RoboSub 2025 Technical Design Report

National University of Singapore (Bumblebee Autonomous Systems)

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***Abstract*—For RoboSub 2025, Team Bumblebee is deploying BBAUV 4.5, a significant upgrade from BBAUV 4.1, featuring overhauled mechanical, electrical, and software systems. These improvements range from small-scale optimizations to large-scale redesigns, all aimed at addressing past challenges and streamlining future development. This year also marks the debut of our Mini-AUV, a specialized platform designed for specific tasks that will lay the groundwork for planned dual-vehicle operations in RoboSub 2026 and beyond. A comprehensive testing strategy is employed to validate critical system developments.**

Fig. 1: BBAUV 4.5 Render.

Fig. 2: Mini-AUV Render.

I. Competition Strategy

A. Core Strategy

Our core objective for RoboSub remains as 100% task accuracy. For RoboSub 2025, we are shifting from rigid task sequencing to a modular, dynamically reconfigurable execution approach. This change boosts flexibility during competition and improves testability, as each task can be independently validated and optimized.

Concurrently, we are undertaking a comprehensive overhaul and optimization of all critical mechanical, electrical, and software systems of BBAUV 4.1 to produce BBAUV 4.5, alongside the development of a new Mini-AUV platform. While this presents short-term development and integration challenges with reduced testing time, it is a strategic decision for long-term sustainability and competitive advantage. RoboSub 2025 will be our crucial validation platform, laying the groundwork for deploying the planned BBAUV 5.0 in our 2026 campaign.

B. Dual-Vehicle Strategy

Our most significant innovation is the introduction of a specialized Mini-AUV for the *Gate* and *Slalom* tasks. This decision comes from analyzing the task requirements, our primary vehicle's capabilities, and long-term development goals of our team. As our Drone subteam in RobotX 2024 proved the effectiveness of a specialized and focused subteam, a similar independent subteam is formed to develop the Mini-AUV from the ground up.

1) Vehicle Specialization

BBAUV 4.5 excels at tasks that require precise control and fine-grained actuation. However, its inherent weight and larger moments of inertia limit its speed and agility, making rapid task completion (e.g., the *Gate* with "style") difficult. Our new Mini-AUV addresses this directly. Its lighter build and optimized dynamics enable significantly faster maneuvering for movement-focused challenges. This dual-vehicle approach allows for strategic task allocation, ensuring faster overall completion and enhancing our tactical flexibility in competition.

2) Multi-Vehicle Benefits

This multi-vehicle approach fundamentally reframes the complexity-reliability tradeoff by distributing capabilities across specialized platforms rather than concentrating them in a single vehicle. This separation enables graceful degradation: failure of one vehicle does not eliminate our scoring potential, as each platform can operate independently to retry and complete its designated tasks.

Beyond immediate performance gains, this deployment validates dual-vehicle operations for our planned RoboSub 2026 setup, which will feature two AUVs operating simultaneously with inter-vehicle communications. The Mini-AUV also doubles as a testbed for planned BBAUV 5.0 hardware components, helping us identify unforeseen challenges early on.

The Mini-AUV can be fitted with a new Doppler Velocity Log (DVL) and an external underwater camera intended for deployment on future platforms. By testing these sensors on the Mini-AUV, we decouple their reliance on the BBAUV 4.5 when evaluating them, a platform intended to remain stable and competition-ready. This eliminates the downtime needed to swap in and out new sensors to test on BBAUV 4.5, while accelerating sensor validation and development timelines for BBAUV 5.0.

C. Capability-to-Task Alignment

Both BBAUV 4.5 and the Mini-AUV share 6-degrees-of-freedom (6-DOF) movement for underwater navigation. The Mini-AUV's thruster layout is specifically tailored for agile, movement-focused challenges like the *Gate* (with "style") and *Slalom* tasks. In contrast, BBAUV 4.5 boasts a comprehensive actuation suite, an in-house pinger detection system, and a precise localization and control system, making it ideal for precision-based tasks such as *Torpedoes*, *Bin*, and *Octagon*. Crucially, both vehicles are equipped with multiple cameras to ensure robust underwater perception of all competition elements.

