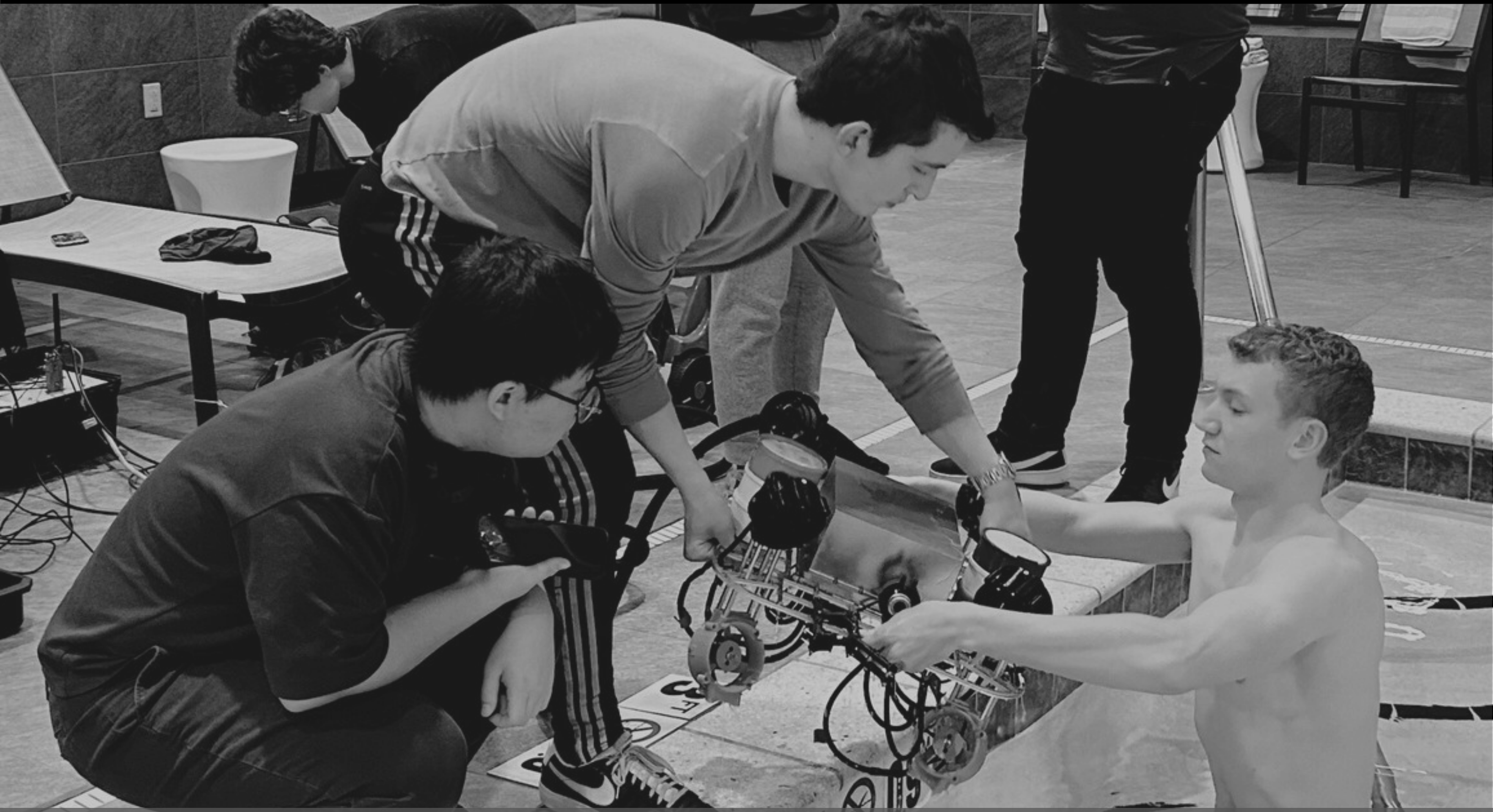
TECHNICAL REPORT

PURDUE ROV '24

PURDUE UNIVERSITY | WEST LAFAYETTE, IN USA



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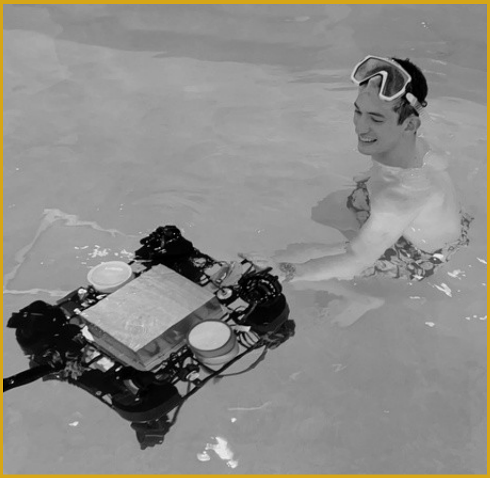
In response to MATE's request for proposals (RFP), Purdue ROV is proud to present X16 *Nemo*, a remotely operated underwater vehicle designed specifically to address ocean restoration and the ten challenges identified by the UN's Ocean Decade. Named to reflect the ingenuity and heroism of Captain Nemo from *Twenty Thousand Leagues Under the Sea*, X16 *Nemo* was developed through the collaboration of over 45 employees across the mechanical, electrical, software, and administrative departments at Purdue.

Using fifteen years of experience, Purdue ROV has developed *Nemo* based on the belief that the best ROVs are reliable, adaptable to any mission, and easy to pilot. *Nemo* builds upon the company's past success while continuing to push the envelope with new innovations and improvements tailoring X16 to the mission. *Nemo* is manufactured out of T6061 aluminum for a rugged and durable chassis and boasts custom electronics, designed in house and rigorously tested to ensure reliability. *Nemo* also features unparalleled ease-of-piloting through a new control station, expanded field of view, numerous control improvements, and a new, user-friendly pilot control interface. During *Nemo*'s development, Purdue ROV emphasized multiple design iterations, rigorous testing, and strict safety practices.

Designed specially for completing mission tasks, *Nemo* is the ideal ROV for deploying floats, laying SMART-cable, restoring coral, and monitoring ocean health. In total, *Nemo* highlights precise custom tools, excellent computer vision, and an articulating primary manipulator, making it well-equipped to aid in ocean preservation.



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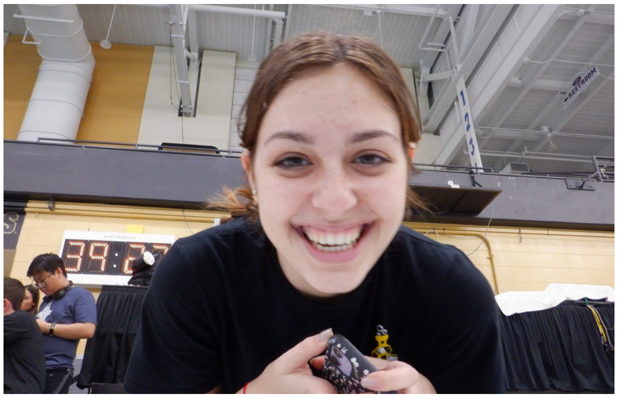


TEAMWORK

COMPANY ORGANIZATION

Purdue ROV is a collaborative team of **forty-seven members** spread across three different colleges and eleven majors. In order to maintain cohesion across such a large and diverse team, Purdue ROV is organized into three different technical departments - mechanical, electrical, and software - as well as an administrative department that oversees finances, outreach, and growth.

Each technical department is organized hierarchically with department leads and project-specific sub-leads for major subsystems such as the tools or front-end. The leads are responsible for creating the vision and design requirements for the ROV as well as acting as project managers for their departments. Each lead reports to the CEO, who enforces competition and university regulations, sets a high-level schedule for the team, and coordinates a team-wide design.

The company recruits new employees every fall, and the department leads oversee their training and mentorship. Employees are given ownership of an individual project, ensuring every employee ends the season as an expert in their subsystem. The leads specify design requirements and ensure the system can be integrated into the project as a whole. Purdue ROV also heavily emphasizes **cross-department collaboration**, with several project teams that function across departments, such as our embedded project team, which is composed of both electrical and software employees.

PROJECT MANAGEMENT

Purdue ROV follows a weekly development cycle, starting with a leadership planning meeting every Monday. In this meeting, leadership will set weekly goals and assess whether each team can adhere to the project schedule. Next, the whole team convenes on Wednesday, where the CEO announces upcoming project milestones. Each department holds its short stand-ups to discuss current progress, weekly goals, and obstacles preventing them from progressing. Employees spend the rest of the meeting working on their respective projects. The week concludes with a Saturday general meeting consisting of the same principles, intended for employees to use to complete their weekly goals.

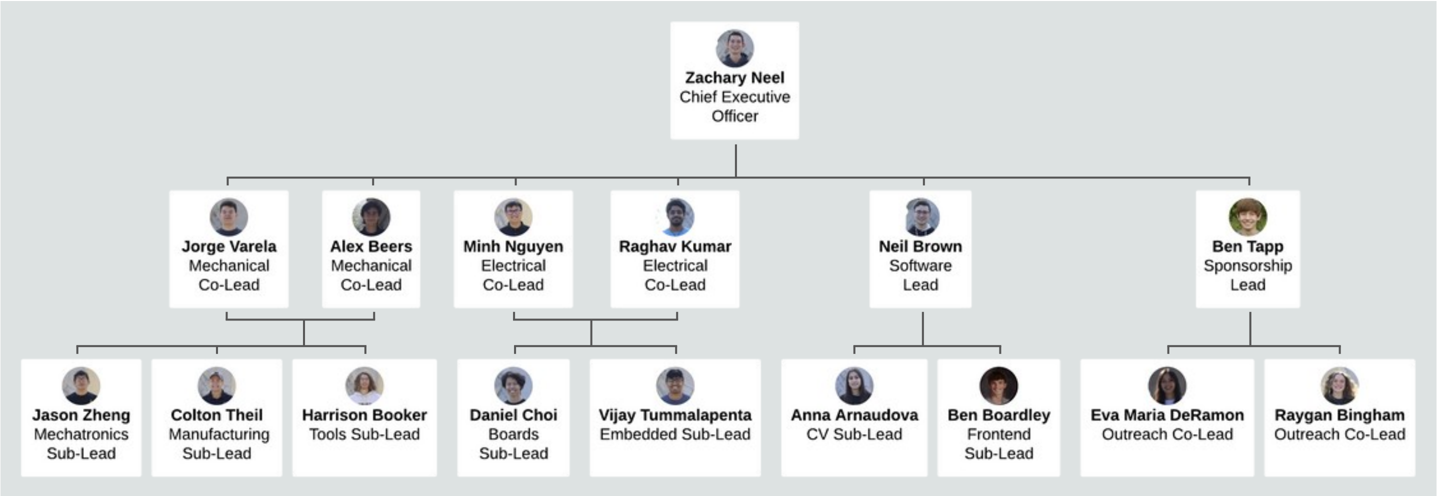


Fig. 1: Company Organizational Chart

In terms of project management tools, the team uses Slack for general communication, Google Drive for general file-sharing, Trello for project management, GitHub for software version control, and more as seen in Figure 2. Additionally, the team adopted Aras Innovator for CAD file-sharing and version control this year. Aras Innovator represents the cutting edge of project lifecycle management (PLM) software, providing employees with valuable experience with enterprise-level project management software and improving the mechanical department's scalability and ease of integration.

