the operator can leverage the additional degrees of freedom to complete tasks.

Buoyancy and Ballast

Maintaining passive stability was a priority from the start of our design process. To minimize costs associated with marine buoyancy foam, we scavenged foam from a pool kickboard to provide positive buoyancy and used scrap buoyancy foam donated by Aperion. This material proved easy to cut to fill spaces of the ROV where foam was needed, and provided significant buoyancy.



Figure 23: Syringe that is used as a modular ballast

We also utilize our signature syringes once again, thanks to their modularity and ability to manipulate buoyancy on the fly. Capped with industrial duct sealant, the syringes can be adjusted poolside to calibrate buoyancy and roll. The syringes are mounted on the insides of the frame in a symmetrical formation to keep the center of buoyancy as central as possible while maintaining a small footprint.



Figure 24: Modular ballast using industrial washers

Industrial sized washers are mounted on the back of the ROV to provide ballast. The added weight helps to balance the center of gravity, which is offset by the large front-mounted arm. Mounted on three side-by-side pegs, these washers allow for further tuning of the center of gravity by changing the weight on each side of the ROV.

Payload and Tools

Cameras

Figure 25: Deepwater Exploration Explore HD 3.0 Camera in Custom Housing



Imugi features four Deepwater Exploration ExploreHD 3.0 cameras. They are rated to 400 meters and have preprocessing color correction for underwater environments onboard. The cameras are also configurable to different resolutions, framerates, and video encodings, which allows us to step down the resolution and framerate before the video even hits the Jetson. Both preprocessing and stepping-down reduces latency by reducing the data throughput to a manageable bitrate before sending it up over the tether to the surface station. With four HD cameras, stepping down the throughput on the cameras themselves prevents us from overloading both the tether and the Jetson's USB bus, causing overflow errors that induce data loss, disconnections, and non-deterministic behavior.

Sensors

We have several sensors onboard Imugi, including a Blue Robotics BarO2 depth sensor, an Adafruit BNO085 breakout, eight Texas Instruments INA226 power monitors, six ams OSRAM AS5047P rotary position sensors, and six Bourns Inc. 3590S-2-L potentiometers.

Sensor	Requirements	Specs	Rationale
BarO2	- Rated to 4 m - <1 mm resolution - I2C	- Rated to 10 m - 0.16 mm resolution - \$80 - I2C	- Meets requirements - Affordable - Excellent depth resolution
BNO085	- 9-DOF - Data pre-processing - I2C	- 9-DOF (triaxial accelerometer, triaxial gyroscope, and magnetometer) - I2C or UART - Pre-calculates 3D orientation, heading, and calibrated acceleration and angular velocity	- Meets requirements - Affordable - State-of-the-art data synthesis
INA226	- Measure bus and shunt voltage - Measure on the 12V line - I2C	- Bus and shunt voltage channels - $\pm 81.92\text{mV}$ input window - 36V common-mode voltage max - I2C, SMBus - \$3	- Meets requirements - Affordable
AS5047P	- Works with SPI - Refresh rate designed for motor control	- SPI, ABI, UVW, or PWM output - Approx. 4.5 Mhz refresh rate - \$21	- Meets requirements - Affordable
3590S-2-L	- Low cost - High resolution - Multi-turn - Simple interface	- 0.023% resolution - Multi-turn - Bushing mount - \$17	- Meets requirements

Figure 26: Sensor Breakdown

The BarO2 balances affordability with high resolution by taking advantage of the low depth requirements. The BNO085's state-of-the-art pre-processing relieves some of the processing burden from the Jetson, such that the data can be delivered directly to the surface station for display on the GUI, reducing latency. It's the only nine-DOF IMU at its price point that's capable of this.

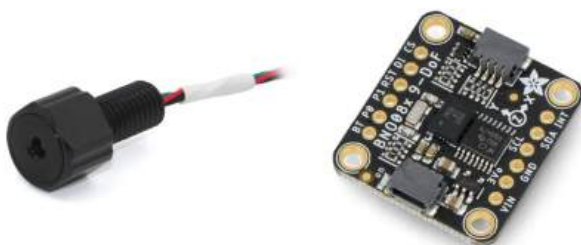


Figure 27: Blue Robotics BarO2 depth sensor (Left) and Adafruit BNO085 IMU (Right)