Task	**Capability Requirement**				**Vehicle**
	Actuation	Maneuverability	Vision	Acoustics	
Gate	No	Yes	Yes	No	Mini-AUV
Slalom	No	Yes	Yes	No	Mini-AUV
Bin	Yes	No	Yes	No	BBAUV 4.5
Torpedoes	Yes	No	Yes	Yes	BBAUV 4.5
Octagon	Yes	No	Yes	Yes	BBAUV 4.5

TABLE I: Task-Requirement-Vehicle matrix.

D. System Overhauls

Despite retaining the hull design of BBAUV 4.1, BBAUV 4.5 seeks to address issues identified by the electrical, mechanical, and software subteams. We detail here the goals and decisions made by each subteam with respect to existing shortcomings of each subsystem and RoboSub 2025.

1) Mechanical Changes

Due to over four years of continuous operation, the hull and frame of BBAUV 4.1 is showing signs of corrosion. Given its aging condition, the mechanical team determined that it was necessary to fabricate a new hull. The new BBAUV 4.5 hull will retain the same core design as the BBAUV 4.1 hull, but incorporate minor modifications such as additional penetrator holes to provide flexibility for possible future integration of new sensors. This decision allocates more time and resources towards developing a different hull for BBAUV 5.0 which we project to have higher demands for heat dissipation and ergonomics.

In line with electrical upgrades, the team will also redesign BBAUV 4.1 actuators for compatibility with newer motors in BBAUV 4.5. Furthermore, the torpedo launcher, will undergo further refinement to meet the evolving task requirements since our last participation in RoboSub 2023.

2) Electrical Architecture Redesign

The electrical team ascertained that our legacy electrical system had become a significant bottleneck, hampered by knowledge gaps from the COVID-19 pandemic and limited new capability integration. Incremental upgrades across team generations had also led to decreased system cohesion. Rather than inherit this technical debt, we opted for a redesign to focus on future-proofing ease of development, extensibility, and reliability for our new vehicle.

3) Software Architecture Upgrades

Our software architecture similarly requires upgrade to contend with End-of-Life (EOL) software and technical debt. Furthermore, software team members in past competitions have experienced various development difficulties such as dealing with legacy software, unstable network, coordination across different platforms, and bugs that are difficult to reproduce in complex software. Beyond resolving these foundational issues, our comprehensive redesign aims to achieve several key objectives:

- Enhanced reliability and safety: We require robust measures to make our system inherently safer from unexpected errors and integrate more comprehensive fallbacks, ensuring greater stability and resilience during operations.
- Improved developer experience: This overhaul seeks to directly addresses aforementioned developer pain points, streamline workflows and simplify complex processes to boost team efficiency and morale.
- Optimized performance: This upgrade is an opportunity to optimize the speed and performance of existing components that already work well, ensuring that our core functionalities are as efficient and effective as possible.
- Increased reusability: A major focus is on refactoring existing components to facilitate seamless reuse across multiple vehicles, which will be crucial for our future dual-AUV operations.

E. Risk Assessment

In summary, our analysis indicates that legacy system limitations were compounding, making incremental improvements insufficient. The multi-vehicle paradigm requires fundamental architectural changes and a long runway for testing and development, resulting in high risk if the team were to commit to a full-featured multi-vehicle approach in RoboSub 2025. Creating a smaller platform in the form of the Mini-AUV and revamped electrical and software systems has short-term reliability risks due to its novel nature, but using RoboSub 2025 as a validation platform reduces long-term risk for RoboSub 2026 and beyond. Further, our team's current size and structure supports parallel development efforts.

By accepting calculated short-term reliability risks, we position ourselves for sustained competitive advantage and establish a platform for continuous innovation in future competitions.

II. Design Strategy

A. BBAUV 4.5 Mechanical Improvements

With the decision to retain the same hull design for BBAUV 4.5, the mechanical subteam focused on redesigning our actuators to make them more compatible with new waterproof servos and align with stricter task requirements.

1) Improved Torpedo Launcher

As additional points were introduced for firing torpedoes from a further distance, our torpedoes underwent a redesign focused on enhancing its stability and hydrodynamic efficiency to increase its effective range. To achieve a self-stabilizing torpedo, the center of pressure was shifted rearward relative to the center of gravity, allowing the torpedo to passively correct its trajectory in flight.

The internal structure is tuned to make the torpedo neutrally buoyant. This minimizes both vertical drop and lift during underwater travel, ensuring a more consistent trajectory path. In addition, the pressure distribution around the torpedo body was optimized to reduce low-pressure zones, particularly those observed in older designs that caused drag asymmetries and instabilities. We utilized Computational Fluid Dynamics (CFD) analysis in SolidWorks to quantify the effectiveness of our new torpedo design. Appendix B details the CFD results.