Resource	Usage Area
Slack & Discord	Team communication and planning
Google Drive	Documents for leadership, subteams, and administrative tasks
GitHub	Code and PCB files
Google Photos	Media from pool tests, various events, and project progression
Book Stack	Documentation of engineering design process
BoilerBooks	Accounting information, funding, and expenditures

Table 1: Project Management Tools

PROJECT SCHEDULE

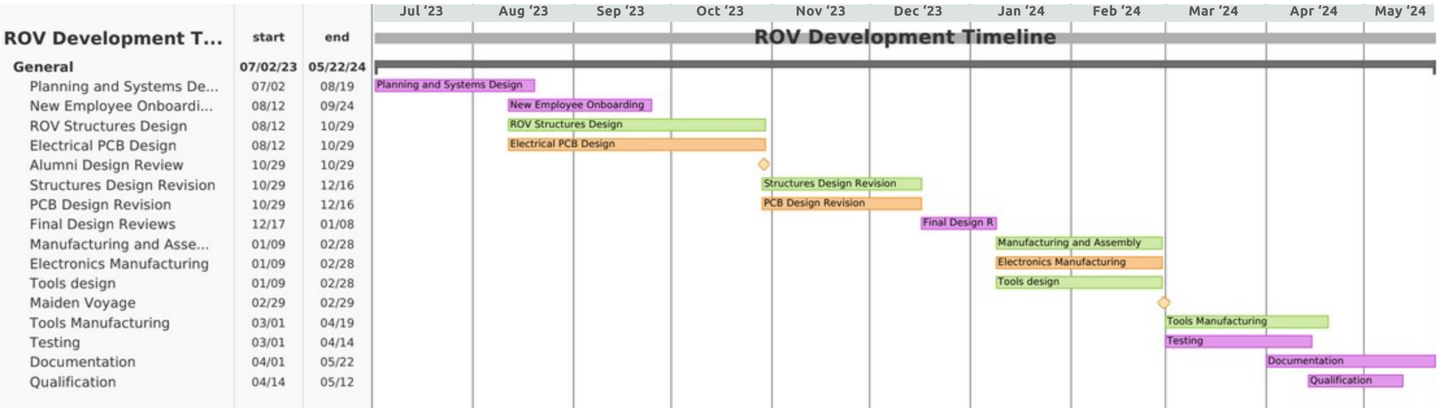
Purdue ROV's design cycle is split into four stages: **training, design, manufacturing, and testing**, all seen in events in Figure 3. Before the school year begins, the leadership creates SIDs, project timelines, and sets design requirements for the base vehicle. At the start of the semester, the team enters the training phase, where new employees are recruited and trained in applicable departmental skills such as NX CAD, Eagle PCB design, Embedded C, Python, ROS, Git, and more.

Next, the team enters the design phase, modeling the ROV in CAD, designing custom electronics, and programming the front-end control software. This phase consists of many internal design reviews and culminates with an alumni design review. During this event, employees present their designs to industry members and gain valuable feedback before manufacturing.

In the manufacturing phase, components for the ROV are fabricated and assembled. Purdue ROV prides itself on manufacturing in-house as much as possible to teach employees industry-applicable skills. Manufacturing culminates in the maiden voyage, marking the moment when the assembled ROV undergoes its inaugural pool test. Finally, during the testing phase, various subsystems of the ROV will be fine-tuned as the team makes the final preparations for the product launch date.

Feature	Innovation	Benefits
Mechanical Features	Custom Pneumatic Enclosure	Better structured manifold, reduce power consumption through pneumatics, and reduce servos/thrusters, reduce cost
	Articulated PM	'Claw Machine' control leads to reduced piloting difficulty
	Valve Turner	Springs allow for self-centering reducing piloting difficulty
	Surface Station	Enhance piloting experience and reduce set-up time
Electrical Features	Additional Wide Angle USB 3.0 Cameras	Enhance piloting experience, increase ease of development, reduced cost
	Customized PCB Design	Increase functional customizability, increase boards modularity, decrease number of boards, reduce cost
Software Features	New Front-end	Increase simplicity, increase responsive control, decrease maintenance, increase flexibility
	Control Mode Changes	Allows individual pilots to create desired piloting scheme

Table 2: ROV Nemo Innovations



ROV Development T...	start	end
General	**07/02/23**	**05/22/24**
Planning and Systems De...	07/02	08/19
New Employee Onboardi...	08/12	09/24
ROV Structures Design	08/12	10/29
Electrical PCB Design	08/12	10/29
Alumni Design Review	10/29	10/29
Structures Design Revision	10/29	12/16
PCB Design Revision	10/29	12/16
Final Design Reviews	12/17	01/08
Manufacturing and Asse...	01/09	02/28
Electronics Manufacturing	01/09	02/28
Tools design	01/09	02/28
Maiden Voyage	02/29	02/29
Tools Manufacturing	03/01	04/19
Testing	03/01	04/14
Documentation	04/01	05/22
Qualification	04/14	05/12

Fig. 2: Company Gantt Chart; Purple is General, Green is Mechanical Dept, Orange is Electrical Dept

DESIGN RATIONALE

VEHICLE OVERVIEW

Throughout the team's 16 years of experience, we have learned that the best ROVs are adaptable to any mission task, easy to pilot, and reliable. X16 *Nemo* is designed with three main principles: **adaptability**, **simplicity**, and **reliability**.

With **adaptability** in mind, X16 *Nemo* is designed with a single plate frame for easy access to the electronics. The grid spacing on the frame plate is standardized to simplify tool mounting design and allow for modular tool placement on the ROV. Additionally, X16 Nemo is designed with adjustable buoyancy through mountable foam blocks to easily tune the center of buoyancy (CoB). To improve drivability, the CoB is positioned slightly above the center of mass. This results in a stable and maneuverable ROV that does not over-correct for rotations. We also opted to maintain the same thruster configuration from X14 and X15, as it is both proven to be reliable and our pilots have found that the symmetric thrust profiles make it easier to pilot. In terms of hardware, X16 Nemo's electronics were designed with **reliability** and modularity in mind, ensuring the ROV could handle any mission tasks and would not fail during a mission.

X16-Nemo continues utilizing pneumatic power for mission tools. Fluid power shifts the power load from the electrical stack toward the mechanical team. This allows for maximal power provided towards the thrusters - which is required due to our use of eight T200 thrusters. It also comes with a myriad of other benefits such as reduced electrical complexity, more lenient power constraints, and better grip strength for manipulators. Therefore, Purdue ROV determined that the benefits of pneumatic power were worth the additional complexity and design effort.

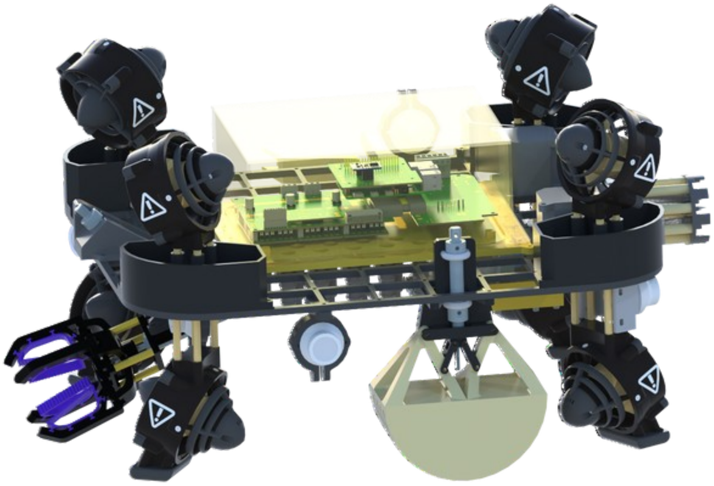
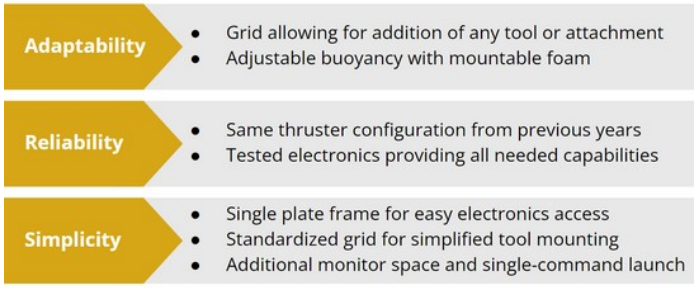


Fig. 3: X16 Nemo Design Rendering



Adaptability	• Grid allowing for addition of any tool or attachment • Adjustable buoyancy with mountable foam
Reliability	• Same thruster configuration from previous years • Tested electronics providing all needed capabilities
Simplicity	• Single plate frame for easy electronics access • Standardized grid for simplified tool mounting • Additional monitor space and single-command launch

Fig. 4: Purdue ROV Core Design Tenet

Finally, X16's software stack was designed for **easy piloting**. X16 sports a new control station with additional monitor screen space along with a new front-end that productizes the ROV, allowing the pilot to launch the ROV with a single command. *Nemo*'s software stack is made modular through the use of ROS2, allowing for rapid software prototyping. Nemo also offers a variety of new control features such as 4 control granularities and front-back reversible controls.

STRUCTURE

FRAME

The frame was designed to serve as a universal mounting system for all of the ROV's subsystems. The frame's main priorities are to enable **easy mounting** for diverse subsystems and provide vehicle rigidity while remaining as **lightweight** as possible.

To cut weight and complexity from previous designs, a single-frame design was chosen. While two plates would seem to provide more mounting and rigidity, in reality, it obstructed access and reduced the total useful volume for mission tool mounting. To simplify mounting, we chose a universal 2" square grid. The overall frame footprint was designed to fit in a suitcase, making air transport possible. The frame was graciously water-jetted from a single sheet of 0.25" Al-6061 by **Waterjet Cutting of Indiana, Inc**. The geometry of the frame itself is based on finite element analysis (FEA) results and experience gathered from the past year.

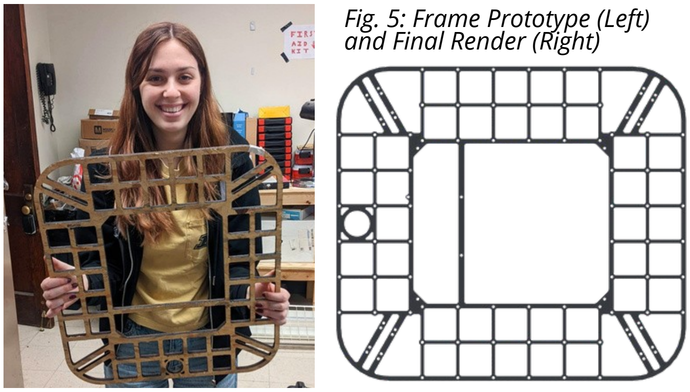


Fig. 5: Frame Prototype (Left) and Final Render (Right)

ELECTRONICS ENCLOSURE

POWER BOX

Mounted in the frame's center, the Power Box is the heart of the ROV, housing our custom circuit boards and routing signals to all the ROV's electrical systems. Continuing from our success with previous machined boxes, this year's Power Box again houses both power and systems. Putting them together in a single enclosure simplifies sealing and implementation of safety features, like the leak sensor, keeping our electronics safe. The Power Box is CNC milled out of a single block of 6061-T6 aluminum, allowing for high strength at minimal cost (welded versions have proven to be far more expensive in terms of time). The enclosure seals to a custom-manufactured lid, the Carrier Plate, via a face, seal using a 1/8" x-profile o-ring and has a vacuum port to test the seal.

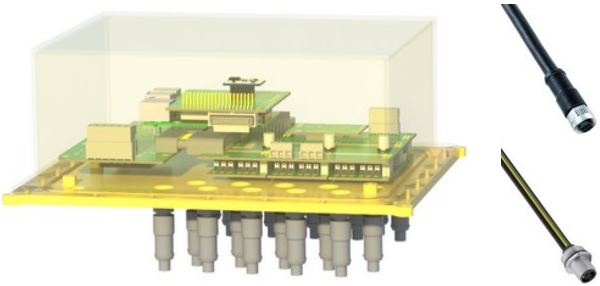


Figure 6: Structure of Binders on Power Box/Carrier Plate; Female Binder (Upper) and Male Binder (Lower)

Many design changes were made to expand reliability. Increasing the box's volume to accommodate boards made electronics more reliable as the extra space prevents wires from disconnecting when closing the box, a prevalent issue last year. Moving the o-ring groove from the Power Box to the Carrier Plate made it easier to work with and seal as the o-ring would not fall out.

With these design changes, hydrostatic finite element analysis (FEA) was performed to determine the minimum wall thickness needed to prevent failure at a depth of 10m with a factor of safety of 2.0.