The INA226 was chosen because per-thruster current monitoring lets the vehicle flag any thrusters drawing abnormal power, automating identification of malfunctioning thrusters. Additionally, its low cost made it practical to place one on every thruster line rather than monitoring the bus as a whole. Adding these monitors required selecting a shunt resistance that balances sensor resolution against thermal losses in the thruster path. A four-milliohm shunt produces $I \cdot R = (9\text{A}) \times (0.004\Omega) = 36\text{mV}$ across the INA226 inputs at the maximum operating current, sitting comfortably within the device's $\pm 81.92\text{mV}$ input window and leaving headroom for transient overcurrent events. The resulting dissipation is $I^2 \cdot R = (9\text{A})^2 \times 0.004\Omega = 0.324\text{W}$, so the selected two-watt package provides significant thermal margin while keeping the monitor from becoming a meaningful loss element in the thruster path.

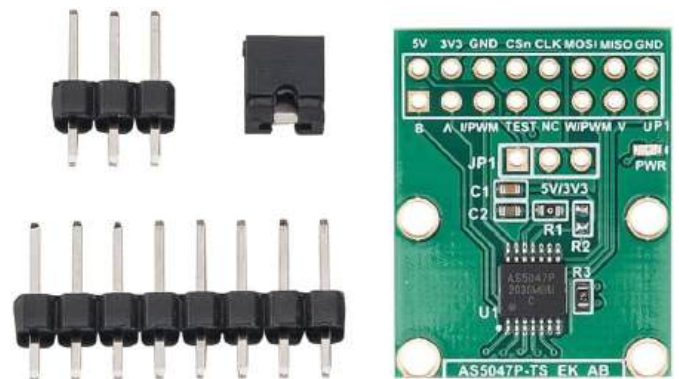


Figure 28: AMS OSRAM AS5047P rotary position sensor

The AS5047P rotary position sensor enables us to use heavily geared-down thruster motors to actuate our arm despite these motors being intended for high-speed use and therefore unstable at low speeds without encoder feedback, giving us an affordable, waterproof motor option for our 5-DOF arm.

The 3590S-2-L potentiometers are used to determine the position of the arm in 3D space, allowing for arm control through inverse kinematics. This means that instead of moving

the arm motors directly, pilots can instead command the arm's position, which feels more natural for most people and gives better performance.

Safety

Safety Rationale

Here at NUWave, safety is our number one priority. Our company philosophy is to prioritize doing something the right way, even if it is not the easiest or fastest way. This year, we also utilized the hierarchy of controls, where we aimed to eliminate and substitute potentially harmful components in our designs, as opposed to just wearing PPE or following certain protocols. This hierarchy was introduced to all of our members on their first day, emphasizing its role in our company, as well as the importance of safety while designing Imugi.

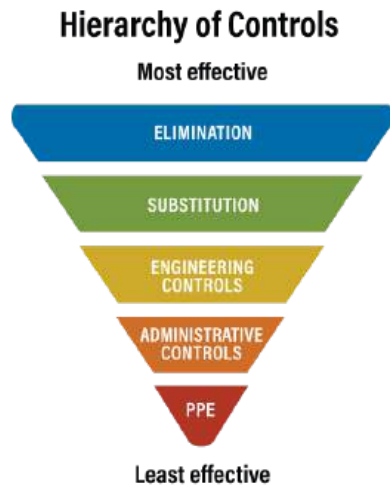


Figure 29: The hierarchy of controls, which demonstrates the effectiveness of different safety methods

Safety Features

Imugi has a variety of features implemented to ensure that it is not harmed and that it is not a risk to those around it. All sharp edges on Imugi have been rounded out, and all eight thrusters are properly shrouded to IP-20

standards, meaning the shrouds have openings that are smaller than 12.5 mm.



Figure 30: The front (left) and back (right) of a shrouded thruster

Additionally, there is a 25A Littelfuse installed within 30 centimeters of our Anderson Powerpole connectors as an additional safety precaution. Within our control box, there is a shut-off switch, so if any issues arise, we are able to quickly and effectively shut down the entire vehicle.

Built-in handles in the frame provide a secure place to grab the ROV. This is essential as many of the tasks require a person poolside to interact with the ROV, often passing or receiving props, such as the cover of the oil platform port. In a pool such as the offshore engineering basin tank, where there may be waves that further obscure the surface of the water, having a secure place to grab the ROV without fear of hitting a thruster or sharp edge is vital.

NUWave takes care to ensure all electronics are fully waterproofed, providing two layers of waterproofing on all wire connections. This may include waterproof solder sleeves, marine epoxy, or duct seal. Electronics, connections, and our electronics tube are all monitored closely and checked frequently to ensure there are no leaks.

