



X18 Technical Documentation

PURDUE ROV '26

PURDUE UNIVERSITY | WEST LAFAYETTE, IN, USA



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ABSTRACT

Purdue ROV is an entirely student-run corporation specializing in underwater technologies such as Remotely-Operated Vehicle (ROV) design and deployment. Our company aims to engineer innovative products capable of addressing the critical oceanic issues of today while pushing the limits in harsh environments, including the cryosphere. In response to MATE's request for proposal (RFP), Purdue ROV is proud to present *Narwhal*, capable of supporting efforts to address challenges raised by the United Nations Decade of Ocean Science.

Building upon seventeen years of experience, *Narwhal* was created through collaboration and labor from forty-five members across the Electrical, Mechanical, Software, and Operations departments. *Narwhal* was developed upon the core principles of reliability, modularity, and precision, ensuring every subsystem will succeed in the most demanding conditions. This ROV iterates on the company's past achievements with various innovations suited to this season's mission. *Narwhal* features a reliable robotic arm and manipulator, six T200 thrusters granting five degrees of freedom, a multi-camera system, a user-friendly pilot control interface, and a fully custom PCB stack engineered and rigorously tested in-house.

Designed specifically for this season's RFP, *Narwhal* is the optimal ROV for coral ecosystem preservation, invasive species detection & mitigation, and subsea infrastructure servicing. *Narwhal's* highlights include advanced computer vision, an adept manipulator, and universal functionality across all systems, equipping it to aid in oceanological research, conservation, and exploration. Purdue ROV is confident that *Narwhal* represents our best work to date, and will prove an invaluable asset in preserving our oceans for generations to come.



Figure 1. *Narwhal* Pool Test



Figure 2. Int'l Women's Day Photo



Figure 3. Members Working on Tools

COMPANY ORGANIZATION

Purdue ROV is a cross-functional team of forty-five members from a multitude of backgrounds and disciplines. In order to effectively structure the team and provide maximum learning opportunity for members, Purdue ROV is organized into three technical departments - Electrical, Mechanical, and Software - as well as an Operations department (consisting of CEO, Vice-CEO, and CTO) serving as the overarching administrative authority by handling company growth, finances, and outreach.

Each technical department is organized hierarchically with department leads responsible to maintain team organization and task delegation. To supplement, for major subsystems or tools, Purdue ROV enlists project-specific sub-leads. Together, these technical leads serve as both visionaries and managers, drafting design requirements, ensuring cross-department integration, and reporting directly to the CEO, who sets a high level schedule, coordinates team-wide design, and enforces competition specifications & regulations.

PROJECT MANAGEMENT

Purdue ROV adheres to the Agile methodology for project management. Transitioning into each season, we kick off with a company-wide Post-Mortem - debriefing previous shortcomings and successes to determine the current state and future expectations for the team. During the season, Purdue ROV follows a weekly development cycle. This is fronted by a leadership planning meeting each Tuesday.

During this time, all department leads review task progress, share updates and express concern if encountering any blockers or if any member needs extra support to drive their project forwards. Leadership sets goals as well as determines feasibility of deadlines and whether or not each subteam can maintain the project schedule. On Wednesdays, we conduct whole team meetings. These open with a short overview, important reminders and deadlines, and progress updates from the CEO and department leads. The purpose of which is to ensure the entire team is on the same understanding of where we are in the current stage of the ROV-design and fulfillment process. Afterwards, each department breaks off for stand-ups - discussing work completed, to-dos, or any challenges faced. Employees then spend the remainder of the meeting progressing on their respective projects. This structure is repeated at our general meeting on Saturdays, which serves the purpose of allowing employees to have sufficient time to meet their assigned targets.

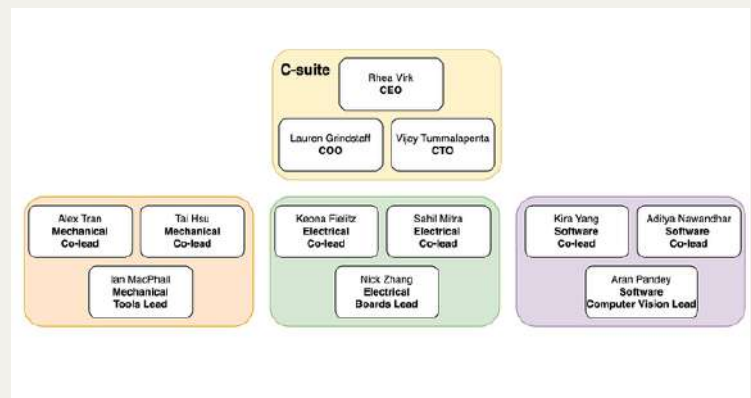


Figure 4. Purdue ROV Leadership Structure

Furthermore, the company uses a few tools for the purpose of project management. Slack is the primary platform for all communications, updates, and reminders. General file sharing across all departments is handled in Google Drive, whereas GitHub is utilized by Electrical and Software for more advanced file version control. Mechanical utilizes product lifecycle management (PLM) softwares such as Aras Innovator to easily share and modify CAD files, providing employees with valuable experience in corporate/enterprise-level tools. Another core component of our project management process involves the use of Notion.

Recognizing the need for greater accountability and visibility across such a large team, Purdue ROV adopted Notion this season as a centralized workspace for task tracking, meeting updates, progress logging, and dependency visualization. Each member is responsible for submitting progress updates by the conclusion of each meeting, with department leads monitoring these and escalating any concerns to leadership. This system is additionally reviewed during weekly leadership meetings to identify critical tasks and reallocate resources to meet approaching deadlines.

PROJECT LIFECYCLE

Prior to each season, the leadership team will create project timelines, Gantt charts, and rough system-interconnection diagrams based on design specifications for a MVP ROV. The company then splits the design phase into four stages : training, design, manufacturing, and testing. During the fall season, Purdue ROV recruits new employees who are subsequently onboarded and mentored by department heads. As an employee of Purdue ROV, one is expected to have full ownership/responsibility for their assigned project. This provides the opportunity for employees to end the season as an expert in their subsystem.

During the first semester, new employees must go through an onboarding phase - attending workshops, learning more about their project, and delving into design work. The second semester is much more hands-on, involving manufacturing, soldering, and prototyping work. This later culminates in the ROV assembly and adequate time for pool testing and bug fixing.

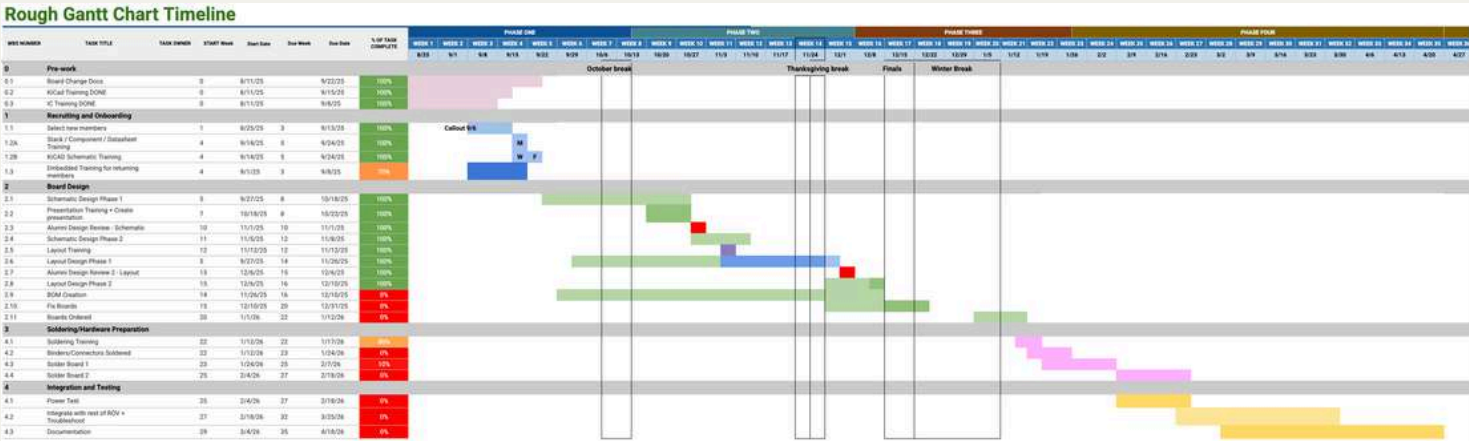


Figure 5. X-18 Gantt Chart



DESIGN RATIONALE

VEHICLE OVERVIEW

Throughout Purdue ROV's nearly two decades of experience, we have determined that the defining characteristics of a competitive ROV are reliability, modularity, and precision. Each subsystem was evaluated against these tenets to ensure X18 would perform under the demanding conditions of this season's mission.

Reliability begins with the frame. X18 uses a single-plate HDPE frame, returning to a design from previous seasons for its superior drag characteristics and structural simplicity. Mounting holes are spaced 1.75" apart in a standardized grid, enabling modular tool placement. SubConn connectors allow quick-release of the tether, facilitating much easier transport and replacement in the case of tether damage. Buoyancy is achieved through an adjustable system of PLA-housed ping pong ball fixtures, positioning the center of buoyancy slightly above the center of mass, allowing X18 to achieve neutral buoyancy and improving overall drivability. The electronics enclosure combines a custom aluminum carrier plate with a FormLabs Clear Resin V5 SLA-printed top hat, waterproofed with an o-ring to protect the electrical stack from the harsh conditions of the ocean environment. The electrical system is engineered to operate reliably under high current and thermal load, supporting all ROV functions simultaneously.