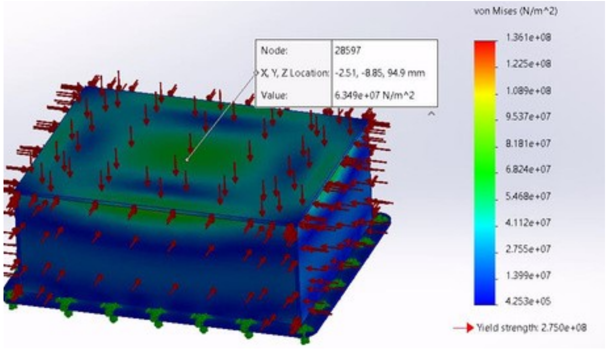


Fig. 7: Power Box FEA

CARRIER PLATE

The Carrier Plate serves as a lid for the Power Box. The plate is designed with cross-department feedback to ensure there would be numerous mounting points for electronics scaffolding and well-placed ports for electrical connectors. The design maintains an even center of gravity while remaining lightweight due to isogrids cut into the bottom of the plate. Since the plate had to remain 0.25” thick for the connectors, scaffolding screws, and o-ring groove, iso-grids were utilized to remove extraneous material.

The plate was designed using 6061 aluminum to withstand at least 40 psi of external pressure, and FEA was conducted for design validation before manufacturing. The combined Power Box and Carrier Plate connect to the tether and provide support for connections to 12 brushless DC motors, including 8 thrusters, the pneumatics enclosure, as well as multiple USB cameras via Binder ports. There are additional ports for further expansion to new capabilities and arrangement flexibility.

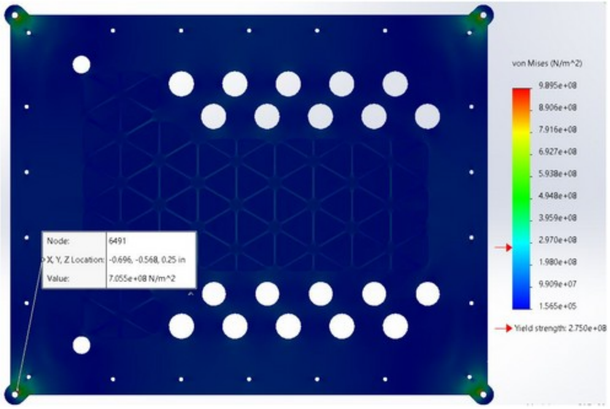


Fig. 8: Carrier Plate FEA

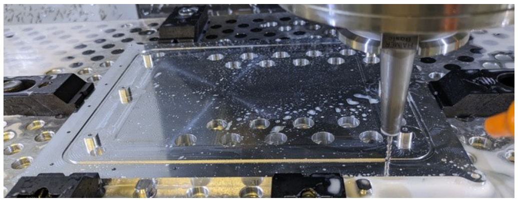


Fig. 9: Carrier Plate during CNC Manufacturing

SCAFFOLDING

Last year, boards were not mounted securely in the electrical enclosure, which led to significant reliability issues. This year we resolved this issue by rigidly mounting the electrical stack to the carrier plate with a 3D printed scaffold. 3D printing was chosen as it allowed rapid modification for new electrical components and provided sufficient structural rigidity to the stack. This proved invaluable as multiple prototypes were created to create the perfect fit between imperfectly toleranced parts.

The scaffolding provides the electrical components with adequate spacing, increasing important buffer time between leak detection by leak sensors and emergency recovery of the ROV. A separate scaffolding component was also developed for the Raspberry Pi, allowing easy removal of the element. All together, this design refresh makes the current electronics enclosure much easier to work with and more dependable than previous iterations.

PNEUMATICS ENCLOSURE

This season, the team opted for pneumatic-driven tools to complete the given mission tasks. The main reason to use pneumatics is to reduce electrical power usage - eight T200 thrusters take up 91% of power capacity. Pneumatics, however, come at the cost of complex manufacturing operations. Manifolds are notoriously hard to manufacture: they require small, tightly packed holes that don’t meet. Even so, we decided to machine it from 6061 aluminum ourselves. Manifolds are already highly custom to each application; a compact waterproof manifold is so specialized that outsourcing was not worth it.

Solution	Performance			Ease of development			
	Versatility	Power Draw	Weight	Cost	System Design Work	Manufacturing	Tool Design Work
All Electronics	Low	High	Low	Medium	Challenging	Easy	Medium
In-house Pneumatics	High	Low	High	Medium	Moderate	Challenging	Easy
Outsourced Pneumatics	Medium	Low	High	High	Challenging	Easy	Easy

Table 3: Pneumatics Decision Matrix

We would either have to adapt our pneumatic system to the manufacturer's requirements or pay large amounts to get a complex milled part.

Most of the design effort was optimizing hole depth ratios (depth:diameter) and wall thickness to **improve manufacturability**. The current design heavily employs drilling from multiple faces. Creating 90-degree bends for fittings to have enough space, drilling THRU holes from opposite faces, and meeting in the middle. This reduced our depth ratios from 19, impossible, to 9 which was attainable with available tools.

Despite intricacies, the manifold was manufactured successfully on the first try and proven to be a great success as it has successfully been tested up to 100psi. It is completely quiet when pressurized, with no audible leaks, and has interchangeable fittings if they were ever to be damaged. The manifold is also highly responsive as the pilot perceives the cylinder movement as instant.

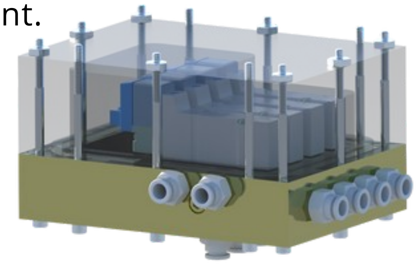


Fig. 10: Pneumatics Enclosure Render

PROPULSION

For the past two years, Purdue ROV has opted to use a novel thruster layout. This layout is unique in that it is symmetric in three planes, resulting in a uniform thrust envelope in the Y (left/right) and Z (up/down) axis while allowing for maximum thrust along the principal X (forward/reverse) axis and a high degree of pitch and yaw authority. This design was selected after extensive research and MATLAB simulations, and anecdotally was also the layout the pilot found easiest to use when completing mission tasks. This year, the team selected to design X16 with this thruster envelope because of its thrust symmetry and proven reliability.

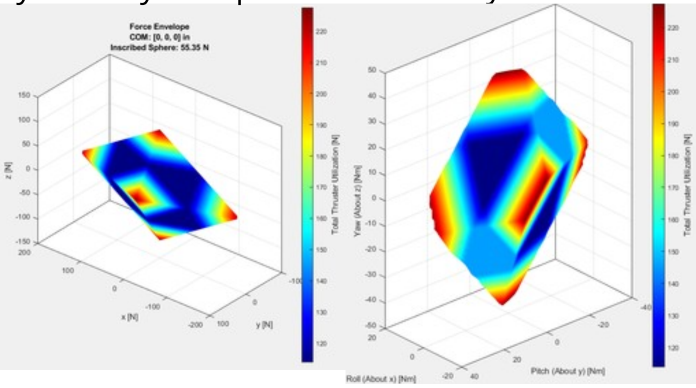


Fig. 11: MATLAB thruster simulations (Left - Force Envelope, Right - Moment Envelope)

TETHER

The tether acts as an umbilical to X16-*Nemo* from the base station, transmitting data and supplying power to the ROV. Last year, Purdue ROV placed considerable resources and time into designing a new and improved tether to achieve as close to neutral buoyancy as possible so that it would not impact the ROV's controllability. After many iterations,

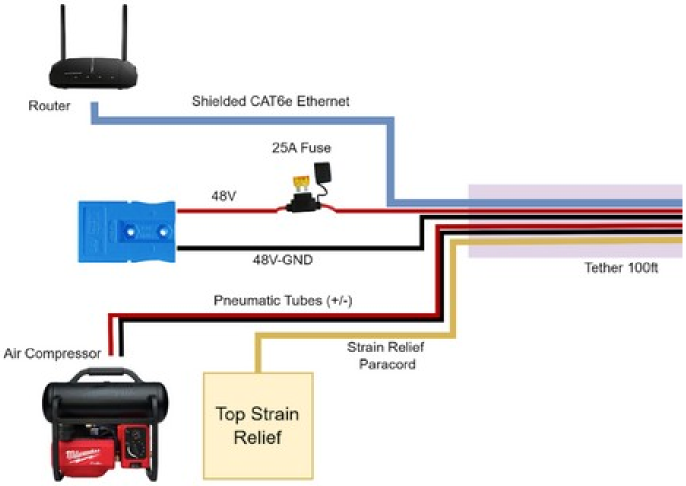


Fig. 12: Tether Connection Diagram

this tether proved to be reliable and close to neutrally buoyant, so the team opted to reuse it this season to focus design efforts on other areas.

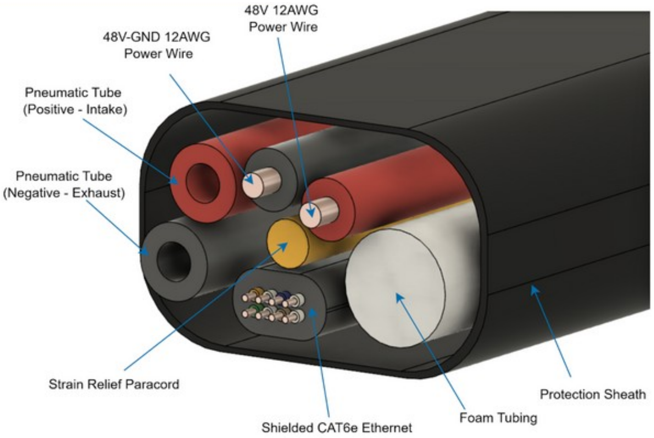


Fig. 13: Tether Cross-Section

The tether supplies power and data to the ROV via a heavy-duty power cable and CAT6e-shielded ethernet cable to limit electromagnetic interference from the water. The tether contains two pneumatic tubes, an intake tube supplying air to the pneumatics manifold, and an exhaust tube venting air back to the surface. Foam tubing also runs through the length of the tether to achieve near-neutral buoyancy of the tether. Finally, the tether relieves strain via the internal paracord and a PET cable sleeve to prevent damage to the wires.

See **Appendix A** for the tether management protocol.

BUOYANCY

In past years, Purdue ROV has found that the most maneuverable ROVs are **symmetric**, ie designed such that the center of mass (CoM) is as close as possible to the geometric center. Likewise, to ensure stability underwater, the center of buoyancy (CoB) should be positioned slightly above the CoM. With this CoB above the CoM, the ROV will naturally self-right its orientation, with the distance the CoB is from the CoM dictating the speed of this behavior.

ROV *Nemo* achieves near-neutral buoyancy through four large corner foam blocks located under the thrusters. These blocks provide approximately 300g of buoyancy each, are symmetric about the robot to maintain a centered CoB, and are designed to take up as little usable mounting space as possible.

Finally, small foam-filled buoyancy cubes were designed to be mountable to the frame. These cubes bring the ROV to a neutral buoyancy and ensure the CoB remains near the ROV's geometric center. These cubes were an improvement on the previous design which required extensive duct-taping to stay on ROV *Nemo*.

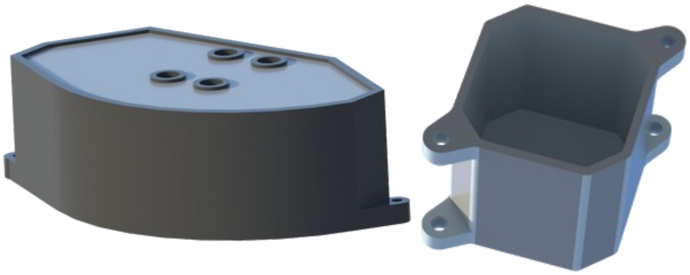


Fig. 14: Buoyancy Solutions.
Corner Foam (Left) and Foam Cube (Right)

CONTROLS

ELECTRONIC OVERVIEW

The Electronic Stack of ROV *Nemo* is centered around four basic ROV requirements: Power, Motion, Vision, and Tools. The stack consists of 5 custom PCBs for optimized modularity: Power Slab, Backplane, Pi Shield, ESC Controller, and ESC Adapter.

First, for **Power**, the Electronic Stack converts **48V** from the tether to **12V** for thrusters, servos, and solenoids**, 5V** for the onboard embedded computer and microcontroller, and **3.3V** of all additional logic components. Most importantly, Power Slab has a DC-DC conversion brick that can convert 48V to 12V at 1300W power output. The Backplane board then distributes power and logic utilizing SAMTEC connectors which ensures solidly mounted connections and reduces unreliable ribbon cables. Properly-rated SAMTEC **ET60S Series connector** were utilized to transfer the high amounts of power required by the Electronic Stack.