Circling back to the hierarchy of controls, when making the initial design decisions for Imugi, we tried to focus on the two most effective safety methods, elimination and substitution. This played a role in decisions such as creating an electronic arm instead of a hydraulic arm. We recognized that our lab was not equipped to handle any kind of fluid power, so we instead

chose to follow the safety method of substitution and implement an electronic arm, as opposed to proceeding with a hydraulic arm and attempting to use personal protective equipment or administrative controls to make up for the lack of proper equipment and space in our laboratory.

Safety Procedures

Personal Protective Equipment (PPE) is always worn in the lab, especially when working with any kind of harmful substance or tool, such as epoxy, power tools, or solder. In line with the hierarchy of controls, we also opt for less harmful substances when they are available, such as only using unleaded solder with proper ventilation in our lab space. All employees are required to wear gloves, masks, goggles, respirators, or any other necessary PPE when working with something that could be harmful.

New members are provided with the proper information on safe practices and PPE when they join the club through safety sheets presented during lessons in our WavePerch program.



Figure 31: Example WavePerch safety sheet

If any member is ever confused or feels unsafe, they are encouraged to ask for help or speak up through our Observation Program, where any unsafe or risky activities can be reported to the team's safety officer so an appropriate action can be taken to address their

concerns. This helps NUWave identify areas of improvement in their safety program and proactively prevents incidents before they occur. Members also announce aloud whenever they are using a tool or interacting with the ROV poolside to ensure additional awareness and caution.

NUWave works to maintain clean and organized workspaces. When working poolside, team members wear proper footwear, communicate, and move slowly, particularly if there is water on the deck or they are moving something heavy. Tripping hazards near the pool's edge must always be immediately cleared. In order to account for the flume tank, the ocean engineering basin, and the ice tank at this year's competition, additional safety precautions are being put into place. These include things such as extra jackets and towels for windy or colder conditions, and being more aware of the surroundings as a whole. Additional safety checklists used poolside can be found in Appendix H.

Critical Analysis

Testing and Troubleshooting Thrusters

An integral process in the engineering design process at NUWAVE is the testing and validation of our product. We believe decisions driven by verified data support a more robust and competitive product. Last season, we discovered that Diamond Dynamics thrusters had more thrust per amp in the forward direction, but Blue Robotics beat them in every other metric tested.

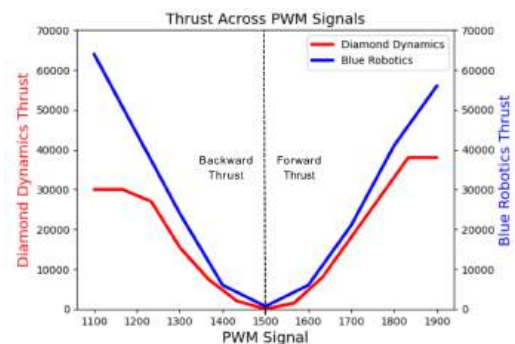


Figure 32: PWM mapped with thrust force

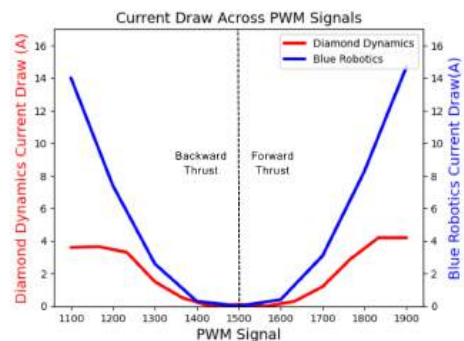


Figure 33: PWM mapped with amperage

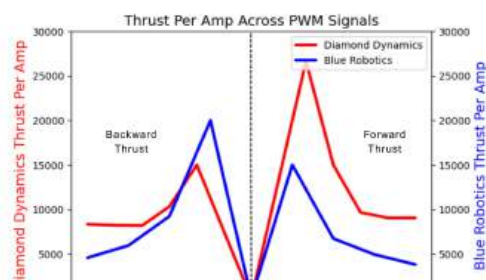


Figure 34: PWM mapped against thrust per amp

This year, we built off this data further, utilizing eight Blue Robotics thrusters as opposed to the four we used last year after making this discovery. At the time these measurements were taken last year, we no longer had the power or monetary budget to acquire four more blue robotics thrusters. However, using that knowledge this year, along with the fact that we would have to fight current in a flume tank, we upgraded to the eight blue robotics thrusters.