The torpedo launcher was also redesigned to complement the improved projectile. A Teflon tube was used as the barrel liner, offering a low-cost method to significantly reduce friction between the torpedo and the launcher walls. This not only minimizes internal wear over repeated use, but also reduces slop which results in more accurate and consistent launches.

The launcher is fabricated using Fused Deposition Modeling (FDM) 3D printing, minimizing weight and cost while offering the flexibility to produce more intricate geometries. As a result, the new launcher design accommodates larger torpedoes without significantly increasing its overall footprint.

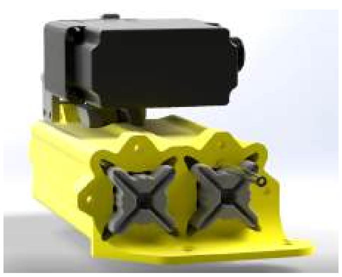

Fig. 3: Render of new Torpedo Launcher lined with Teflon tubes.

2) Improved Grabber

Drawing from our experience in previous RoboSub competitions, we observed that specialized grabbers often required multiple iterations while development is only able to start after core vehicle capabilities are ready. This has historically left us with limited time to design and test task-specific manipulators. In response to this, we decided to develop a more versatile grabber capable of handling complex, unseen geometries, a shift from our previous approach of designing a competition-specific grabber suited to the geometry of a given year's task.

For this year's iteration, we calibrated the soft fingertips of the grabber, designed with a Fin Ray structure [1] and printed using Thermoplastic Polyurethane (TPU) to enhance it's versatility. To address the difficulty in stationkeeping at close distances above the *Octagon* task's table, we moved away from a simple worm-driven rotary design to a 4-bar linkage system. While still worm-driven, it features a longer stroke parallel motion to improve reach and deliver a constant grip area at every given opening.

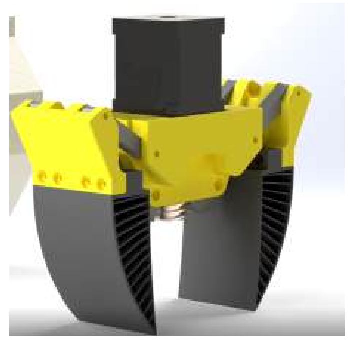

Fig. 4: Render of redesigned Grabber.

B. BBAUV 4.5 Electrical Stack

The team revamped the electrical stack of BBAUV 4.5, moving away from its aging architecture to create a clean slate for future iterations. Also integrated into the new design are best practices learned from developing BBASV 4.0, enhancing overall reliability.

1) Microcontroller Changes

We have shifted away from the Atmel microcontrollers (MCUs) that we have been using in the past to STM32 32-bit MCUs. This architectural change opens up new opportunities to explore with advanced firmware features such as Real-Time Operating System (RTOS), support for higher-resolution timers, and better peripherals overall. STM32 MCUs also lowers our Bill of Materials (BOM) cost as it has a reliable internal oscillator, and the MCU chip itself has a cheaper unit cost. The STM32 ecosystem supports robust development environments such as STM32CubeMX, which further streamlines and standardizes our firmware development across the subteam.

2) Backplane Redesign

In the new architecture, we undertook a redesign of the Power Switching Board (PSB), increasing its support from two to four daughter boards. This modification allowed us to redistribute and compartmentalize subsystem functionalities more effectively, resulting in a cleaner PCB layout, more modular firmware, and additional flexibility to accommodate future upgrades.

We also refined the stack's communication architecture, where the Electronic Speed Controller (ESC) Backplane now integrates a passive CAN Bus Arbitration Logic circuit that forwards CAN messages directly to the ESCs. This redesign eliminates the need for a dedicated MCU to handle message forwarding to our un-isolated CAN line — a task previously assigned to the Thruster and Actuation Board in BBAUV 4.1. By removing this dependency, we freed up one daughter board slot on the PSB and reduced system redundancy, streamlining both hardware and firmware complexity.

3) Improved Power Distribution and Filtering

Following our positive experience at RobotX 2024 with the ability to selectively toggle power to key hardware components, we have also redesigned the PSB to better support power monitoring and control for each power channel via load switches. This allows for power sequencing implementation, which suppresses sudden inrush current and consequently lowers the electrical stress on key components. Additionally, it offers the flexibility to disable power-hungry hardware components when not in use, reducing overall battery consumption and extending our operational runtime.