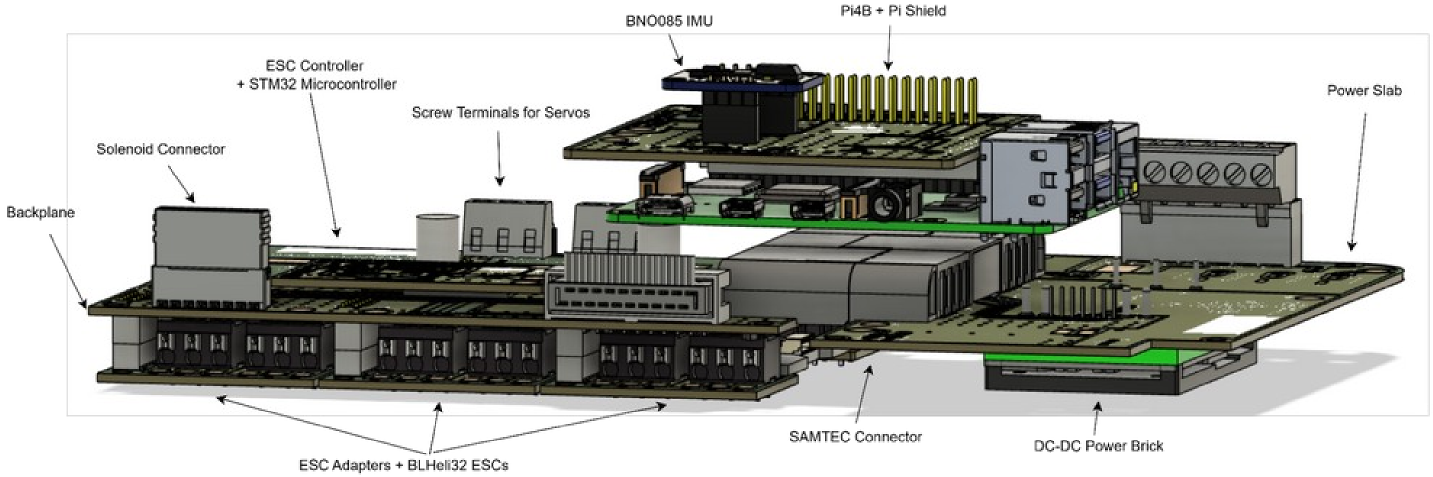


Fig. 15: 3-D Model of Electronics Stack

Second, X16-Nemo's stack achieves its **Motion** by controlling 8 Blue Robotics T200 Thrusters. With 12V power supplied, the stack can reliably operate all 8 thrusters simultaneously with controls from 2 Lumenier BHeli32 4-in-1 ESCs (Electronic Speed Controller), STM32 Microcontroller, and Raspberry Pi 4B (Pi4B). The embedded communication between multiple microcontrollers is done through SPI protocol between the Pi4B and STM32 chip to output 8 PWM signals to the BHeli32 ESCs.

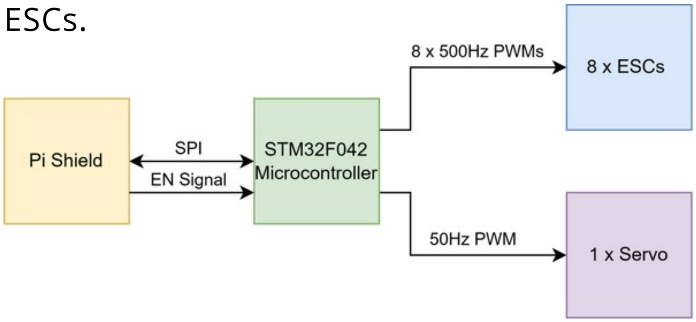


Fig. 16: Electrical Communication Pipeline to Control Thrusters

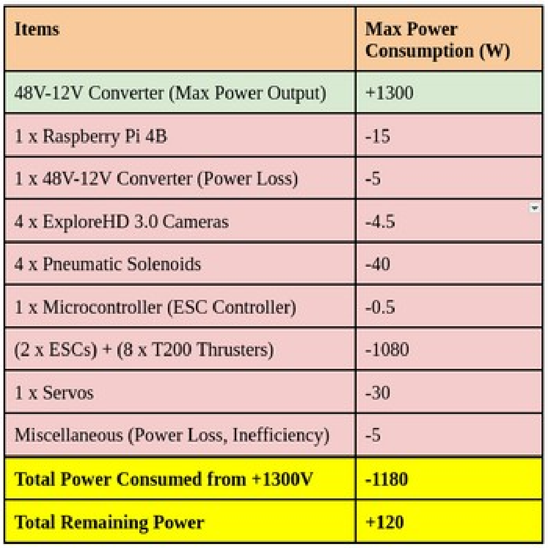
Third, the electrical stack achieves **Vision** through 4 digital cameras. We use DWE ExploreHD 3.0 Digital Cameras for 3 reasons: USB compatibility with Pi4B, onboard H.264 Compression, and with a wide field of view and high frame rate (30fps). To maximize the performance of the cameras, we also use a third-party 4-port USB 3.0 Hub to distribute the streams to the USB 3.0 port of the Pi4B. The camera streams will be processed by the Pi4B and sent via the Ethernet of the Tether to the Surface Station.

Fourth, the Electrical Stack of X16-Nemo can operate its **Tools**, consisting of pneumatic solenoids and servos. For the pneumatic solenoids, we can open and close the 4 solenoids on the ROV by 4 GPIO pins of the Pi4B. For the servos, we have screw terminals on the side of the Backplane which consists of a 12V power and PWM signals from the STM32.

POWER CONSUMPTION

In the design of the X16 Nemo's Electrical Stack, we need to take into account all components that have high power consumption, and with our configuration of 8 thrusters, we need to be extra careful about the energy usage of the ROV. Because of that, we have some estimations of the wattage of each component based on datasheets and we have the following table:

To elaborate, our system consumes a total of 1180W maximum with the majority of power drawn from the 8 T200 Thrusters with 2 ESCs. Additionally, a total of 1180W maximum means that the system is drawing about 24.58A of maximum current from 48V power; therefore, we chose a 25A fuse to prevent over-current damage to the ROV.



Items	Max Power Consumption (W)
48V-12V Converter (Max Power Output)	+1300
1 x Raspberry Pi 4B	-15
1 x 48V-12V Converter (Power Loss)	-5
4 x ExploreHD 3.0 Cameras	-4.5
4 x Pneumatic Solenoids	-40
1 x Microcontroller (ESC Controller)	-0.5
(2 x ESCs) + (8 x T200 Thrusters)	-1080
1 x Servos	-30
Miscellaneous (Power Loss, Inefficiency)	-5
Total Power Consumed from +1300V	**-1180**
Total Remaining Power	**+120**

Table 4. Power Consumption Table of X16-Nemo's Electrical Stack

ELECTRICAL RATIONALE

Purdue ROV prides itself in custom-designing all five PCB boards, developed in Autodesk Eagle. These boards are rigorously reviewed and tested, offering the team greater modularity and control over functionality, physical footprint, and design. In the end, this is a design decision that offers strong benefits to both member education and ROV performance.

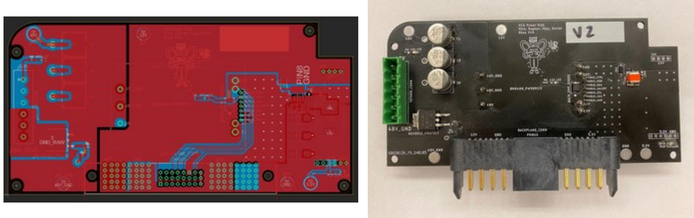
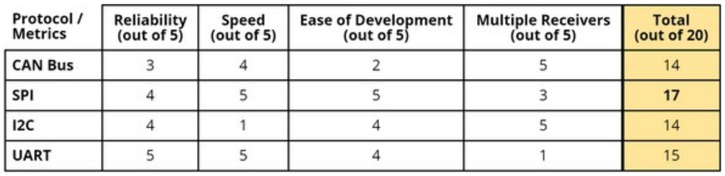


Figure 17. Power Slab PCB in Eagle (Left) and completed (Right)

The chief design goal of X16-Nemo's Electrical Stack is to improve the reliability and functionality of X15's Electrical Stack. For instance, last season, the team struggled with establishing embedded communication to drive thrusters. This year, after deciding to redesign the system from the ground up, the team performed market research on potential protocols and used decision matrices to select the best improvements to address these issues. Four protocols were considered: CAN Bus, SPI, I2C, and UART.

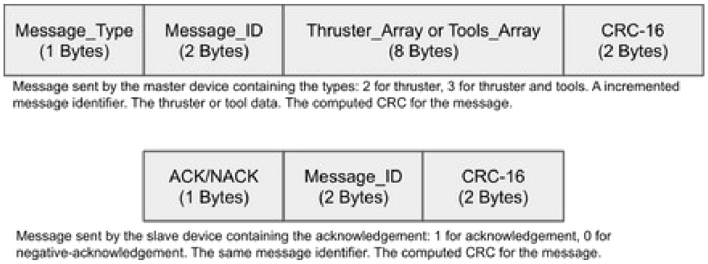
Based on the decision matrix, we decided to adopt SPI instead of the previously used CAN Bus because of various reasons. First, SPI was simple as it does not require additional circuitry. Second it is reliable as proven by our temporary fix last year. Finally it best fit our intended application since we only have a single receiver.



Protocol / Metrics	Reliability (out of 5)	Speed (out of 5)	Ease of Development (out of 5)	Multiple Receivers (out of 5)	Total (out of 20)
CAN Bus	3	4	2	5	14
SPI	4	5	5	3	**17**
I2C	4	1	4	5	14
UART	5	5	4	1	15

Table 5. Decision Matrix for Protocol between Micro controllers

In addition to selecting a new embedded protocol, we opted to rethink our packet format. The previous season's implementation of SPI was unidirectional and fire-and-forget, resulting in an unreliable protocol with minimal debugging information. Messages were expanded to include two-way communication, error checking (CRC), multiple message types to control both thrusters and servo tools, sequence numbers (message IDs), and acknowledgments. All of these features result in negligible communication overhead while ensuring reliability and offering valuable diagnostic information should an error occur.



Message_Type (1 Bytes)	Message_ID (2 Bytes)	Thruster_Array or Tools_Array (8 Bytes)	CRC-16 (2 Bytes)

Message sent by the master device containing the types: 2 for thruster, 3 for thruster and tools. A incremented message identifier. The thruster or tool data. The computed CRC for the message.

ACK/NACK (1 Bytes)	Message_ID (2 Bytes)	CRC-16 (2 Bytes)

Message sent by the slave device containing the acknowledgement: 1 for acknowledgement, 0 for negative-acknowledgement. The same message identifier. The computed CRC for the message.

Fig 18: SPI Thruster Command and Ack Packet

The new packet protocol was developed collaboratively between the software and electrical departments. The protocol was first prototyped at the beginning of the season on development boards, with new features added one at a time and rigorously tested before implementing the next feature. Before the boards were ordered, the embedded software developers conducted a design review of the final PCBs to ensure compatibility with the new protocol. Once the electrical manufacturing phase was complete, the code was flashed to the ROV and, once again, tested and debugged the code on the stack. Through this collaborative process and systematic design process, the team was able to avoid any major design issues and prevent major project schedule delays, unlike last year.

See **Appendix C** for additional rationale.