Low Speed Commutation

Another challenge of the arm design was overcoming actuator control schemes. As the actuators used BLDC (Brushless DC) thruster motors, we chose to pair them with Hobbywater waterproof ESCs to simplify waterproofing and wiring. However, testing and research showed that this control method was not suitable for robotic actuators as they use the sensorless control scheme. Sensorless relies on the back EMF generated by the rotor spinning to determine position. This is perfect for thruster motors as they don't experience significant load until they produce thrust, don't require position control, and are therefore able to spin at an RPM above the sensorless regime threshold to produce readable

back EMF. A robotic actuator has the exact opposite requirements and therefore can't use this control method. Under load and potentially stalling, the motor, even with a gearbox, can't achieve the RPM needed for sensorless. As a result, the motor fights itself as the ESC can't properly communicate with the motor and determine which pole pair to turn on.

Although this was a potential concern, due to the high reduction of the custom actuators, it was believed the motor could overcome the RPM requirement and properly commute.

Prototyping

Gearboxes

This year, our company utilizes a cycloidal gearbox for arm actuators and claw reducers. As opposed to other gearboxes, cycloidals can achieve high gear ratios in a small footprint, very low backlash, and most importantly, cannot be backdriven.

Testing initially started in the summer of 2025, validating the design of a cycloidal gearbox, as well as confirming that FDM printing cycloidal gearboxes is possible.

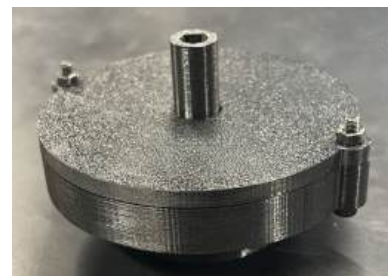


Figure 35: One of the prototyping designs verifying The use of a cycloidal gearbox

Using this success as a jumping-off point, we designed a dual-stage cycloidal gearbox that would control each DOF of the arm. Each gearbox would have the same framework with slight modifications for clearance, coupling, etc.

With our initial version of the cycloidal gearbox, we ran into multiple issues. One was that the gearbox was binding under any use other than perfect free-spin conditions. This was caused by a combination of tolerance stackup as well as a

design oversight that placed our input directly next to our output. These were fixed, tightening our tolerances as best as possible as well as shifting out input further away from our output. The other is that the torque output of the gearbox wasn't great enough. This was addressed by increasing the ratio by about 7 fold. These issues were addressed in the second version of this gearbox.



Figure 36: First version of the cycloidal gearbox

Accounting

Budget and Cost Accounting

At the end of the 2023 fiscal year, the NURobotics club, home to the NUWave team, had its budget cut almost completely. As such, NUwave receives only a portion of its funding from the school. The majority of our funding is obtained from research grants and fundraising. From a grant standpoint, this isn't necessarily a negative, as it allows team members to develop skills in scientific writing. However, it imposes constraints on our ability to fund our robot improvements, as we have to frame them as research. This means we need a very good idea of exactly how much funding we need and what areas we need it in to make a plan for grant writing.

Last year, we created a comprehensive spreadsheet to track the history of our funding sources and spending habits over the course of NUWave's existence, allowing us to estimate that we spend between \$16,000 and \$21,000 annually. We used this estimate to find appropriate research grants and decide which we

were most likely to achieve, so we could strategically apply to our most likely funding sources first.

This year, we expanded on this system to track a single year's worth of funding and spending. We created a comprehensive spreadsheet to calculate the balance on each of our funding sources, create a breakdown of our total travel expenses versus component expenses, track spending, reimbursements, and cost center balances.

We also found other ways to improve our accounting system. For example, we noticed that when members requested part orders, there was no central place to put the needed items and track the progress of their order. To fix this, we created a designated purchasing repository, where members could enter components, as well as desired links, prices, and quantities. Each sheet also required specification of the intended project so the purchaser could identify appropriate cost centers for reimbursement, and the order was tracked through delivery.

To travel 15 of our members to the competition, we will spend \$13,248.14 USD. This number includes gas, ferry rides, flights, and hotels, both for our stay in St. Johns and a night in a hotel each way for those making the 30+ hour journey in a car (Appendix C).

Build vs. Buy, New vs. Used

When possible, our team emphasizes the reuse of components, as well as making the effort to create professional relationships with companies and institutions to use old components or receive sponsorships.

We reused many of our most expensive components, including four Blue Robotics T200 thrusters and corresponding ESCs, three DeepWater Exploration HD Cameras, and our six-inch acrylic Blue Robotics electronics enclosure and aluminum endcaps. All of these new components would have cost our team \$2,488.