Modularity is reflected across both hardware and software. X18 transitions fully from pneumatic to electromechanical actuation. This decision was made this season in order to simplify the ROV and electrical design - allowing for reduced potential failure points.

The power budget recovered from reducing the thruster count from eight to six is reallocated to servo-driven tooling. The primary manipulator achieves two degrees of rotational freedom using a wrist differential gearbox driven by two servos, with a third servo actuating a four-mandible claw via a piston-crank mechanism. Mandibles are manufactured from Elastic 50A resin, allowing for proper grip across a variety of objects. X18's software stack is built on ROS2, enabling a modular architecture that supports rapid prototyping and independent subsystem testing. The Flask-based pilot interface is served over a local web server, allowing interface updates to propagate instantly across without redeployment.

Finally, precision is central to both piloting and task execution. X18 employs a six-thruster configuration providing five degrees of freedom (surge, sway, heave, pitch, and yaw). The control station features a redesigned front-end GUI (graphical user interface) providing simultaneous feeds from four camera views alongside real-time sensor data and thruster outputs. A flight-style HOTAS controller provides the pilot with fine and intuitive vehicle control.

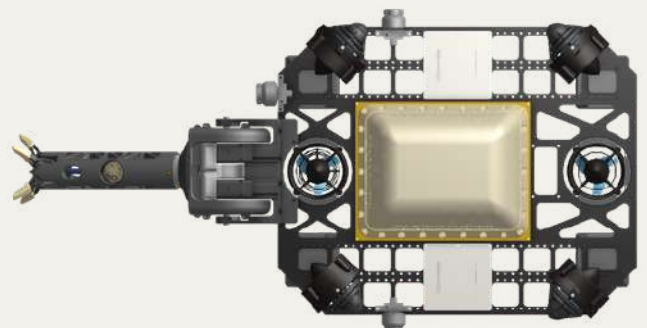


Figure 6. Top-Down View of *Narwhal*

SYSTEM DESIGN

STRUCTURE : FRAME

The purpose of the frame is to serve as the primary mounting structure for all ROV subsystems. Several key requirements were established during the design phase. First, it must provide convenient mounting and protection of all subsystems. Second, the frame must have sufficient structural rigidity while being as lightweight as possible.

In evaluating frame design for X18 *Narwhal*, the team moved away from the double-frame HDPE design used on X17, returning to the single-frame approach from earlier seasons. The driving factors were improved drag characteristics and reduced manufacturing complexity as well as the lessened need for additional tools for the mission tasks. Our latest ROV has a simpler, more effective design - which is critical given this season's competition environment and transport constraints. The streamlined design also accelerated the build timeline, allowing integration and testing to begin earlier in the season.

HDPE was retained as the frame material for its adequate strength, machinability, and buoyancy advantage over aluminum. The mounting pattern was redesigned from X17's hexagonal grid (2" circumscribed diameter) to a conventional row layout with holes spaced 1.75" apart. While the hexagonal grid was intended to maximize mounting points, tool and accessory orientations in practice caused adjacent hexagons to be blocked, reducing usable mounting space. The linear grid resolves this by providing predictable, unobstructed mounting across the full frame surface.

	Manufacturing	Assembly	Cost	Rigidity	Flexibility	Integration	Total
HDPE	4	4	4	4	4	5	5
Aluminum	3	4	4	3	5	3	4
PVC	5	3	3	5	1	3	1

Figure 7. Frame Material Design Rationale



Figure 8. *Narwhal* Frame Manufacturing

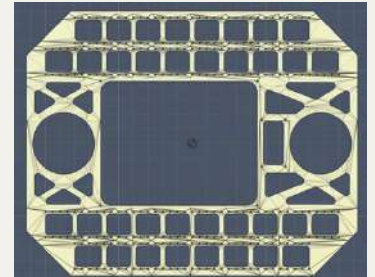


Figure 9. Frame CAD

STRUCTURE : ELECTRONICS ENCLOSURE & ROUTING

The Electronics Enclosure is mounted at the center of the frame and consists of a custom aluminum carrier plate and a clear resin-printed top hat. It houses the team's PCBs (printed circuit boards) and routes signals to other electrical systems on the ROV via penetrators. This design, consistent with previous years, centralizes all electronics in one location, simplifying sealing and leak monitoring.

The top hat is SLA printed from FormLabs Clear Resin V5, which allowed us to incorporate tapered faces and rounded edges for improved hydrodynamics. Unlike previous years' CNC milled aluminum lids, resin printing made this geometry much more practical to manufacture. The strength and transparency of the material were additional factors in this design decision. The lid seals to the carrier plate using an 1/8" x-profile o-ring.

SYSTEM DESIGN

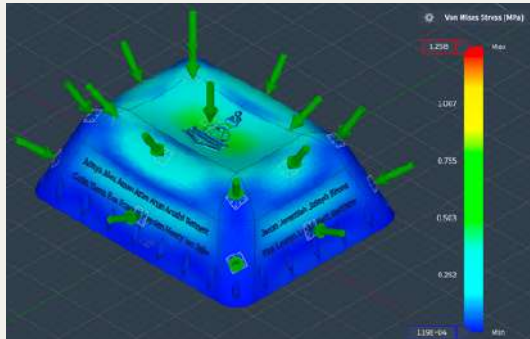


Figure 10. FEA on Enclosure Lid

Several design changes were made to increase reliability. Additional screw holes were added to improve clamping force between the lid and plate. The enclosure height was reduced to eliminate excess space, and exterior features were embossed rather than cut to preserve material strength. Hydrostatic Finite Element Analysis (FEA) was conducted at 7.5m depth to validate wall thickness.

STRUCTURE : CARRIER PLATE & SCAFFOLDING

The carrier plate serves as a mounting platform for the electronics enclosure. It was designed with cross-department feedback to ensure numerous mounting points for scaffolding for the electronics stack and well-placed ports for electrical connectors. The design maintains an even center of gravity while remaining lightweight and modular. The plate was designed using 6061 aluminum to withstand at least 40 psi of external pressure, and an FEA was conducted for design validation before manufacturing.

The combined electronics lid and carrier plate design connect to the tether and provide support for connections to six thrusters, three servos, and multiple USB cameras.

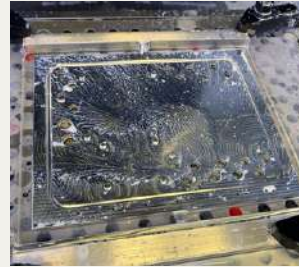
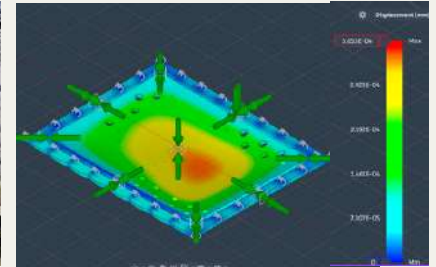


Figure 13. Carrier Plate



Additional ports are included for further expansion and arrangement flexibility, along with a vent plug for vacuum testing.

During manufacturing and pool testing, however, the team encountered several challenges. The o-ring groove in the carrier plate was uneven, and the resin print was warped, dimensionally inaccurate, and failed to sit flat. As a result, the enclosure leaked during testing. To address and resolve these issues within the limited remaining project time frame, the team pivoted to a Polycase enclosure, which offered a clear top for visibility, an IP67-rated seal, and greater flexibility in penetrator hole placement.

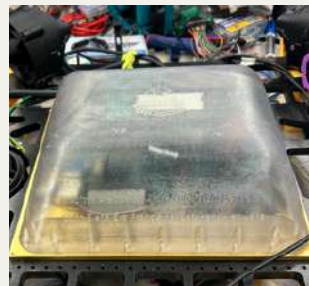


Figure 11. Resin Lid



Figure 12. Polycase

PROPULSION

X18 *Narwhal's* thruster layout departs from previous years, using 6 thrusters instead of 8. The main driving factor was electrical and packaging constraints.

SYSTEM DESIGN

Moving from pneumatics to servo-based tools reduced the total power available for thrusters, and early studies indicated up to 5 servos may be required for tooling, making 8 thrusters difficult to support. An additional design constraint included that *Narwhal* needed to be compact enough for air transport to the mission location in Newfoundland.

The 6-thruster layout was designed to maximize lateral movement and the mobility necessary to complete tasks. Four thrusters are mounted in an X configuration for lateral control, while the two remaining thrusters are mounted vertically at the fore and aft of the ROV for pitch control. Pitch control enables greater pilot visibility and accessibility for specific tasks. Roll control was omitted, as it is rarely needed to complete the requested missions and *Narwhal's* high metacentric stability passively returns the ROV to a level resting position.

TETHER & SPOOL

The tether transfers power and communication between the control station and the ROV. Considerable resources and time were invested into designing a new tether and spooling system to achieve neutral buoyancy, consistency, and efficient operations during ROV operation.

The greatest change from previous years is the elimination of pneumatic tubing, which significantly reduced the size and cost of the tether. Power is transmitted through two 12AWG copper wires and data via CAT6 ethernet cable.