SURFACE CONTROL STATION

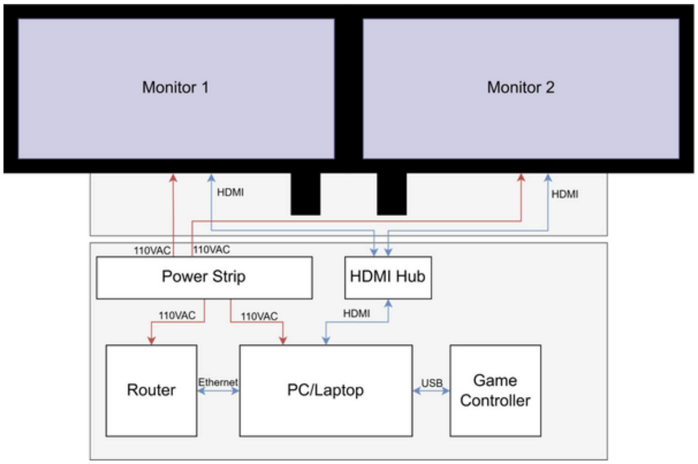


Figure 19. Control Station SID

Previously, Purdue ROV did not have a dedicated surface station, opting to use a laptop to display camera streams and the user interface. This made piloting difficult during competition, as the pilot was limited to one camera view at a time. This season, the team addressed this problem by designing a new, dual-monitor surface station, designed to be assembled and torn down in five minutes or less. The surface station was built into a large Pelican case, comparable in size to a checked bag, to facilitate easy transport.

Figure 20. Surface Station Inaugural Test

The team selected a dual monitor setup to maximize screen real estate, however, this also comes at the cost of increased setup and teardown time. The selected arms were chosen to partially mitigate this disadvantage; they are easy to assemble and can slide directly off the wall mount, reducing setup time. After the mission is completed, the monitors are stowed inside a dual monitor storage bag along with their associated cables, which all fit neatly inside the base of the box. Finally, the deck crew drilled the assembly and teardown of the surface station to verify it could be completed during the 5-minute setup stage.

PILOTING INTERFACE

This year the software department decided to deprecate our previous, node.js piloting interface in favor of developing a new user interface developed in PyQt5. The previous front-end was supported by the team for several years but was becoming clunky, hard to update, and sub-optimal for continued use. After performing market analysis, the team settled on PythonQT5 over node.js because it was easier to develop and integrated well with the rest of the software stack. Using QtDesigner, a user interface can be created with a simple drag-and-drop program and then easily converted to a Python file and connected to a Python environment.

Environment / Metrics	Simplicity (out of 5)	Ease of Maintenance (out of 5)	Flexibility (out of 5)	Responsivity (out of 5)	Total (out of 20)
node.js	2	2	2	3	9
PyQt5	5	5	5	4	19

Table 6. Front-end Development Environment Decision Matrix

Having selected the environment, the front-end sub-team began development, designing the front-end to be user-friendly and productized. The frontend was designed so that every sub-system could be launched with a single command, and would terminate when the front-end was closed. Finally, rigorous testing was conducted to ensure the UI comprehensive launch would not negatively impact ROV operation.

Figure 21. Piloting Interface: Displays Sensor Info, Thruster Speed, Commanded Velocity, and Start Cameras

The UI separates each camera stream into independent windows that can then be moved to various monitors on the surface station. The user interface then remains on the pilot's laptop and displays information including thruster outputs and sensor data.

CONTROL BOX

The Control Box is the power supply box that provides 48V power to the ROV *Nemo*'s Tether from the normal 110VAC wall outlet. Similar to the standard MATE Control Box, our control box consists of an Anderson Connector, a power switch, an extra AC outlet, and an LCD power monitor. To convert 48V at 1440W from AC sources, we use four AC-DC power supplies, each of which can convert AC to 12V at 30A. Connected in parallel, voltage is quadrupled from 12V to 48V @30A providing a maximum Wattage of 1440W.

Onboard is a power switch that turns on and off the 48V power to the ROV's tether acting as an emergency power switch. Additionally, we have a wattage meter LCD monitor that can measure the voltage, current, and power consumption of the ROV providing another layer of security.

Internally, the Control Box's internal connection and wiring are done with high-power screw terminals and 10-12AWG wires as all the internal components are securely mounted and organized to ensure no exposed wiring or electrical hazards. Lastly, the Control Box is protected by a hard plastic casing box from any physical damage.

Fig. 22: Control Box opened with tether disconnected

CAMERA VIEWS

Camera positions were selected to make piloting the robot and interacting with the environment as easy as possible. There are four total cameras each placed around a tool being used. The first camera is placed in front of the robot facing the primary manipulator. One camera is mounted under a thruster to the right of the primary manipulator.

COMPUTER VISION

This camera allows the driver to see forward while moving the robot but also is angled so the pilot can gauge distance when using the primary manipulator. The second camera on the front is mounted on the PM itself moving with the PM as it articulates. This camera is critical for navigating over deployment areas and also provides a view of the primary manipulator in the downward position allowing for easy manipulation of items on the ground.

The next camera is placed on the back of the robot to the left of the value turner above a thruster.

Like the front camera, this camera is angled, giving the pilot an optimal view of the Valve Turner tool.

The last two cameras are placed on the left and right side of the robot expanding the overall field of vision. They also provide the pilot with a view of the Rock Collector and Plier tool respectively.

ASPECT RATIO MEASUREMENT

To achieve the coral modeling task for the “From the Red Sea to Tennessee” task, we first devised a way to measure the unknown measurements using known values. To do this, we created an algorithm based on the math from Zhang and He to project any quadrangle into a rectangle on a flat plane to calculate the aspect ratio of the rectangle to use known measurements to find unknown ones (pp. 419-425).

CAMERA CALIBRATION

To correct the distortion of the fisheye lens Explore HD cameras, we made a checkerboard calibration algorithm that takes many pictures of the checkerboard calibration pattern and outputs a camera matrix as well as distortion coefficients. These allow us to take the image, undistort, and crop the usable part of the image to get more accurate values when measuring.

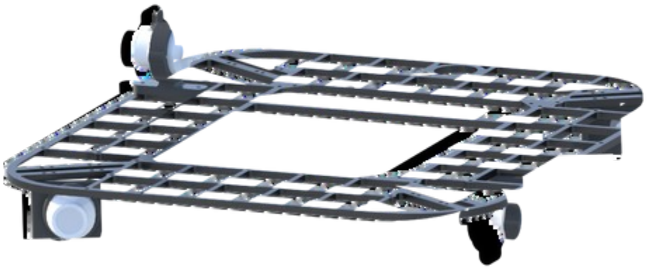


Fig. 23: ROV Frame and Camera positions (Front of ROV is bottom in this image)

RECTANGLE DETECTION

To autonomously measure the unknown lengths of the structure, we devised an algorithm to find the points of the rectangle and input them into our aspect ratio measurement function to get the unknown lengths in real-time. First, we filtered images to get rid of red and black to prevent interference from zip ties, different colored pieces, and red velcro. Then we used canny edge detection to find all contours in the image. With the contours, we did a few blurring steps to get the most clear contours. Then we mapped contours to polygon lines only if the contour would create 4 points and found the biggest one of these quadrangles and passed it to our aspect ratio function to get an aspect ratio. Then depending on the part we multiplied by a different value to get the unknown lengths.

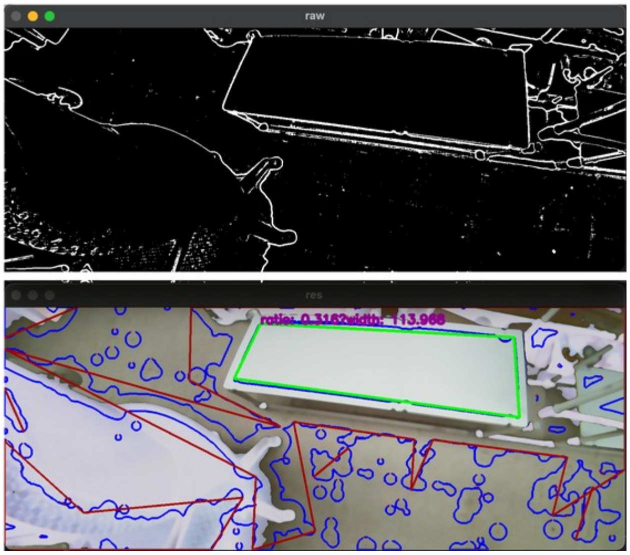


Fig. 24: Contouring Edge Detection (Top) and Resulting Measurement (Bottom)

SPECIALIZATIONS

PNEUMATIC TOOLS

These tools utilize pneumatically actuated cylinders powered by compressed air to accomplish tasks. These tools are reliable, and fast, and can vary in power depending on the task. With the optimization of pneumatic cylinders for the task through mathematical calculations below and verification through prototypes, pinching hazards and sample damage from the excessive gripping force was eliminated. This makes these tools the safest and most **reliable** tools possible.

The **Primary Manipulator** (PM) is powered by two pneumatic cylinders for opening/closing the claw and rotating the claw horizontally and vertically.

Inner Claw with Flexible TPU	Increased grip strength on odd elements, i.e. AUV docking station connector
PM Articulation	Reduced complexity and completion time of SMART cable deployment & AUV power connector task
Borescope Camera	Precise alignment with targets

Fig. 25: Primary Manipulator Features

Fig 26. Primary Manipulator in Vertical Position

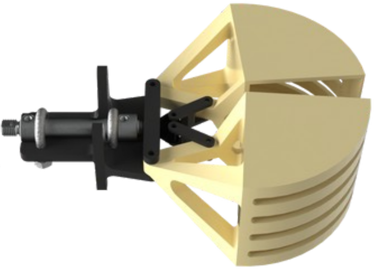


Fig 27. Rock Collector slightly ajar

The **Rock Collector** utilizes a large 3D printed 'bucket' similar to the tried and true excavator buckets. The bucket allows for easy collection of samples from the ocean floor. 'Vents' in the bucket made possible by 3D printing decreases drag and allows for ocean debris to be sifted away leaving only the desired sample.

The **Plier Tool** uses a small pneumatic cylinder which allows for a large acquisition zone and high speeds with minimal strength allowing for soft tubing to be clamped with minimal damage. Suitable for grabbing difficult-to-grab small objects such as the Smart Repeater Cable.

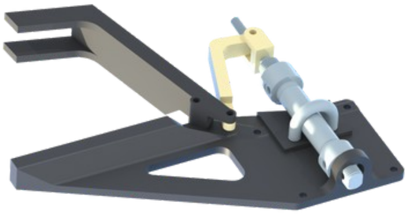


Fig 28. Plier Tool in open state

SPECIALIZED TOOLS

These tools are custom-designed for their specific role on the ROV to accomplish tasks that the pneumatic tools can not accomplish easily. These tools are designed to aid in our core principle of decreasing piloting difficulty. All these tools were custom-designed for their specific mission task. Because of our standardized frame, new tools can be easily added and removed if so desired, thus tools such as the Magnet Tool which is used only for one task - removal of the recovery float's manual release pin - were included on the ROV.

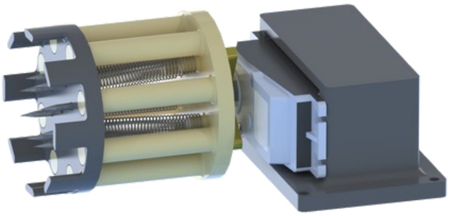


Fig 29. Valve Turner tool with servo to the right and interface to the left

The **Valve Turner** utilizes a modified servo powered by the ROV to operate objects like the probiotic irrigation valve. The custom-designed interface utilizing low spring constant springs allows for self-centering, minimizing piloting difficulty.

The **Temp Sensor** allows for temperature readings to monitor ocean health. Custom software GUI allows for easy calibration against a known temperature target.

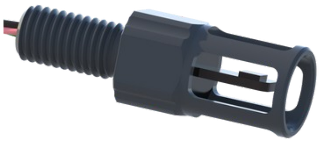


Fig 30. BlueRobotics Temperature sensor

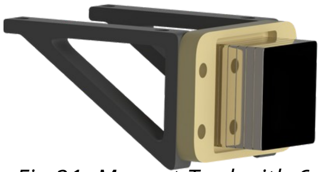


Fig 31. Magnet Tool with 6 stacked magnets

The **Magnet Tool** utilizes high-strength neodymium magnets that allow for easy recovery of magnetic items such as the recovery float's manual release pin. Simplistic design makes this tool adaptable to any form required of the tool.

The **Custom Carabiner** contains 3D printed geometry that maximizes the acquisition zone and easily interfaces with the Primary Manipulator through a standard ½" PVC Tee fitting. With a strong torsion spring and PETG components, this tool is made to easily open yet locks into position to firmly grip onto U-bolts.