Our design this year involves an upgraded on-board computer, specifically a Jetson Orin Nano. We were able to partner with Dr. Hanumant Singh and the Northeastern Institute for Experiential Robotics (IER) to reuse a Jetson from a research project, as well as receive a brand new Jetson as a donation from IER.

We also partner with HobbyWater to get our arm motors for a discounted price. They are a company that we have used for years, in nearly every iteration of our robot.

Formlabs donated a Form3 Resin printer to our NURobotics Club and significant amounts of resin material. Our frame is the product of many donated waterjet hours and materials from Formlabs.

We were also very lucky to recycle buoyancy foam from Aperion Labs to add additional buoyancy to our ROV.

Below is a table detailing the evaluations of all of these contributions.

Our philosophy in terms of budget is: do it safely, do it reliably, keep it cost-effective, and plan ahead. Bad design is a result of bad planning and a series of panicked and expensive decisions. The time it takes to form professional relationships is worth it for many reasons, but especially financially. We use our funds thoughtfully, effectively, and with the future in mind.

For detailed information on our component spending, please see Appendices C, D, and E.

Table 1: Reused Components

Component	Vendor	Unit Price	Quantity	Total Price
Blue Robotics T200 Thruster	Blue Robotics	\$230	4	\$920
Blue Robotics Basic ESC	Blue Robotics	\$40	4	\$160
Blue Robotics Watertight Enclosure for ROV/AUV (6" Series)	Blue Robotics	\$508	1	\$508
DeepWater Exploration HD Camera	DeepWater	\$300	3	\$900
Total Saved				\$2,488

Table 2: Donated Components

Organization	Type	Components, Services, or Materials	Evaluation
Formlabs	Donation	Waterjet Time and Materials, Form3 Resin Printer, SLS and SLA Prints	\$5250
Northeastern IER	Donation	2x Jetson Orin Nano	\$480

HobbyWater	Discount	15% Discount on Arm Motors	\$100
Polymaker	Sponsorship	FDM Filament	\$200
Aperion	Donation	Scrap Buoyancy Foam	\$150
Total Components, Services, or Materials Donated			\$6,180

Acknowledgements

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

FormLabs: For letting us use their waterjet and their extremely generous donation of a Form3 and materials.

NURobotics: For helping grow this team from two people into the project it is today.

Prof. Hanumant Singh: For securing us a new Jetson Orin Nano, providing access to Northeastern's Institute of Experiential Robotics resources, and allowing us to borrow Pelican cases to transport our robot.

Prof. Bahram Shafai: For advising the Arm PEAK Ascent Award.

Northeastern Undergraduate Research and Fellowship: For supporting our underwater research endeavors through PEAK awards.

MIT Sea Grant: For giving us the space to test and for the MIT STREAM Grant.

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

Lauren Colby: For helping us get access to the pool and for being so accommodating.

Mr. Expert and all Individual Donors: For supporting our projects in their most uncertain times.

All Giving Day Donors: For supporting our beloved projects.

Prof. Bridget Smyser: For sharing her lab space.

Jill Zande: For her incredible support whenever we had questions or hurdles to overcome, and for showing us so much kindness.

Matt Gardener: For his unbelievably fast answers to any of our rules questions.

Jonah Jaffe: For his continued mentorship, support, and friendship

MATE: For hosting the competition and allowing us to compete

Woods Hole Oceanographic Institution: For all of their help on our Thruster Test Stand journey.

American Society of Naval Engineers: For supporting our club's growth into new avenues.

HobbyWater: For providing us with reliable parts at a discounted rate.

Schmidt Ocean Coalition: For helping our members get to competitions these past years, helping us inspire the future of the team and the field.

Zero Robotics and the MIT Media Lab: For their partnership and donation to our project.

Polymaker: For their sponsorship and filament donation.