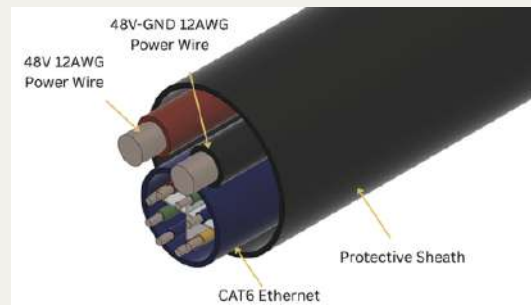


Figure 15. Tether Cross Section

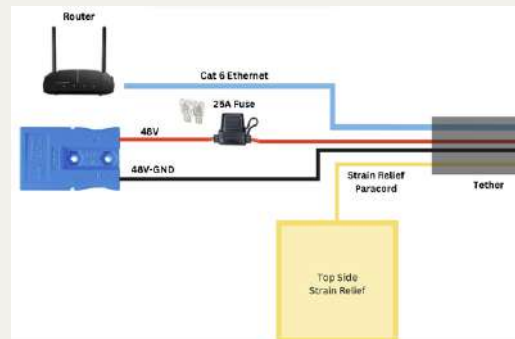


Figure 16. Tether Connection Diagram

The spool was designed in-house to reduce costs and improve on the usability of previous years' designs. The two primary considerations were tangle prevention and portability. Tangle prevention was achieved using two slip rings, concentric but opposite on either side of the spool (one for power and one for data) allowing the spool to spin unencumbered without complicated geometry or bi-directional spooling. For strain relief, a Pass and Seymour style wire mesh strain relief with a single eye was used on either side of the tether, hooking onto the ROV and spool via carabiner.

Tether management protocol can be referenced in the Appendix.

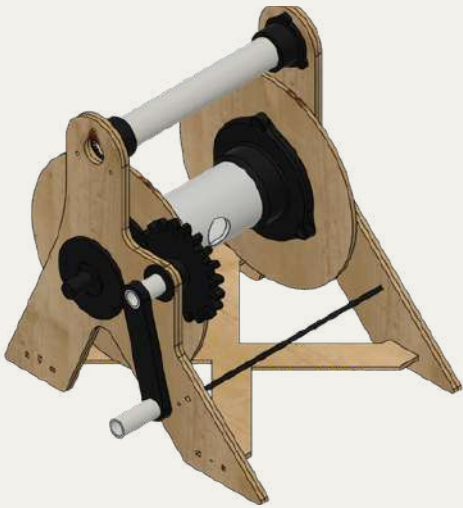


Figure 17. Tether Reel Spool

BUOYANCY & BALLAST

Based on past years' work, Purdue ROV has found that locating the center of buoyancy above the center of gravity (known as metacentric buoyancy) of the ROV provides the best stability, which is particularly important given the rough water conditions of Newfoundland and Labrador, Canada. When tilted, the relative positions of the center of gravity and center of buoyancy cause *Narwhal* to self-right, swinging back to level like a pendulum. X18 achieves this by positioning buoyancy fixtures to extend vertically upward from the frame while placing ballast to sit below the frame.

Each buoyancy unit consists of two three-star ping pong balls contained within a 3D-printed PLA fixture, attached to the frame via 6-32 screws. Each fixture produces approximately 0.69 N of buoyancy force and can be added or removed as needed for trim adjustment.

Ballast containers are designed to hold steel shot and mount to the underside of the frame via screws. In order to minimize its effects on vehicle hydrodynamics, the containers were designed with optimal water flow in mind.



Figure 18. Buoyancy Module

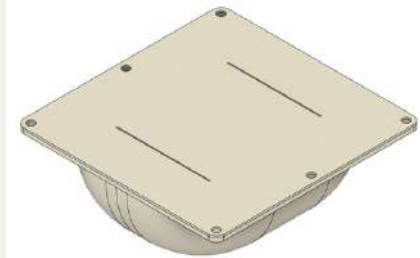


Figure 19. Ballast Module

CONTROLS : ELECTRONICS RATIONALE

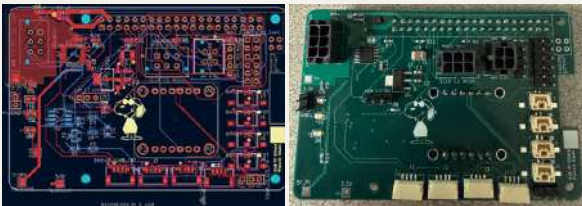
The electrical stack provides power and control to *Narwhal's* subsystems. The stack's six custom PCBs each have a unique functionality, collectively integrating motor and manipulator control, camera streams, power, and communication. Purdue ROV prides itself in teaching new members custom PCB design end-to-end via these boards.

Each year, the stack undergoes an iterative design process to improve upon the previous season's design. The aim is to balance making meaningful improvements against unnecessary changes that could introduce new issues. For our X18 ROV, the key theme was reliability.

The first improvement from X17 was updating the communication protocol. Previously using UART, the team faced hardware issues with RS-485 and software issues with Raspberry Pi UART communication. After evaluating SPI, UART, I2C, and CAN via a decision matrix, SPI was adopted. Purdue ROV has experienced success with SPI in the past and it lacks additional hardware requirements as well as is compatible with Pi pinout constraints. Breadboard prototyping confirmed reliable SPI communication even over connectors with reduced signal integrity.

SYSTEM DESIGN

The second improvement was designing with troubleshooting in mind. Issues with hardware integration are inevitable, so the team learned to embrace troubleshooting when making design choices for this season. To demonstrate this, more reliable connectors were carefully researched and selected. Connector upgrades included Samtec keyed connectors with appropriate power ratings, such as the IPBS Power Socket, which the team customized to fit ROV-specific mechanical and power requirements. Wago 2604-1106 connectors were chosen for thruster motor connections, enabling faster motor swaps - simplifying the troubleshooting process. Additional signal test points were also integrated for embedded protocol debugging. Together, these changes reduced the Electrical Team's troubleshooting time by one week, keeping the team on schedule and freeing additional time for drive practice.



Figures 20, 21. Pi Shield Design and Board

Criteria	Weight	CAN (out of 5)	SPI (out of 5)	I2C (out of 5)	UART (out of 5)
Reliability	40	3	5	4	3
Speed	20	4	4	1	5
Development Complexity	20	2	5	3	2
Number of Devices supported	10	5	2	5	1
Communication Distance	10	5	3	2	3
Total Weighted Score	100	3.4	4.3	3.1	3

Figure 22. Serial Communication Protocol Decision Matrix

CONTROLS : STACK OVERVIEW

The X18 electrical stack functions as the central nervous system of *Narwhal*, translating high-level software commands into precise physical outputs. It is engineered to provide a modular and robust architecture across four pillars of vehicle operation: Power, Motion, Vision, and Tooling.

Power is managed on the Power Slab, where a 1500W DC-DC brick converts 48V tether input to 12V at 31.25A, and a 50W DC-DC brick steps down to 5.2V at 9.6A for the Raspberry Pi 5. Boards requiring 3.3V use local linear regulators for conversion. Power and logic are distributed through the Backplane via board-to-board connectors using SAMTEC ET60T series connectors, eliminating unreliable ribbon cables.

Motion is achieved through six Blue Robotics T200 thrusters driven by two Lumenier BHeli32 4-in-1 ESCs (Electronic Speed Controller), controlled by an STM32 microcontroller communicating with the Raspberry Pi 5 (Pi5) over SPI. The STM32 outputs three PWM signals to each ESC for precise thruster control.

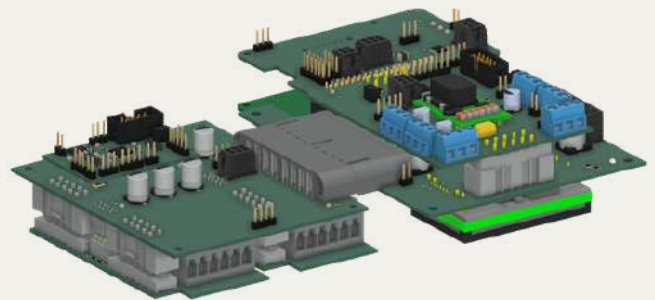


Figure 23. *Narwhal* PCB Stack CAD

Vision is achieved through four cameras. *Narwhal* utilizes ExploreHD 3.0 digital cameras for their USB compatibility with the Pi5, onboard H.264 compression, wide field of view, and high frame rate of 30 fps. A 4-port USB 3.0 hub distributes camera streams to the Pi5, which processes and transmits them to the surface station over Ethernet in the tether.

Tooling is handled through the Tools Board, which supplies 6V power and PWM signals from the STM32 via screw terminals to drive the servo-actuated primary manipulator.

SYSTEM DESIGN

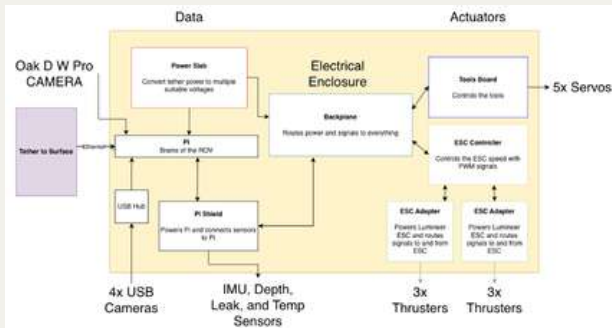


Figure 24. *Narwhal* Boards SID

CONTROLS : POWER CONSUMPTION

Narwhal's power consumption was carefully calculated based on downstream loads and their peak current draws, informing the selection of a power converter that meets system specifications while accounting for losses and overhead. The following table shows the overall power consumption of the ROV along with a breakdown of contributing components.

The primary power draw comes from the six T200 thrusters, which consume approximately 1080W at maximum load. While this threshold is unlikely to be reached in practice, the system is designed to handle it. Based on this analysis, a 1500W DC-DC converter was selected to drive mechanical and electrical loads. To select the appropriate fuse, the full load amperage (FLA) was measured at the theoretical maximum draw.