Fig 32. Custom carabiner grabbing onto multifunction node

DESIGN PROCESS

When deciding which tools to include on the ROV, each task was characterized and carefully examined. From there, mechanical leadership decided with input from members on the final list of tools to design. Decisions were based on A) demonstrated need per task list, B) member bandwidth, C) previous need for tools, and D) suitability of other tools.

With the Plier Tool, for instance, we had to decide if keeping the tool for tubing tasks or freeing up space and utilizing the PM was most beneficial. Ultimately based on our goals of decreasing piloting requirements, a custom tool was chosen to increase the acquisition zone and reduce the already long list of tasks for the PM.

After generating the tools list, the design phase began. We started with a **Build vs. Buy analysis** and performed market research. In almost all cases, it was demonstrated that we could both make a tool cheaper and more suited for our use case than COTS solutions. In one exceptional case of the temperature sensor, the BlueRobotics model was chosen since it was faster to integrate and also cheaper when factoring in the time and opportunity cost of an in-house design.

Only two tools, the PM and Magnet Tool qualified for a **Reuse vs. New decision** as they were the only two tools with previous designs. For the Magnet Tool, the initial design failed a simple test of pulling out the float's release pin, so a new tool had to be designed. For the PM, it was decided that a new tool would be made since it was the most critical tool in our arsenal, our **primary** manipulator. Even the slightest improvement in quality would lead to a large decrease in piloting difficulty due to its amount of use.

With these analyses completed, individual members were assigned tools and began design. With the emphasis on rapidly producing design iterations, the assigned member would have weekly progress checks to ensure members were not stuck on roadblocks. Leadership also utilized design reviews to ensure the proper tool was designed for the job.

An example of the design process is the primary manipulator's articulation, now purposefully designed for the AUV docking station connector task. However, it originally started as its own tool. In the first ideation stage, a guide tool was created to align the repeater up with the connector. However, after finishing the entire design process, it was decided that it was far too bulky and too specialized, making piloting harder and the ROV less reliable. The task was re-examined and ultimately, the current design arose after multiple stages of design changes.

CRITICAL ANALYSIS

TESTING METHODOLOGY

A variety of testing methodologies were employed throughout the initial design process and iterations following thereafter. To begin, mechanical parts underwent varying levels of finite element verification before manufacturing. Pressure-critical components, such as the Power Box, and expensive components or components with a high manufacturing time were verified to have a minimum factor of safety (FoS) of 2.0 before manufacturing. For non-sensitive components, a minimum FoS of 1.5 was ensured for the final version of the part, with initial prototypes not undergoing rigorous finite element tests. Potentially pressure-sensitive components were also tested utilizing a pressure testing chamber up to 50 psi before being installed on the ROV to ensure the safety of critical electronics and structures. Finally, custom tools were tested with our standard 1-meter stick test (can the tool work after sticking it on the end of a 1m stick?) before being installed on the ROV. This verification allowed the team to identify and differentiate between issues caused by the part being submerged and purely mechanical issues.

TROUBLESHOOTING

When parts were found to be structurally inadequate the first step was to optimize the geometry of the components. Using FEA stress concentrations could be identified and reduced by optimizing component geometries. In cases where a simple geometry change was not sufficient to fix the part, multiple potential solutions were available. On some components, a design change would be made to add additional support to at-risk structures. For other elements, manufacturing changes could be utilized to resolve structural failures. Many tools were made using 3D printing, so increasing the infill of components or varying the filament material used would fix these parts. For some mission-critical tools, multiple versions were designed and produced in parallel allowing the team to select the best-performing version and for cross-member mentoring. Rapid prototyping practices were also heavily encouraged to ensure members could physically understand components being designed in CAD software and reduce misjudgments in component sizing.

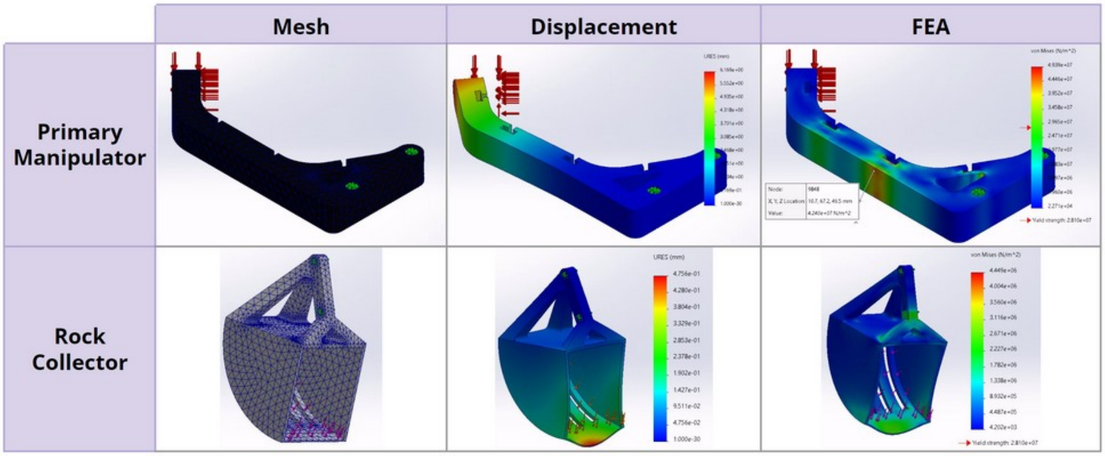


Fig. 33: Analysis Results for Custom Tools

SAFETY

PHILOSOPHY

Safety is the highest priority for Purdue ROV. A safe work environment does more than prevent workplace injuries; it improves employee comfort, productivity, and enjoyment. The safety of all employees, bystanders, and equipment is examined in each and every action taken or product used.

STANDARDS

Purdue ROV utilizes numerous standard operating procedures (SOPs) that every employee must follow when working on ROV Nemo. To ensure this occurs, new employees must complete hazard training before using the team workspace, and receive permission from a senior member before operating hazardous equipment. This year, multiple onsite safety officers were appointed to ensure safety infractions are recorded for remedial training.

Safety rules range from the one-hand rule when handling high voltages to proper PPE equipment when operating power tools. These rules were created over the years of the club's existence with the assistance of resources such as the Oceaneering HSE Employee Handbook (2018). During the ROV's construction, specific checklists (See **Appendix A**) are followed to ensure risks are minimized.

A new safety measure expanded upon this year was the proper handling of hazardous materials. The team self-audited our chemical inventory, safely disposing of chemicals the team no longer uses and verifying hazardous materials were being stored properly.

New systems have also been put in place to review and reduce the usage of hazardous materials where possible.

During the operation of the ROV at pool tests, employees are also required to follow safety checklists (See **Appendix A**) to ensure both that ROV Nemo is safe to operate and that members remain safe while operating ROV Nemo. Any infraction at this stage disbars said member from the pool test and a follow-up safety meeting is scheduled to prevent future incidents from occurring.

FEATURES

ROV Nemo has numerous safety features. First, the tether has both a master fuse for the device and a strain relief cord to ensure physical and electrical safety. Secondly, sharp edges are minimized on the metallic parts via manual hand-reaming. Anodization is also performed to reduce potential health hazards from aluminum allergies.

Additionally, ROV Nemo's custom thruster ducts integrate ingress protection features. They satisfy IP20, blocking objects larger than 12.5 mm while also minimizing any reduction in water flow.

Finally, the vehicle's software provides the pilot with diagnostic information to ensure correct functionality before deploying into the water. Data on the current draw, Raspberry Pi temperature, and leak detections are continuously updated on the pilot's screen so the pilot can shut off the ROV if conditions become unsafe.

Interested parties can view our Company Safety Review for further info.

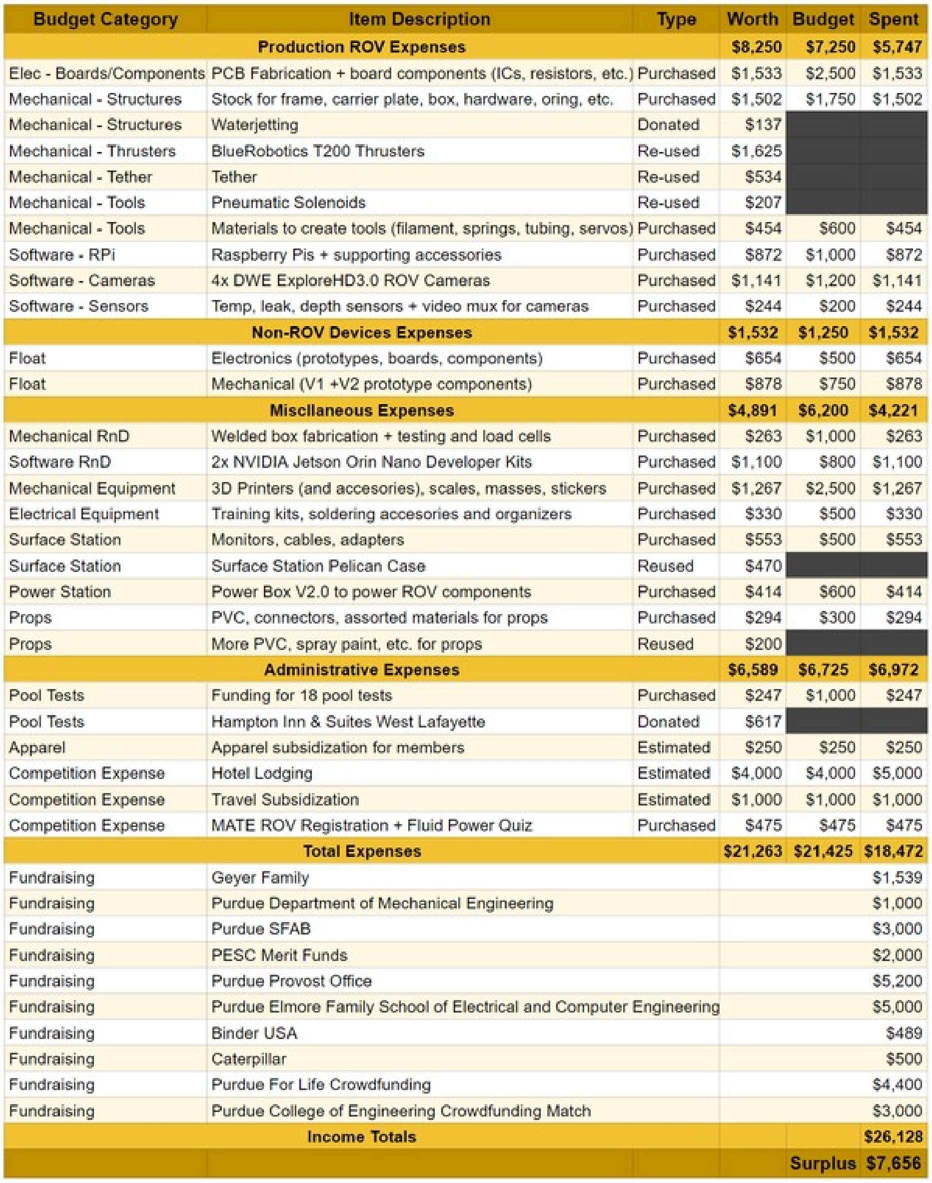
ACCOUNTING

Purdue ROV creates its yearly budget based on a combination of previous budgets, projected incomes, and projected future expenses. These expenses include the cost of producing ROV Nemo, the costs of attending the MATE competition, and the costs of R&D and new equipment for the workstation. This year, Purdue ROV's main financial objective was to reduce overall development costs while increasing overall income.

To reduce our development costs, the team carefully budgeted and tracked purchasing decisions while also strongly emphasizing the reuse of old materials. Efforts were also made to pursue sponsors who could provide discounted parts or services to aid in the development of our ROV. One such discount, by Binder USA, saved the team $500 on connectors. Similarly, the team opted to reuse thrusters from a decommissioned ROV, saving $1,600 on new T200 thrusters.

To increase funding, the team placed significant emphasis on utilizing academic connections and leveraging our Alumni network. The team was able to pursue our first ever crowdfunding campaign this season with the help of the Purdue College of Engineering. This uncertain venture ended up netting the team $4400 in alumni support as well as a $3000 College of Engineering match.