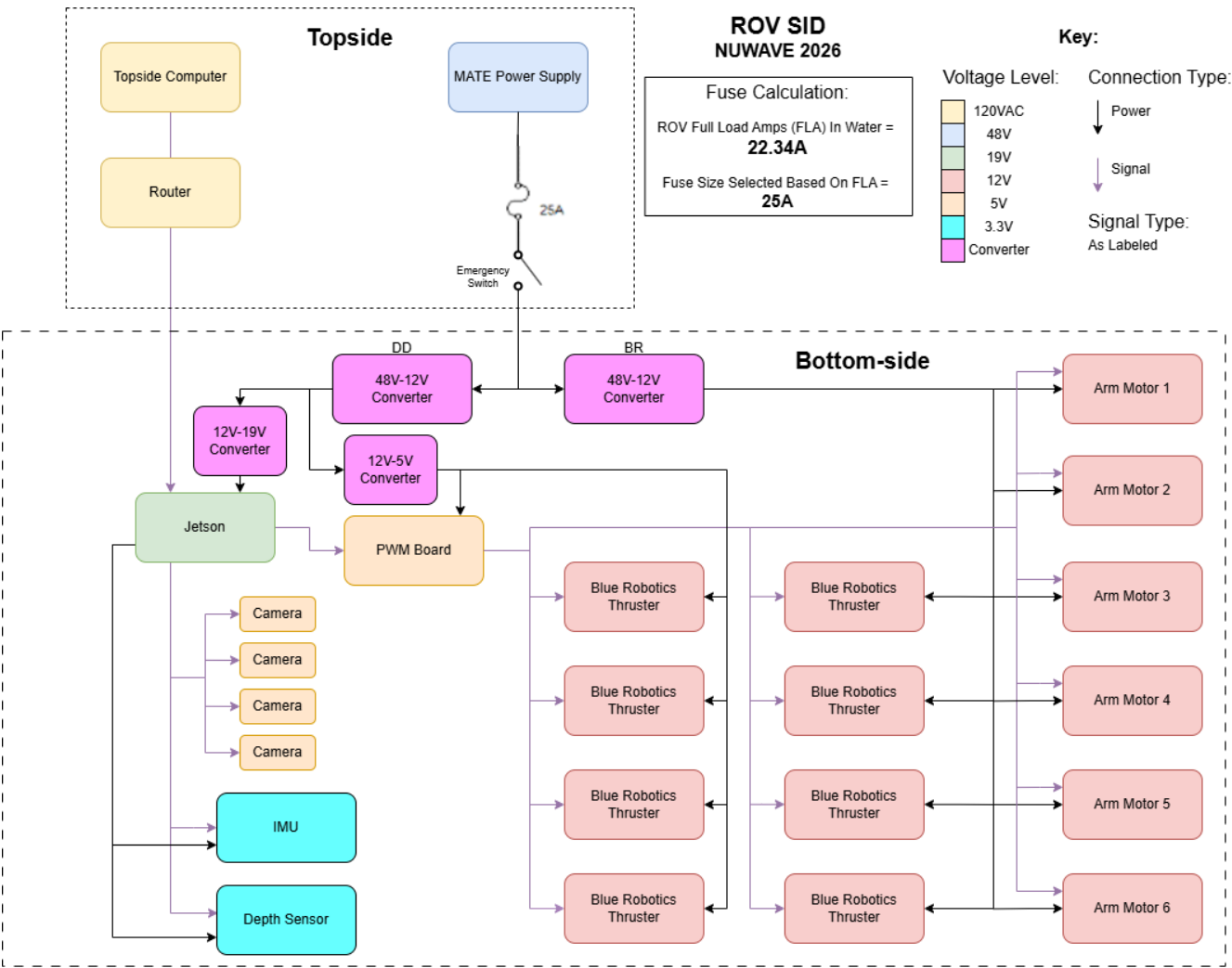
Aperion Labs: For allowing us to use their leftover buoyancy foam.

Automation Direct (Chip McDaniel): For the donations of a range of items from wires to sensors to stepper motors, Automation Direct was the first to help, and Chip made everything easy.