Items	Max Power Consumption
1 x Raspberry Pi 5	25W
1 x DC-DC Converter Brick (Power Dissipation)	5W
4 x DWE ExploreHD 3.0 Cameras	5W
1 x Oak-D Pro W CV Camera	4W
2 x STM32 Microcontroller (ESC Controller)	2W
(6 x Blue Robotics T200 Thrusters)	1080W
3 x Servos	36W
Miscellaneous (LED, Power Loss, Inefficiency)	5W
Max Total Power Consumed	1162W
Max Current Drawn from 48V Power	24.72A

Figure 25. Fuse Calculation

CONTROLS : TOPSIDE CONTROL BOX

The Control Box serves as the surface-side power station for *Narwhal*. Its primary function is to safely convert 110 VAC power (from a wall outlet) to the 48 VDC required by the ROV, while also providing monitoring and emergency shutoff capability during operation. The system uses four AC-DC power supplies, each converting 110 VAC to 12 VDC at 30A. These are connected in series to produce a 48 VDC, 30A output that provides up to 1440W through the tether. This voltage level was selected to support the high-power demands of the X18 system's thrusters, servos, cameras, and more - while still reducing current draw and heat generation compared to lower-voltage alternatives.

Safety and reliability were significant design priorities. A main power switch serves as an emergency shutoff, allowing the pilot to immediately cut power if any issues occur. The box also includes an LCD power monitor that displays voltage, current, and power consumption in real time for immediate diagnostic feedback, helping operators identify power concerns before ROV failure.

Internal wiring uses 10-12 AWG wire for high-current connections, with components securely mounted and organized to prevent loose wiring or accidental shorts during transport and operation. The system is housed in a hard plastic protective Pelican case for physical protection and ease of transport. The Control Box serves as a power supply as well as a monitoring and control system, allowing the team to operate *Narwhal* safely and diagnose concerns efficiently.



Figures 26, 27. 48V Power Supply

CONTROLS :

SURFACE STATION

In previous seasons, Purdue ROV used a dedicated dual-monitor surface station to maximize space for camera feeds and the pilot interface. While this made it easier to visualize each camera stream individually, it increased system complexity, setup and teardown time, and transportation difficulty. For X18, the team simplified the surface station to better align with the constraint of the mission location being international.

The updated surface station consists of a single laptop, a router, and two HOTAS controllers. This compact setup reduces the number of components that must be transported, assembled, powered, and troubleshoot during competition, making it quicker to pack and deploy.

This redesigned station also improves ease of use for the pilot. Rather than splitting focus across multiple monitors, the pilot views the GUI, camera feeds, and additional key information from one central laptop. The double HOTAS drone flight-simulation controllers allow the pilot to operate and maneuver *Narwhal* with ease. By prioritizing practicality over aesthetics, the team was able to eliminate unnecessary complexity to provide an effective surface control station.



Figure 28. Piloting Station



Figure 29. *Narwhal* Pool Testing

R&D - INNOVATION

Beyond the current season's electrical stack, Purdue ROV actively pursues long-term system innovation through two electrical R&D initiatives: a Hardware-in-the-Loop (HIL) test bench and custom Electronic Speed Controller (ESC) development.

The HIL test bench was developed to solve the critical bottleneck in the team's ROV development process - the dependency on a completed 6-board electrical stack before any software could be validated. The bench replicates the ROV's core control architecture at a surface level, hosting a Raspberry Pi 5 alongside both an STM32 and RP2350B microcontroller (MCU). A muxing system allows real-time toggling of control for thruster ESCs and servos between the two MCUs without hardware reconfiguration, enabling direct comparison to facilitate a potential architecture migration depending on system needs. A separate, external test bench power board adds current sensing, voltage monitoring, and an STM32 for data processing.

In parallel, Purdue ROV is developing custom ESCs to gain full in-house control over one of the most vital subsystems of the vehicle: thrusters. Rather than rely on off-the-shelf ESCs, developing custom technology provides the team with a deeper understanding of motor control, allowing for optimized performance. The current prototype uses an ESP32 microcontroller to generate a six-step PWM commutation sequence through a Texas Instruments DRV8329 gate driver, controlling MOSFETs that drive three-phase Blue Robotics thrusters. Dead time insertion prevents shoot-through, and a high-resolution timer ensures precise, low-jitter commutation for stable thruster operation. The resulting system is a fully functional three-phase inverter to drive brushless DC motors with controlled startup torque, reliable steady-state performance and a clear pathway toward closed-loop control in future seasons.

PILOTING INTERFACE & GUI

The piloting interface is implemented on the surface station using a Flask server that manages communication between the backend system and frontend interface. WebSockets enable real-time interaction with GUI (graphical user interface) elements. The frontend is built with HTML and JavaScript, providing a flexible interface accessible through a standard web browser, so any updates made on the central server are immediately reflected for all operators. Individual subsystem pages allow for modular testing, enabling *Narwhal's* operators to selectively test systems such as thrusters or cameras in isolation, which is especially useful during debugging and development.

The main interface view presents all necessary information to the pilot in an organized layout. It supports simultaneous display of three camera perspectives for situational awareness, real-time sensor data and thruster outputs for system monitoring, and an integrated task management component for tracking mission progress and ensuring correct execution. Together, these elements provide the pilot with ease of control, monitoring, and workflow management within a single interface.



Figure 30. Graphical User Interface

CAMERA ARCHITECTURE

The camera architecture pipeline consists of four main components: the camera devices, the Raspberry Pi, the surface device, and the user interface. The camera devices include three ExploreHD cameras, one Arducam Wide Angle Lens camera, and one OAK-D Luxonis camera, mounted in the front, back, left, right, and downward directions for precise monitoring, movement, and task execution.

The Raspberry Pi captures these feeds as H.264 formatted data for efficient compression and high video quality. MediaMTX, an efficient media server, handles multiple simultaneous streams by assigning each stream a separate RTSP (Real-Time Streaming Protocol) endpoint and packetizing and transmitting the video data to the surface laptop over TCP (Transport Control Protocol).

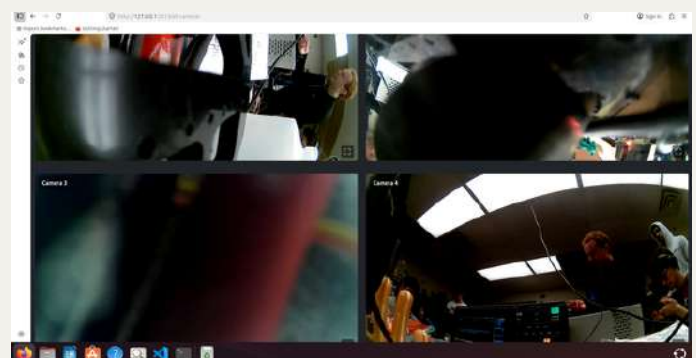


Figure 31. Live Camera Streams

SENSORS

Narwhal is equipped with four sensors to provide the pilot and software stack with critical environmental and vehicle state data.

The MS5837 depth and pressure sensor measures hydrostatic pressure and water temperature via I2C (a serial communication protocol) to calculate precise depth. It operates across a pressure range of 300–1200 mbar, with a pressure accuracy of ± 0.5 to ± 4 mbar and temperature accuracy of $\pm 2^\circ\text{C}$ at 0.1°C precision, transmitting data in a 3-byte message format.

The IMU is the primary navigation sensor, measuring angular acceleration and velocity across all three axes via I2C. It outputs a 12-byte message, allocating 2 bytes per axis across all six degrees of freedom, and is used to continuously track vehicle orientation and motion.

Thermal monitoring is handled by two sensors. The internal Raspberry Pi temperature sensor monitors the core processor's thermal state over SPI (Serial Peripheral Interface - a serial communication protocol), with a range of -40°C to 125°C , $\pm 4^\circ\text{C}$ accuracy, and a 2-byte message format. The Pi is programmed to initiate a safety shutdown before the upper thermal limit is reached. The external hat temperature sensor measures ambient water temperature outside the hull via I2C, providing a refined $\pm 0.4^\circ\text{C}$ to $\pm 1.0^\circ\text{C}$ accuracy in a compact 2-byte format to ensure efficient bus communication. These are especially crucial to aid *Narwhal* in navigating the frigid water conditions of the cryosphere.

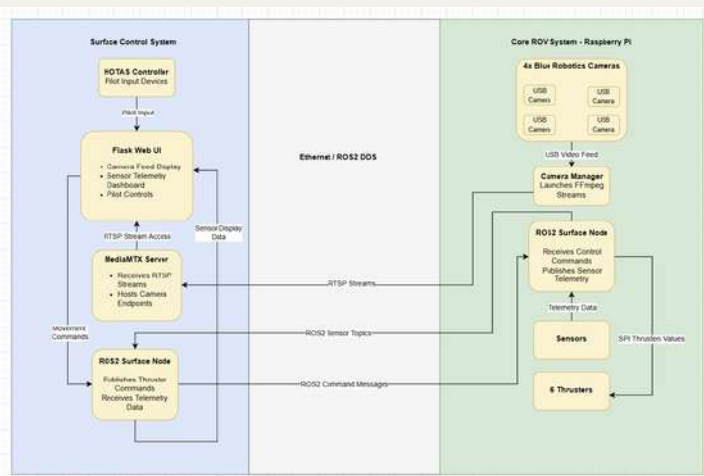


Figure 32. Software Control SID

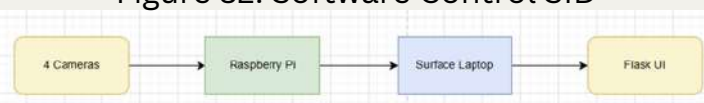


Figure 33. Camera Architecture Pipeline

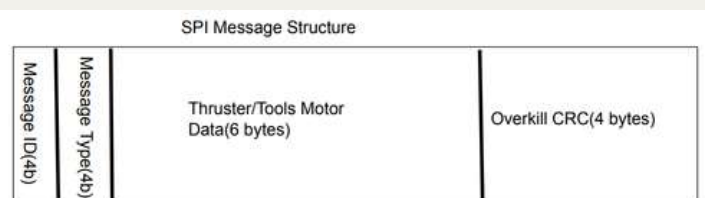


Figure 34. SPI Message Structure

COMPUTER VISION

All CV (Computer Vision) programs obtain relevant camera streams for inference by subscribing to the RTSP endpoint of the MediaMTX server on the surface control station computer. These programs are then run on a separate computer to promote modularity between the CV and software stacks, allowing each program to select the most appropriate camera for its task.