Overall, our strategy resulted in a budgetary surplus of nearly $8000 while also providing us with invaluable contacts and future income sources in place for the future. This year's surplus has entirely eliminated the deficit from the previous year and will provide the team with significant capital to pursue more R&D projects and finish our workspace renovations in the future.



Budget Category	Item Description	Type	Worth	Budget	Spent
	Production ROV Expenses		**$8,250**	**$7,250**	**$5,747**
Elec - Boards/Components	PCB Fabrication + board components (ICs, resistors, etc.)	Purchased	$1,533	$2,500	$1,533
Mechanical - Structures	Stock for frame, carrier plate, box, hardware, oring, etc.	Purchased	$1,502	$1,750	$1,502
Mechanical - Structures	Waterjetting	Donated	$137		
Mechanical - Thrusters	BlueRobotics T200 Thrusters	Re-used	$1,625		
Mechanical - Tether	Tether	Re-used	$534		
Mechanical - Tools	Pneumatic Solenoids	Re-used	$207		
Mechanical - Tools	Materials to create tools (filament, springs, tubing, servos)	Purchased	$454	$600	$454
Software - RPi	Raspberry Pis + supporting accessories	Purchased	$872	$1,000	$872
Software - Cameras	4x DWE ExploreHD3.0 ROV Cameras	Purchased	$1,141	$1,200	$1,141
Software - Sensors	Temp, leak, depth sensors + video mux for cameras	Purchased	$244	$200	$244
	Non-ROV Devices Expenses		**$1,532**	**$1,250**	**$1,532**
Float	Electronics (prototypes, boards, components)	Purchased	$654	$500	$654
Float	Mechanical (V1 +V2 prototype components)	Purchased	$878	$750	$878
	Miscllaneous Expenses		**$4,891**	**$6,200**	**$4,221**
Mechanical RnD	Welded box fabrication + testing and load cells	Purchased	$263	$1,000	$263
Software RnD	2x NVIDIA Jetson Orin Nano Developer Kits	Purchased	$1,100	$800	$1,100
Mechanical Equipment	3D Printers (and accesories), scales, masses, stickers	Purchased	$1,267	$2,500	$1,267
Electrical Equipment	Training kits, soldering accesories and organizers	Purchased	$330	$500	$330
Surface Station	Monitors, cables, adapters	Purchased	$553	$500	$553
Surface Station	Surface Station Pelican Case	Reused	$470		
Power Station	Power Box V2.0 to power ROV components	Purchased	$414	$600	$414
Props	PVC, connectors, assorted materials for props	Purchased	$294	$300	$294
Props	More PVC, spray paint, etc. for props	Reused	$200		
	Administrative Expenses		**$6,589**	**$6,725**	**$6,972**
Pool Tests	Funding for 18 pool tests	Purchased	$247	$1,000	$247
Pool Tests	Hampton Inn & Suites West Lafayette	Donated	$617		
Apparel	Apparel subsidization for members	Estimated	$250	$250	$250
Competition Expense	Hotel Lodging	Estimated	$4,000	$4,000	$5,000
Competition Expense	Travel Subsidization	Estimated	$1,000	$1,000	$1,000
Competition Expense	MATE ROV Registration + Fluid Power Quiz	Purchased	$475	$475	$475
	Total Expenses		**$21,263**	**$21,425**	**$18,472**
Fundraising	Geyer Family				$1,539
Fundraising	Purdue Department of Mechanical Engineering				$1,000
Fundraising	Purdue SFAB				$3,000
Fundraising	PESC Merit Funds				$2,000
Fundraising	Purdue Provost Office				$5,200
Fundraising	Purdue Elmore Family School of Electrical and Computer Engineering				$5,000
Fundraising	Binder USA				$489
Fundraising	Caterpillar				$500
Fundraising	Purdue For Life Crowdfunding				$4,400
Fundraising	Purdue College of Engineering Crowdfunding Match				$3,000
	Income Totals				**$26,128**
				Surplus	**$7,656**

Table 7. X16 Nemo Budget

ACKNOWLEDGEMENTS & REFERENCES

Gold Partners

PURDUE UNIVERSITY Office of the Provost

PURDUE UNIVERSITY Elmore Family School of Electrical and Computer Engineering

PURDUE UNIVERSITY College of Engineering

SFAB Purdue University Student Fee Advisory Board

Silver Partners

Geyer Family

PESC

PURDUE UNIVERSITY Mechanical Engineering

Bronze Partners

WCI Waterjet Cutting of Indiana

COLORS, INC. Anodizers of Aluminum

CAT®

binder

Purdue ROV Thanks

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 | Purdue Cordova Recreation Center and Hampton Inn for their provision of pools for testing | Bechtel Innovation Design Center for their manufacturing assistance

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APPENDIX A: SAFETY CHECKLISTS

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 places ROV into the water and holds 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

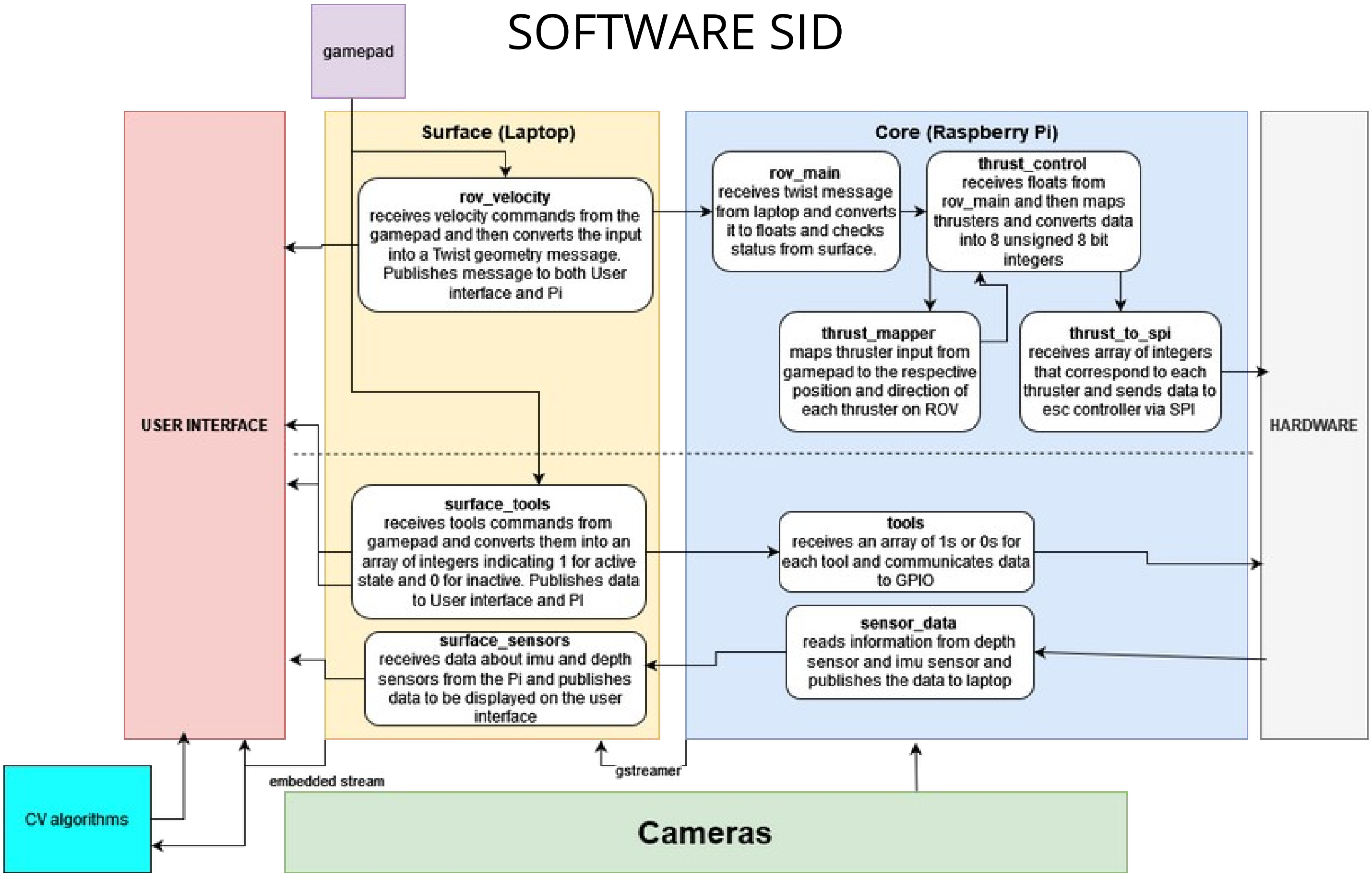
- ☐ Co-pilot turns off power and calls "Power Off"
- ☐ Deployment members do visual inspection for damage
- ☐ Pilot powers off battle station
- ☐ Anderson connectors of tether are removed from power supply
- ☐ Turn off air compressor and vent line
- ☐ Remove air line from pneumatics enclosure

Assembly Check

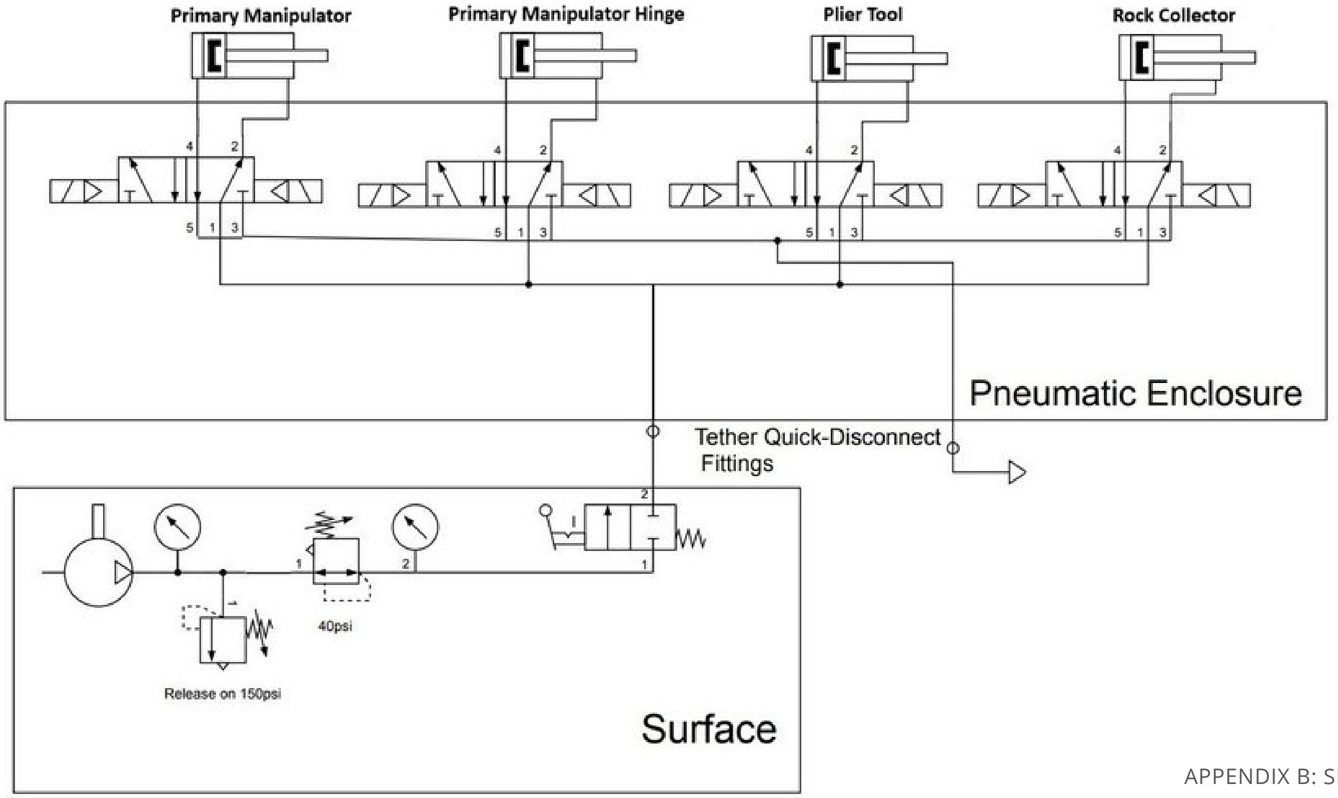
- ☐ ROV disconnected from power and pneumatics
- ☐ PCBs are clean without visible damage
- ☐ No wires are disconnected, loose, exposed or can get pinched by box or thrusters
- ☐ Inside of the box is clear of water (residue)
- ☐ Enclosure shows no sign of damage
- ☐ All ports on the carrier plate are 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 B: SID