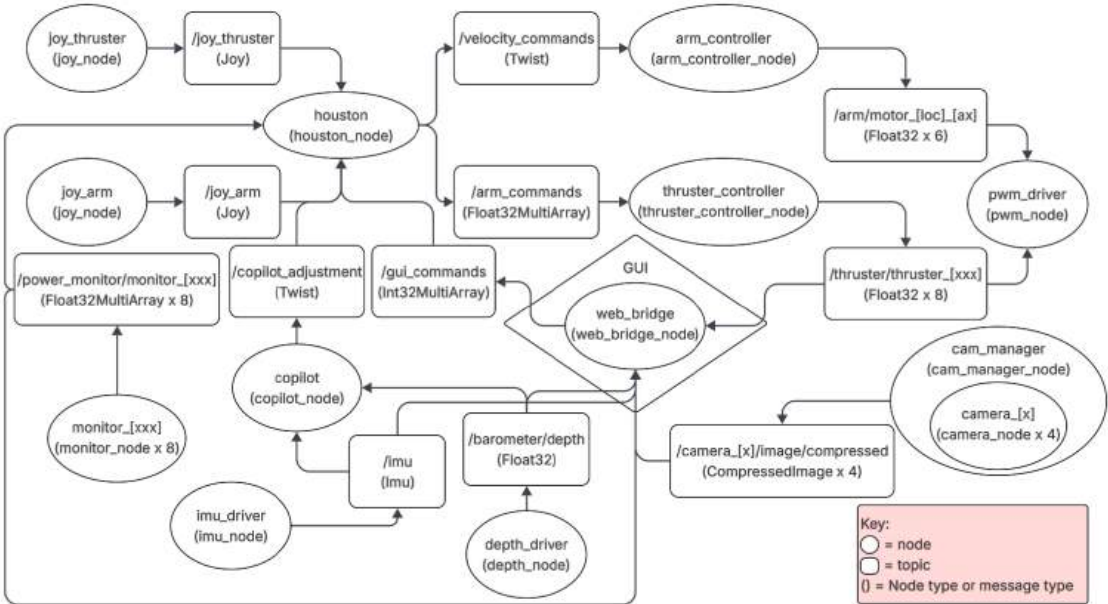
Igus: For their donation of lead screws and lead screw nuts for the float

Appendix

APPENDIX A: Imugi SID



APPENDIX B: ROS 2 Software Architecture



APPENDIX C: Comprehensive Spending Tracker

Purchaser	Amount	Funding Source	Project	Purpose	Reimbursed	Notes
Dylan	529.7	ARM PEAK	mate	Components	yes	
Dylan	710.11	ARM PEAK	mate	Components	yes	props and components
Dylan	571.49	ARM PEAK	mate	Components	yes	
Dylan	145.59	ARM PEAK	mate	Components	no	passthroughs
Lily	2928.77	cash	mate	Hotel	no	mate hotel 12 p
Lily	1648.48	cash	mate	Hotel	no	mate hotel 3 p
Nik	1250.52	cash	mate	Flights	no	flights - 9 people
Lily	721.23	cash	boat	Hotel	no	
Dylan	2993.16	cash	mate	Flights	no	flights - 9 people
Dylan	327.21	cash	mate	Ferry	no	not in concur - CAD
Dylan	650	cash	mate	other	no	mate registration
PROECTED	3400	cash	mate	Flights	no	to be booked
PROJECTED	400	cash	mate	Hotel	no	to be booked
PROJECTED	1050	cash	mate	other	no	Merch
PROJECTED	400	cash	mate	other	no	Pool Time
Nik	265.49	NURobotics Budget	mate	Components	no	digikey -V2 electronics
Nik	310.03	NURobotics Budget	mate	Components	no	passthroughs, escs?
Lily	1019.97	NURobotics Budget	both	Components	no	
Dylan	278.34	NURobotics Budget	mate	Components	no	esc tubes
Dylan	862.52	NURobotics Budget	mate	Components	no	Electrical V2
Lily	2957.14	STREAM	both	Components	yes	
Lily	1569.47	STREAM	both	Components	submitted	

APPENDIX D: Example of Cost Center Balances

Cost Center	Arm PEAK	NURobotics Budget	#	Cash Account	#	STREAM
Balance	43.11	263.65		5605.63		1473.39

APPENDIX E: Component versus Cash Account Breakdown

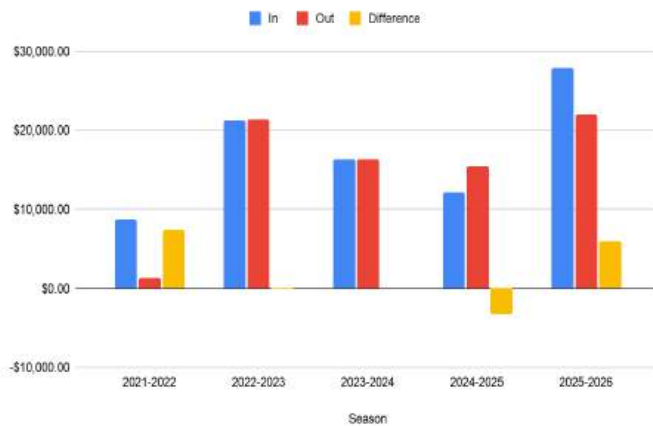
Total Funding Remaining	Total Spent (projected)	Component Total Spent	Cash Total Spent (projected)	Travel Total (projected)
7085.78	25289.22	9219.85	16069.37	13248.14