ICEBERG KEEL DEPTH ESTIMATION

Iceberg keel depth for offshore oil platform risk mitigation is determined using the Luxonis OAK-D camera, which captures hardware-undistorted RGB imagery via its onboard ISP (Image Signal Processor) for real-time lens de-warping. The on-camera VPU (Vision Processing Unit) encodes and streams this data] for low-latency, remote analysis.

Rather than relying on noisy underwater stereo depth data, *Narwhal* uses a custom 3D coordinate transformation algorithm. The pilot captures a frame from the stream, and the system uses calibrated intrinsic parameters (fx, fy, cx, cy) to treat each pixel as a high-precision angular vector. The pilot then identifies four key points: the endpoints of a 15cm reference pipe and the variable-length pipe (representative of iceberg keel). From these, the software determines assembly tilt via an inverse cosine function, applies a Y-axis rotation matrix to normalize both pipes to the same virtual Z-depth, and projects the result back into 2D pixel space. The height ratio between the normalized variable pipe and the 15cm reference then yields the keel depth measurement.

This approach eliminates perspective foreshortening and scaling errors caused by ROV pitch and yaw, producing reliable measurements even in unpredictable, high-current environments where vehicle stability is compromised.



Figure 35. Iceberg Keel Depth Estimation

GREEN GRAB IDENTIFICATION

Narwhal can assist with the detection and elimination of invasive European green crabs, which cause aggressive damage to native habitats. This is achieved through a YOLOv8 CNN (Convolutional Neural Network) running on the OAK-D camera's onboard VPU, freeing compute resources on the Raspberry Pi and surface laptop. YOLOv8 was selected as more reliable over a transformer architecture due to dataset size and available compute constraints as well as the team's prior experience using the YOLO library.

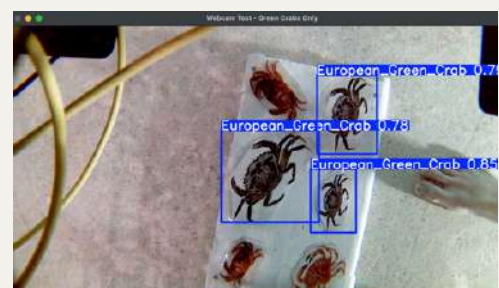


Figure 36. Crab Identification

COMPUTER VISION

The model was trained on a combination of ~1000 images generated from synthetic data and 300 photos of actual crabs. Synthetic data was generated by adjusting reflection, opacity, and orientation of crab images onto pool backgrounds before being fed into the CNN.

The initial model achieved a mAP (mean Average Precision) of 0.84 (model correct 84% of the time, on average) but showed overfitting. The team attempted to switch from RGB to the HSV (High Saturation Value) colorspace to make it simpler for the model to distinguish color underwater and focus on more minute structural details. However, this reduced performance, so the RGB model was retained with the confidence threshold raised from 50% to 73% to reduce false positives.

Lighting variability across underwater conditions remains a known limitation of the current model. This concern was far less pronounced when testing underwater than on-land, suggesting that the training data did not adequately capture the full scope of potential lighting. This will diminish as further pool testing and data can be collected by *Narwhal*.

CORAL REEF RECONSTRUCTION

Narwhal provides the capability to scan and reconstruct environments such as cold-water soft-bodied coral reefs, allowing researchers to deeply understand an inaccessible seafloor environment. Coral reef 3D reconstruction is handled using the RealityCapture API, selected after comparative evaluation of seven approaches (see decision matrix). COLMAP was ruled out due to difficulty detecting thin white PVC pipes and reconstruction times exceeding the 15-minute competition limit. RealityCapture was chosen for its speed, accuracy, and consistency.

Our reconstruction workflow is designed to be both efficient and reliable. The pilot triggers image capture via a mapped controller input and maneuvers *Narwhal* around the coral structure to capture images from multiple angles, ensuring sufficient coverage. This multi-view dataset is transmitted to the RealityCapture API, which performs feature matching, depth estimation, and image alignment to generate a dense 3D model of the coral reef.

The model is then processed within the team's custom-built visualization tool supporting region cropping, scale calibration via a reference object, point-to-point measurement, and model rotation and scaling. This pipeline enables *Narwhal* to successfully address mission critical functionalities - visualizing marked regions, measuring specified dimensions, and recalibrating on judge input.

Approach	Time to Process	Quality of Results	Reliability / Consistency	Ease of Use
Full Manual Reconstruction (In-house)	Very Slow >1 hour	Low-Medium	Low	Low
COLMAP	Medium-Slow	Medium	Medium	Medium-Low
RealityCapture API	Fast	Very High	Very High	High
Agisoft Metashape	Medium	Very High	High	Medium
OpenMVG + OpenMVS	Slow	High	Medium	Low
Meshroom (AliceVision)	Medium-Slow	High	Medium	Medium
VisualSFM	Medium	Medium-High	Medium	Medium

Figure 37. Reconstruction Approach Rationale



Figure 38. Photogrammetry Reconstruction 17

SPECIALIZED TOOLS

PRIMARY MANIPULATOR

This season, Purdue ROV transitioned fully from pneumatic to servo-based tooling. While pneumatics offer compactness and do not require additional waterproofing, their limited extended & retracted states and bulkiness of the manifold are complications and points of failure. Servo tooling necessitates waterproofing around each servo, which is handled on *Narwhal* via custom resin-printed enclosures. These provide flexibility in terms of continuous range of tool motion and eliminate system complexity.

A new primary manipulator (PM) was designed from scratch, as the previous pneumatic system could not be reused. Following in-depth analysis of the mission tasks in the RFP (Request for Proposal) and a build vs. buy evaluation, it was evident the team could custom design a tool with better performance and a lower cost than most COTS (Commercial Off-The-Shelf) solutions. A decision matrix identified a differential drive connected to a piston-crank as the optimal design for arm and wrist motion & claw actuation. The team underwent a series of conceptual iterations and prototyping before the final design, which achieves two degrees of rotational freedom using a wrist differential gearbox driven by two servos for roll and pitch of the arm, with a third servo actuating four claw mandibles via piston-crank. Mandibles are manufactured from Elastic 50A resin for compliant grip, with structural components in Tough 2000 resin and PLA. The PM is integral to *Narwhal's* mission capability, allowing for precise manipulation across tasks ranging from collecting coral & basket stars to deploying whale-safe fishing gear (lobster pot and buoys), and making repairs to underwater facilities and infrastructure through the installation of floating turbines for renewable energy.

Mechanism	Design Complexity	Manufacturing Complexity	Design Quality	Underwater Performance	Cost	Totals
Compound gear train	5	6	5	6	4	26
Cam drive	3	5	7	7	5	27
Ball screw	6	4	4	1	3	18
4-bar linkage	3	8	5	4	5	25
Piston-crank	6	5	6	8	5	30
Lead screw	6	4	4	4	3	21

Figure 39. Arm Mechanisms Decision Matrix



Figure 40. Primary Manipulator

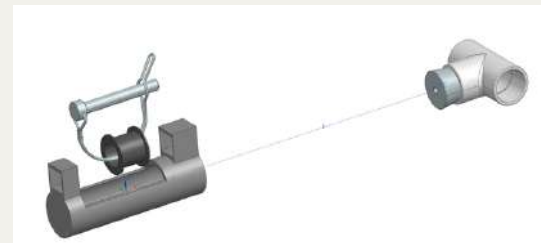


Figure 41. Reel Tool

REEL TOOL

Narwhal includes a specialized, passive reel tool that is designed to recover subsea buoy anchor. The reel tool can latch onto an underwater hook and unspool nylon thread to the surface for an operator to retrieve. The base component is a 3D-printed PLA tube holder that mounts to the frame and contains the nylon thread or attaching line, a clevis pin that serves to secure the thread to the frame, and a rubber stopper that prevents premature unspooling. The hook attachment for the anchor consists of a T-joint and carabiner. As *Narwhal* ascends, the T-joint separates from the main tube and remains attached to the underwater hook.

Mechanism	Design Complexity	Manufacturing Complexity	Design Quality	Underwater Performance	Cost	Totals
Serial linkage	6	6	2	4	6	18
Parallel linkage	5	5	4	3	4	17
Differential drive	3	5	10	9	5	27
Coaxial belt drive	4	4	7	2	3	17

Figure 42. Claw Actuation Decision Matrix

CRITICAL ANALYSIS

TESTING & TROUBLESHOOTING

A variety of testing methodologies were employed throughout the initial design process and iterations following. Mechanical parts underwent finite element verification prior to manufacturing. Pressure-critical and high-cost components were verified to a minimum factor of safety (FoS) of 2.0, while non-sensitive components required a minimum FoS of 1.5 for final versions. Potentially pressure-sensitive components were also tested utilizing a pressure testing chamber up to 50 psi before ROV installation, allowing the team to isolate leakage and submersion-related failures from purely mechanical ones.