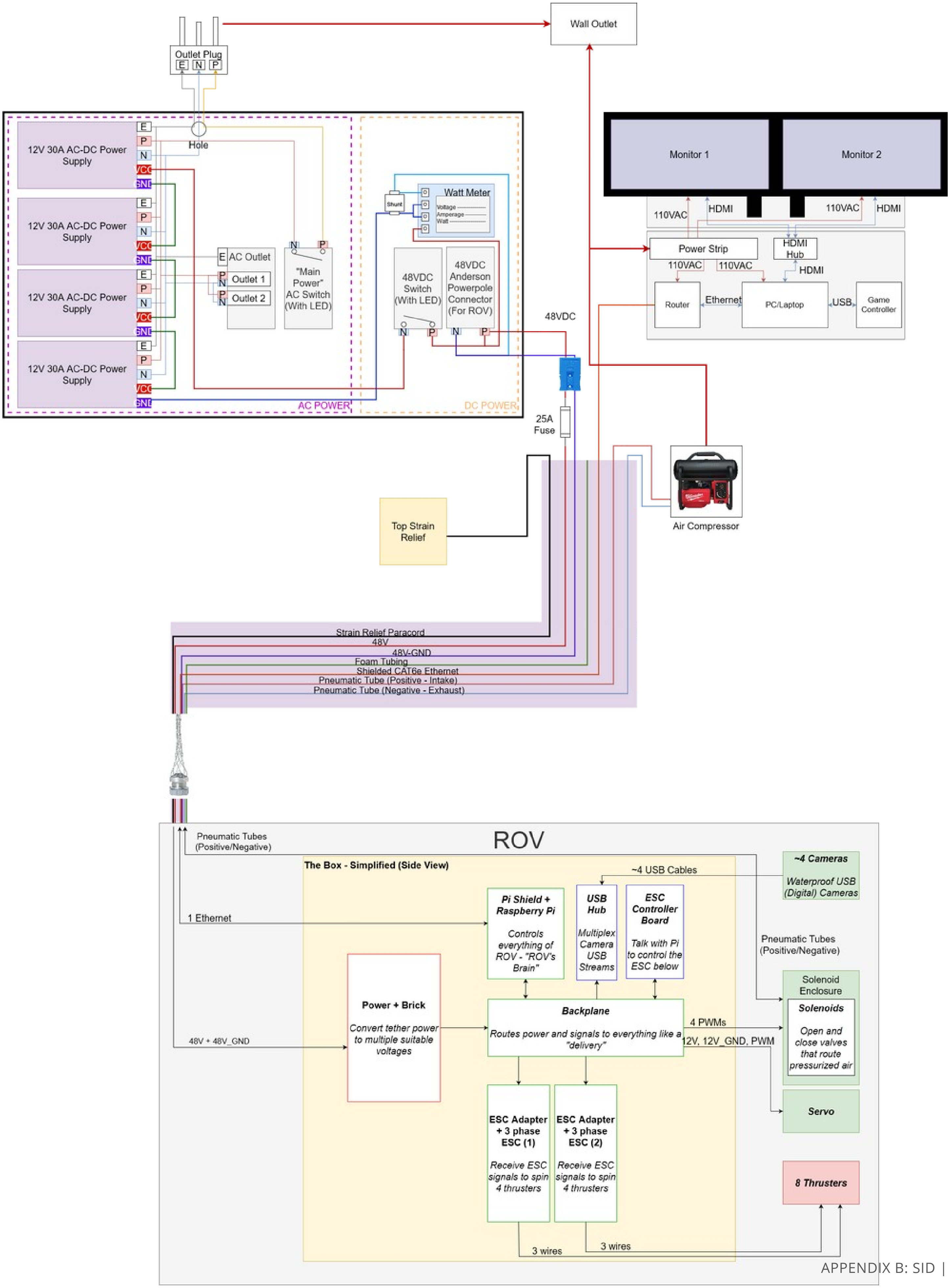
SOFTWARE SID



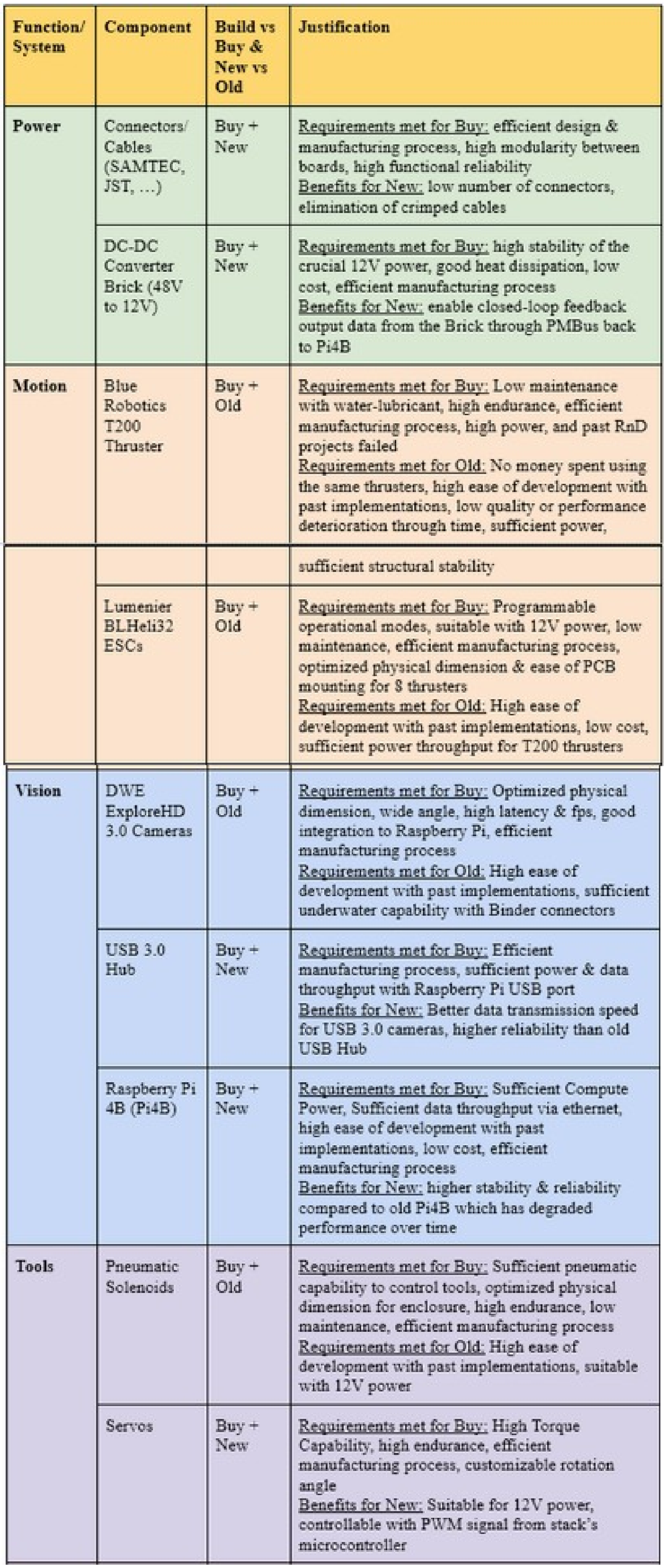
FLUID POWER SID



ELECTRICAL SID

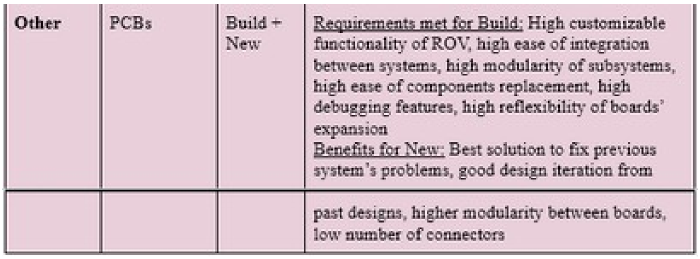


APPENDIX C: EXTRAS



Function/ System	Component	Build vs Buy & New vs Old	Justification
Power	Connectors/ Cables (SAMTEC, JST, …)	Buy + New	Requirements met for Buy: efficient design & manufacturing process, high modularity between boards, high functional reliability Benefits for New: low number of connectors, elimination of crimped cables
	DC-DC Converter Brick (48V to 12V)	Buy + New	Requirements met for Buy: high stability of the crucial 12V power, good heat dissipation, low cost, efficient manufacturing process Benefits for New: enable closed-loop feedback output data from the Brick through PMBus back to Pi4B
Motion	Blue Robotics T200 Thruster	Buy + Old	Requirements met for Buy: Low maintenance with water-lubricant, high endurance, efficient manufacturing process, high power, and past RnD projects failed Requirements met for Old: No money spent using the same thrusters, high ease of development with past implementations, low quality or performance deterioration through time, sufficient power, sufficient structural stability
	Lumenier BLHeli32 ESCs	Buy + Old	Requirements met for Buy: Programmable operational modes, suitable with 12V power, low maintenance, efficient manufacturing process, optimized physical dimension & ease of PCB mounting for 8 thrusters Requirements met for Old: High ease of development with past implementations, low cost, sufficient power throughput for T200 thrusters
Vision	DWE ExploreHD 3.0 Cameras	Buy + Old	Requirements met for Buy: Optimized physical dimension, wide angle, high latency & fps, good integration to Raspberry Pi, efficient manufacturing process Requirements met for Old: High ease of development with past implementations, sufficient underwater capability with Binder connectors
	USB 3.0 Hub	Buy + New	Requirements met for Buy: Efficient manufacturing process, sufficient power & data throughput with Raspberry Pi USB port Benefits for New: Better data transmission speed for USB 3.0 cameras, higher reliability than old USB Hub
	Raspberry Pi 4B (Pi4B)	Buy + New	Requirements met for Buy: Sufficient Compute Power, Sufficient data throughput via ethernet, high ease of development with past implementations, low cost, efficient manufacturing process Benefits for New: higher stability & reliability compared to old Pi4B which has degraded performance over time
Tools	Pneumatic Solenoids	Buy + Old	Requirements met for Buy: Sufficient pneumatic capability to control tools, optimized physical dimension for enclosure, high endurance, low maintenance, efficient manufacturing process Requirements met for Old: High ease of development with past implementations, suitable with 12V power
	Servos	Buy + New	Requirements met for Buy: High Torque Capability, high endurance, efficient manufacturing process, customizable rotation angle Benefits for New: Suitable for 12V power, controllable with PWM signal from stack's microcontroller

Table 8. Electrical Build vs Buy & Reuse vs New Rationale



Other	PCBs	Build + New	Requirements met for Build: High customizable functionality of ROV, high ease of integration between systems, high modularity of subsystems, high ease of components replacement, high debugging features, high reflexibility of boards' expansion Benefits for New: Best solution to fix previous system's problems, good design iteration from past designs, higher modularity between boards, low number of connectors

Table 8. (Cont.)

1. Designate a deck hand as the tether handler.

2. Tether handler removes tether from storage bin and uncoils as little as is needed for handling on the deck. This prevents the tether from kinking or tangling.

3. Tether is connected to the surface station strain relief, then ethernet, then power, then pneumatics, with outlet valve closed.

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. Never step on the tether, which could build unsafe pressure spikes in pneumatic lines.

8. Tether handler must provide just enough length necessary to allow the ROV to reach its working depth.

9. ROV pilot must avoid 360° rotations & close maneuvers around obstacles when possible, to avoid tangling.

10. Once operations are completed, the tether handler is in charge of disconnecting the tether from surface station and power, closing the outlet valve before disconnecting pneumatics.

11. After disconnection, the tether handler coils tether.

Table 9. Tether Management Protocol
Adapted from Christ & Wernli, 2013