APPENDIX F: Funding Source Tracker

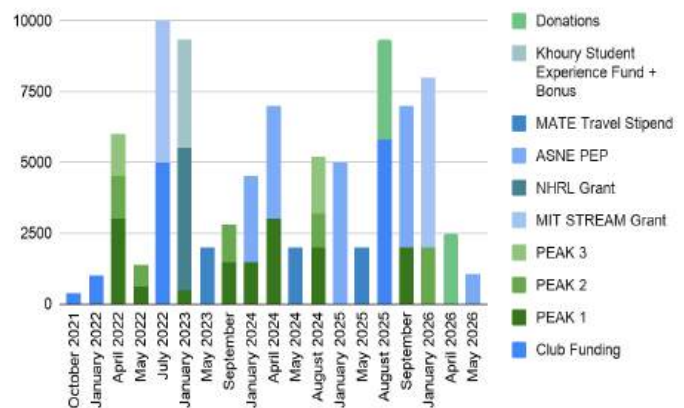
Source	Type	Secured	#	Amount	Notes	Cash Total	Component Total
Cash Account (NURobotics)	Cash	yes		2800		21375	11000
Nik PEAK	Cash	yes		2000			
PEP	Cash	yes		5000			
Donations (including Zero Robotics)	Cash	yes		3525			
Extra PEP Travel Check	Cash	yes		1050			
Giving Day	Cash	yes		2500			
Member Contribution	Cash	optimistic		4500			
NURobotics Component Funding	Component	yes		3000			
MIT STREAM grant	Component	yes		6000			
Arm PEAK	Component	yes		2000			
Khoury Honors Student Global Scholarship	Cash	no		2500			
Husky Starter	Cash	no		3000			
Schmidt Ocean Coalition	Cash	optimistic		2000			

APPENDIX G: Funding and Spending Charts

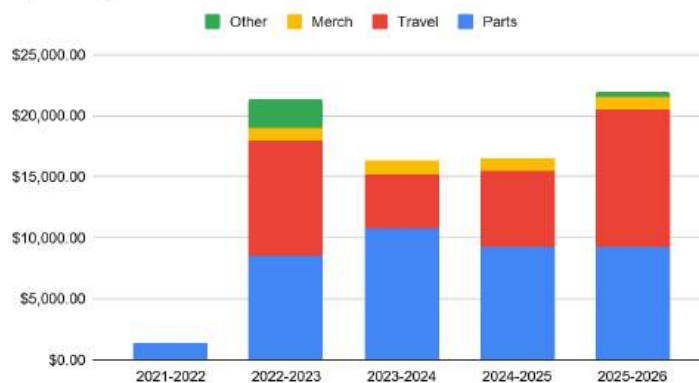
In vs Out and Difference



Income Over the Years



Spending Over the Years



APPENDIX H: Safety Checklist

Construction Checklist	Operational Checklist	Emergency Checklist
☐ Get the proper personal protective equipment (PPE) for the construction task ☐ Ensure workspace is clear, with nothing nearby that could be damaged ☐ Inspect machinery and cords before use, and do not use if damaged ☐ Tell all people around you to be aware of any tools that are going to be in use ☐ Follow instructions and safe practice guidelines of all tools ☐ Make sure all electrical equipment is properly grounded ☐ Unplug any equipment when it is not in use ☐ Store all materials properly and securely when finished	☐ Clear testing area, including removing any personal items or unnecessary materials ☐ Verify power supply is OFF ☐ Check over ROV and tether to ensure there is no damage ☐ Ensure all cables are secured, tether support is in place, and the tube is fully closed with nothing interrupting the seal ☐ Check connectors and make sure all passthroughs are fully tightened ☐ Make sure all members are ready then announce as power is turned on ☐ Wait for ESC startup sequence to play and check for camera feed ☐ Place the ROV into the water, burp it, then check functionality of thrusters and claw ☐ Communicate during launch and retrieval	Excessive Bubbles ☐ All poolside members should be on the lookout for large bubbles exiting the ROV, particularly from tube passthroughs or connectors ☐ If spotted, inform pilots to stop flying and immediately pull ROV in from the water ☐ Pilots announce as power is turned off ☐ Dry off ROV and identify source of leak to be fixed Lost Communication ☐ Power cycle the ROV to see if it reinitializes ☐ If it succeeds, continue with the mission ☐ If it fails, then the ROV is pulled in while the pilots announce as power is turned off