When parts were found to be structurally inadequate, the first step was to optimize component geometry using FEA to reduce stress concentrations. Where simple geometry changes were insufficient, the team came up with multiple potential solutions. On some components, design modifications included adding structural support or manufacturing changes (e.g. increased 3D print infill or alternative filament materials) which resolved failures. For mission-critical tools, multiple versions were produced in parallel to select the best-performing design and foster cross-member mentoring. Rapid prototyping was heavily encouraged throughout to improve member understanding of component sizing and reduce CAD misjudgments.

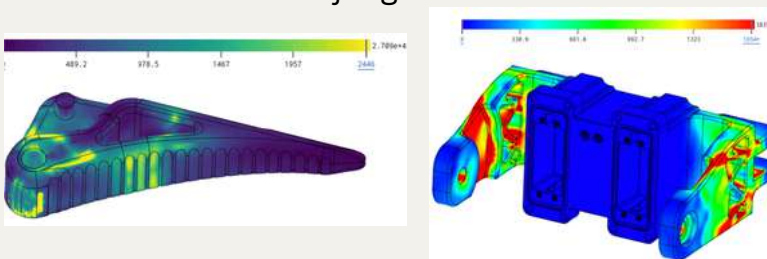


Figure 43,44: FEA Conducted on PM Parts

BUILD V. BUY & NEW V. USED

Purdue ROV strongly prioritizes in-house manufacturing to maximize technical and hands-on experience for team members. However, the team also recognizes that some items are more practical to purchase. Stock materials such as PLA, HDPE, and aluminum are purchased but machined in-house into components including the frame, primary manipulator, feet/stands, camera enclosures, and buoyancy & ballast modules. Specific resin-printed components were outsourced to FormLabs due to printer availability constraints at Purdue. Electrical purchases are limited to components that cannot feasibly be fabricated in-house such as power bricks, SMD LEDs, JST connectors, and ESCs. All six PCBs in the electrical stack are designed and assembled in-house, and the ongoing R&D project developing custom ESCs will eliminate that purchase in future seasons.

Purdue ROV's eighteen-year history has resulted in a substantial inventory, therefore, the team's policy is to maximize the reuse of working systems and components to eliminate wasteful spending. Topside components (Pelican cases, power supplies, and monitors) have been reliably reused across multiple seasons. On *Narwhal*, BlueRobotics T200 thrusters, o-rings, screws, and penetrators are reused from inventory. For software, existing Arducam and ExploreHD cameras are reused for primary streams, while the Luxonis OAK-D was purchased this season to meet computer vision performance requirements. It contains an onboard VPU handles video encoding to reduce Raspberry Pi compute load and a OV9782 sensor that reduces latency and flickering during vehicle motion. Teamwide, all workspace tooling is reused, and software such as Onshape and KiCad is utilized under free educational licenses. Altium has been provided through sponsorship for advanced PCB analysis.

PHILOSOPHY

At Purdue ROV, safety is non-negotiable. A safe, secure work environment extends beyond just injury prevention but also is a contributing factor to employee, productivity, comfort and general team morale. Every decision made and tool used is first evaluated through the perspective of safety for all employees, bystanders, and equipment involved.

STANDARDS

Purdue ROV enforces a comprehensive set of standard operating procedures (SOPs) that applies to all employees working on *Narwhal*. Before receiving access to the team workspace, new members must complete mandatory hazard and safety training modules. Additionally, operating hazardous equipment and tooling requires approval from team leads and senior employees. This season, a Safety Officer was appointed to monitor compliance to these SOPs and ensure proper and up-to-date documentation.

Over the team's eighteen years of competition experience, rules governing handling of high-voltages, PPE requirements, and power tool operation have been developed and continuously reviewed - informed by resources such as the Oceaneering HSE Employee Handbook. ROV construction-phase safety checklists are also followed to minimize risks at every stage of the process.

Following recent seasons' emphases on chemical safety, the team conducted a full chemical inventory audit. Outdated chemicals were properly disposed of and it was verified that all hazardous substances are being stored in compliance to building safety regulations.

SAFETY FEATURES

Narwhal takes into consideration safety requirements across electrical, mechanical, and software subsystems.

On the mechanical side, the HDPE frame features rounded, smooth edges. Aluminum parts such as the carrier plate have been anodized to prevent corrosion and mitigate any associated risks. *Narwhal's* custom thruster shrouds satisfy IP-20 ingress protection, meaning they can block objects larger than 12.5mm without significantly affecting water flow. These serve to protect the pilot and any handlers of the vehicle.

On the electrical side, the tether is equipped with a master fuse as well as adequate strain relief to protect the electrical system and frame. All high-current wiring in the control box utilizes 10-12 AWG wire and all components in the electronics enclosure are securely mounted using scaffolding.

Finally, the pilot interface and GUI provides real-time monitoring of current draw, Raspberry Pi temperature, and leak detection status. These enable the pilot to identify any potentially unsafe conditions and shut off power to *Narwhal* before any issues can worsen or damage the ROV.

ACCOUNTING

At Purdue ROV, financials are handled prior to the start of each season. The annual budget is created from a variety of combined factors that include - previous budgets, projected incomes, and potential future expenditures. Some costs are guaranteed, such as the costs of producing X18 *Narwhal*, securing new and improving workspace equipment, and traveling to the mission location. As a result of cuts in provided grant funding, the objective this season was to reduce overall development costs as much as reasonably achievable. A core belief is that spending must only happen if absolutely necessary and thorough justification is provided.

To reflect these, the team strongly emphasized the re-use of stock materials and components (mentioned in more detail in Critical Analysis) over making large, COTS purchases. For instance, re-using T200 thrusters from the X17 ROV allowed us to save \$1,200 on new thrusters. Purdue ROV also made larger pushes to pursue sponsors to provide discounted parts or services to aid in the design and fabrication of X18 *Narwhal*. Milwaukee Tool agreed to a partnership where the team will receive any necessary or missing tools rather than direct cash funding. Resin prints for servo and electronics enclosures were donated by an alumni at FormLabs. Altium and Onshape graciously sponsored the team by providing multiple free licenses.

To improve funding, Purdue ROV leveraged our extensive alumni network and academic connections. The team applied for and received a grant of \$8,400 from the Student Fee Advisory Board (SFAB) at Purdue University. After pitching proposals and partnership opportunities to the Departments of Mechanical & Electrical and Computer Engineering (ECE), we received \$2,500 and \$3,000 respectively. Alumni contributions totalled \$1,200, with a match from Analog Devices bringing that to \$2,200. Additionally, the team led crowdfunding efforts through partnerships with Chipotle, Panda Express, and Purdue For Life.

This strategy and strong focus on limiting costs resulted in a budgetary surplus of approximately \$3,930, eliminating deficits from the previous season and providing Purdue ROV with decent capital to enter the next season. This has provided the team with invaluable connections and contacts as well as income streams for the future.

Thing	Things Price	Purchased?	Total Price	Included Under	Link to thing
Desoldering Guns	39	1	39	Hot Air Gun Stat	https://www.amazon.com/high
Rework Station	135	1	135	Hot Air Gun Stat	https://www.amazon.com/dp/B0
Clamp Fancy Thing	63	1	63	Hot Air Gun Stat	https://www.newegg.com/p/2A
Jumper Wires	7	1	7	Hot Air Gun Stat	https://www.amazon.com/Eleg
Wick	9.99	1	9.99	Hot Air Gun Station	
Solder Vent	33.99	1	33.99	Hot Air Gun Station	
JLPCB Boards	682.92	1	682.92	Board Fabrication	
Soldering Supplies	190.41	1	190.41	Soldering Iron Station	
Brick 48 -> 12	125	2	250	Power Electronic	https://www.digikey.com/en/pro
Brick 12 -> 5	55	1	55	Power Electronic	https://www.digikey.com/en/p
Digikey Parts	368.57	1	368.57	Electronics Passive Components	
Soldering Stands		1			
Samtec Connectors	98.12	1	98.12	Electrical Components	
Lumineer ESC	52.94	1	52.94	Electronic Speed Controllers	
Category	Budget	Spent	Remaining	Notes	
Electronics Passive Components	\$500	368.57		\$131	Parts ordered
Microcontroller & semiconductor components	\$400				
Power electronics components	\$500	305		\$195	
Board fabrication	\$400	682.92		-\$283	
Electronic speed controllers	\$360	52.94		\$307	one ESC
Soldering iron station	\$632	537.33		\$95	
Raspberry Pi 5 CM Kit	\$324				
Hot air gun station	\$900	291.06		\$609	
Raspberry Pi 5	\$480				
Electrical Components	\$200	155.01		\$45	lec and IMUs

Figure 45. Electrical Department Financial Tracking

X18 Narwhal Budget					
Budget Category	Item Description	Type	Cost	Budget	Spent
Production ROV Expenses					
Elec - Boards/Components	PCB Fabrication (JLPCB) = board components (ICs, resistors, passives)	Purchased	\$683	\$1,000	\$683
Elec - Boards/Components	Passive components, Digikey parts (SMD LEDs, JST connectors, etc.)	Purchased	\$369	\$500	\$369
Elec - Boards/Components	Power electronics (48V -> 12V 1500W brick x2, 12V -> 5V converter)	Purchased	\$305	\$400	\$305
Elec - Boards/Components	Samtec connectors (IPBS Power Socket Strip, ET60T series)	Purchased	\$98	\$200	\$98
Elec - Boards/Components	Lumenier BHeli32 4-in-1 ESCs x2	Purchased	\$106	\$300	\$106
Elec - Boards/Components	Raspberry Pi 5 + accessories	Purchased	\$480	\$500	\$480
Mechanical - Structures	HDPE stock for frame, carrier plate, hardware, o-rings, screws	Purchased	\$560	\$750	\$560
Mechanical - Structures	Waterjetting services (frame)	Donated	\$200		
Mechanical - Thrusters	BlueRobotics T200 Thrusters x6	Re-used	\$1,600		
Mechanical - Tether	Tether (CAT8 + 12AWG, spool, slip rings, strain relief)	Purchased	\$420	\$500	\$420
Mechanical - Tools	ServoCity 2000 Series 5-Turn Dual Mode Servos x5	Purchased	\$375	\$400	\$375
Mechanical - Tools	Materials for PM, tools, filament (PLA, PETG), springs, tubing	Purchased	\$454	\$600	\$454
Mechanical - Tools	FormLabs resin printing (Tough 2000, Elastic 50A) for enclosures + parts	Donated	\$380	\$400	\$380
Mechanical - Enclosure	Polycase enclosure (IP67-rated)	Purchased	\$85	\$100	\$85
Software - Cameras	DWE ExploreHD 3.0 Digital Cameras x3	Re-used	\$900		
Software - Cameras	Arducam Wide Angle Lens Camera	Re-used	\$120		
Software - Cameras	Luxonis OAK-D Pro stereo vision camera (CV tasks)	Purchased	\$400	\$1,000	\$429
Software - Sensors	MS5837 depth/pressure sensor, IMU, leak sensors, temp sensors	Purchased	\$244	\$250	\$244
Non-ROV Device Expenses					
R&D - HIL Testbench	HIL carrier board components (STM32, RP2350B, mux, headers)	Purchased	\$320	\$500	\$320
R&D - Custom ESC	Custom ESC prototype (ESP32, TI DRV8329 gate driver, etc.)	Purchased	\$175	\$300	\$175
R&D - Float	Mechanical prototype components (V1+V2 PM iterations, FDM parts)	Purchased	\$878	\$750	\$878
Miscellaneous Expenses					
Mechanical Equipment	3D printers, digital calipers, scales, hand tools	Re-used	\$800		
Electrical Equipment	Soldering stations, hot air rework station, desoldering guns,	Purchased	\$828	\$1,432	\$828
Software Tools	Onshape CAD (educational license)	Donated	\$0		
Software Tools	KiCad PCB design (open source)	Donated	\$0		
Software Tools	Altium Designer (sponsored access)	Donated	\$3,500		
Surface Station	HOTAS dual-throttle flight controllers x2	Purchased	\$250	\$250	\$250
Surface Station	Surface station laptop, router, cables, adapters	Re-used	\$1,200		
Surface Station	Surface station Pelican case	Re-used	\$470		
Power Station	Control box (AC-DC power supplies x4, enclosure, LCD monitor, etc.)	Re-used	\$414		
Props	PVC, connectors, assorted materials for competition props	Purchased	\$294	\$300	\$294
Administrative Expenses					
Pool Tests	Hampton Inn & Suites - overnight pool test accommodation	Donated	\$817		
Competition Expense	World Championship hotel lodging (international)	Estimated	\$5,000	\$4,000	\$5,000
Competition Expense	Travel subsidization (flights, van rental, gas)	Estimated	\$1,000	\$1,000	\$1,000
Competition Expense	MATE ROV registration	Purchased	\$650	\$650	\$650
Total Expenses			\$24,147	\$16,182	\$14,250

Figure 46. X18 Budget and Spending

Fundraising & Income	
Purdue SFAB (Student Fee Fund)	\$8,400
Purdue School of Mechanical Engineering	\$2,500
Purdue School of ECE	\$3,000
Purdue For Life & Additional Crowdfunding Campaigns	\$1,000
Michael Hayashi - Previous Captain (private donor)	\$1,000
Hayashi - Analog Devices match (corporate donor)	\$1,000
Seth Baklor - Founder (private donor)	\$200
Emergency / Captain Fund (cash)	\$1,080
Income Total	\$18,180
Surplus	\$3,930

Figure 47. X18 Income Totals

ACKNOWLEDGEMENTS

GOLD SPONSORS



SILVER SPONSORS



THE HAYASHI FAMILY

BRONZE SPONSORS



Purdue ROV would like to thank:

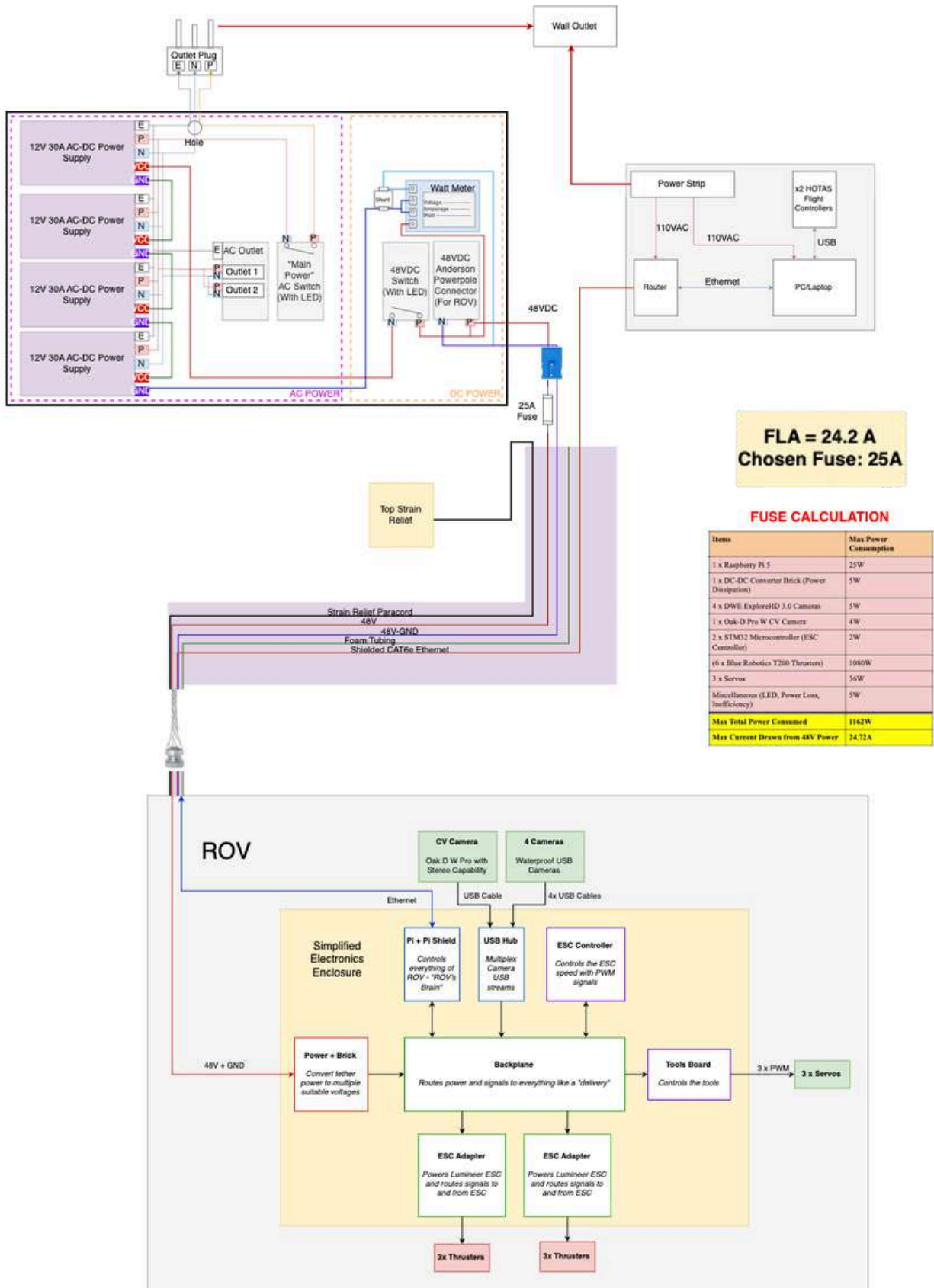
Parents and Family for advice and support | MATE Center for providing us this opportunity
Volunteers and Judges at the MATE Competition | Company alumni for their support throughout the year | All our employees for their hard work throughout the year | Purdue IEEE Student Branch for being a great parent organization | Lafayette Jefferson High School and Hampton Inn for their provision of pools for testing | Bechtel Innovation Design Center for their manufacturing assistance

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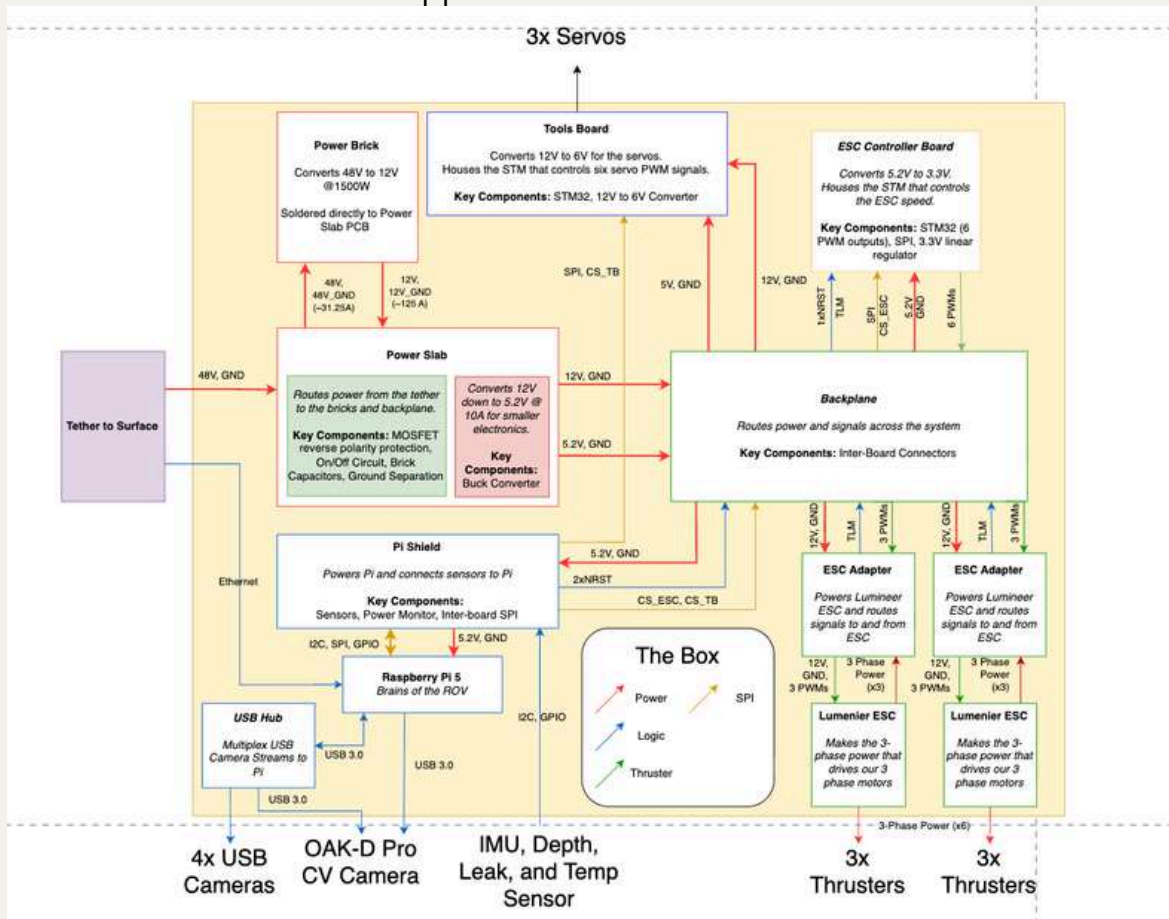
APPENDIX - SIDS & PROTOCOLS

Appendix A. Full Electrical SID

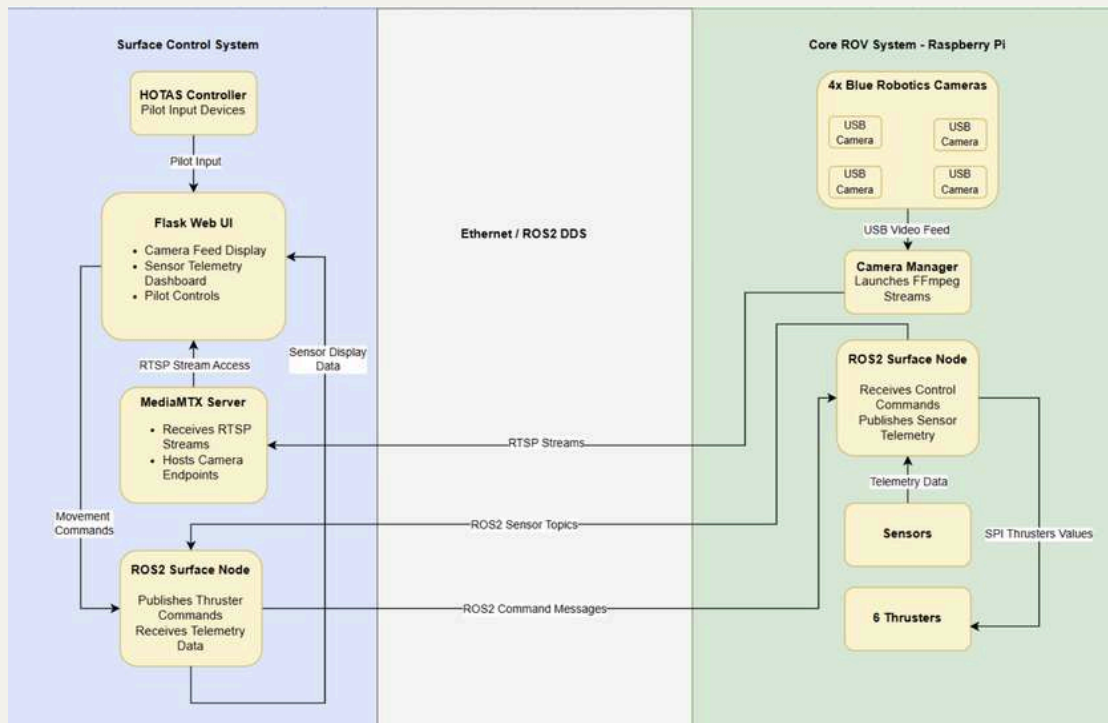


APPENDIX - SIDS & PROTOCOLS

Appendix B. Boards SID



Appendix C. Software Control SID



APPENDIX - SIDS & PROTOCOLS

Appendix D. Safety Checklist

Pre-Deployment (Power OFF)

- ☐ Area is clear of obstructions/hazards
- ☐ Power supply is OFF
- ☐ Cables and tether are undamaged
- ☐ Cables are tied down and not loose
- ☐ Connectors are fully inserted
- ☐ Tether strain relief wire are attached to a stable structure
- ☐ Screws are tightened on electronics and pneumatics enclosures

Deployment (Power ON)

- ☐ Pilot sets up surface station
- ☐ Pilot calls team to attention
- ☐ Co-pilot calls out "Power ON" and switches on power supply
- ☐ Deployment members verify ROV is on with thruster ESC startup sequence
- ☐ Deployment members place ROV into the water and hold it securely underwater
- ☐ Deployment members release air pockets
- ☐ Deployment members check for signs of a leak (e.g. bubbles)
 - ☐ Leaked, go to **Failed Bubble Check**
 - ☐ Else, deployment members shout "ROV ready" and continue checklist
- ☐ Pilot arms ROV and ensure controller movements correspond to thrusters
- ☐ Pilot checks camera streams and tool actuation
- ☐ Continue to Launch

Failed Bubble Check

- ☐ Deployment members pull ROV out of water
- ☐ Co-pilot turns off power supply and calls out "Power OFF"
- ☐ Members wipe off water on ROV
- ☐ Members visually inspect to determine source of leak
- ☐ Members document cause of leak, implement corrective actions and check all systems for damage

Launch

- ☐ Pilot calls "ROV Launch" and starts timer
- ☐ Deployment members let go of ROV and shout "ROV released"
- ☐ Continue to ROV retrieval if no issues arise

Lost Communication

- ☐ Steps attempted in order. Mission resumes when one succeeds.
- ☐ Co-pilot checks tether and laptop connections on the surface
- ☐ Pilot attempts to reset the BattleStation
- ☐ Co-pilot cycles the power supply
- ☐ Co-pilot turns power supply off and calls out "Power off"
- ☐ Deployment team pulls ROV to surface

ROV Retrieval

- ☐ Pilot drives ROV to side of pool, disables thrusters and calls out "Retrieve ROV"
- ☐ Deployment members pull out ROV
- ☐ Deployment members call out "ROV retrieved"
- ☐ Continue to demobilization or launch

Demobilization

- ☐ Co-pilot turns off power and calls "Power Off"
- ☐ Deployment members do visual inspection for damage
- ☐ Pilot powers off battle station
- ☐ Anderson connectors of tether are removed from power supply
- ☐ Turn off air compressor and vent line
- ☐ Remove air line from pneumatics enclosure

Assembly Check

- ☐ ROV disconnected from power and pneumatics
- ☐ PCBs are clean without visible damage
- ☐ No wires are disconnected, loose, exposed or can get pinched by box or thrusters
- ☐ Inside of the box is clear of water (residue)
- ☐ Enclosure shows no sign of damage
- ☐ All ports on the carrier plate are firmly screwed on
- ☐ O-rings are undamaged and lubricated.
- ☐ O-ring grooves are clean and unmarred
- ☐ Tools are firmly attached to frame with little to no play
- ☐ Power on pneumatics and check for leaks via "hiss" sounds and soapy water spray bottle
- ☐ When powered, PCB warning lights are off

Appendix E. Tether Management Protocol

1. Designate a deck hand as the tether handler.
2. Tether handler positions tether spool and uncoils as little as is needed for handling on the deck, preventing the tether from kinking or tangling.
3. Tether is connected to the surface station strain relief, then ethernet, then power.
4. Strain relief is checked on both ROV and surface station side.
5. While the ROV is operating the tether handler must always have contact with the tether.
6. Do not pull on the tether to clear a snag
7. Do not step on the tether to prevent damage
8. Tether handler must provide just enough length necessary to allow the ROV to reach its working depth.
9. ROV pilots must avoid 360 rotations and close maneuvers around obstacles when possible, to avoid tangling.
10. Once operations are complete, the tether handler is in charge of disconnecting the tether from the surface station and power.
11. After disconnection, the tether handler respools tether.