Similarly, the ESC backplane has also been redesigned to feature a soft starter system to further reduce the in-rush current when we re-supply power to the thrusters from a killed state. Additional power filtering and real-time monitoring circuitry were also implemented along the power rails. These enhancements ensure cleaner and more stable power delivery across all subsystems, ultimately improving system reliability and overall electrical performance.

C. BBAUV 4.5 Software Stack

The software architecture for BBAUV 4.5 represents a significant evolution from its predecessor, BBAUV 4.1, with a primary goal of maintaining feature parity or improving upon our strong existing set of capabilities through targeted optimizations and a keen consideration of development bottlenecks.

A foundational shift in BBAUV 4.5 is the migration from the ROS1 Noetic stack to ROS2 Humble. This transition, while substantial, has been meticulously executed to ensure core capabilities are maintained, laying a robust and future-proof groundwork for continued development and integration.

1) Perception

Our new perception pipeline leverages multiple machine learning and computer vision strategies to significantly increase robustness in navigating novel and challenging underwater environments. We use YOLO11 [2] to perform initial detection of underwater elements before using XFeat [3] to perform feature matching for precise determination of the location of these elements. This is supplemented by traditional computer vision algorithms like Perspective-n-Point (PnP), clustering algorithms like HDBSCAN, and monocular depth estimation [4] for robust pose estimation. This multi-faceted approach allows us to capitalize on the strengths of each individual method and have several fallbacks in case an individual method fails to perform in adverse conditions. We retain use of MUSIC [5] to determine direction-of-arrival of acoustic pings.

2) Localization

The localization pipeline continues to leverage our established approach using an Unscented Kalman Filter (UKF). This system fuses data from the sensors to provide a reliable estimate of the vehicle's position underwater. To push the limits of our localization capabilities, we have also implemented several safeguards, including inferring and discarding extreme sensor readings and falling back on recalibration based on visual elements, further enhancing the system's resilience in challenging scenarios.

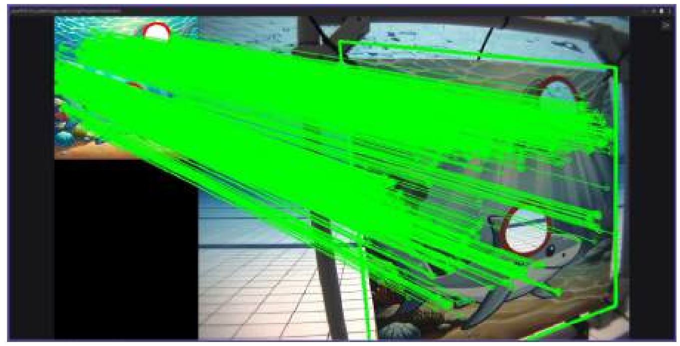

Fig. 5: Pose estimation of torpedo target underwater via feature matching.

3) Control System

Our tried and tested control system retains its effective form, designed for precise and stable vehicle maneuvering. High-level movement goals are passed into a trajectory planner which determines a smooth and continuous path using polynomial interpolation with consideration for known physical limits, preventing thruster saturation. This trajectory is passed into feedforward and feedback controllers [6] which compute the net body force required to realize the trajectory. Finally, a thrust allocator utilizes a quadratic programming solver to optimize the command to each thruster, ensuring efficient and effective propulsion to prolong in-water testing time and mitigate wear.

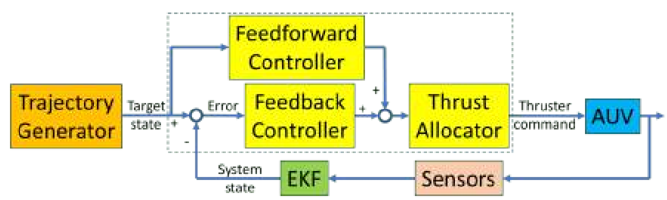

Fig. 6: BBAUV 4.5 control system block diagram.

4) Mission Planner

The mission planner is the primary component that has received a significant overhaul in BBAUV 4.5. We continue to use a behavior tree-based mission planner, valuing its modularity, composability, and ability to scale effectively for larger missions. The team migrated away from BT.CPP and towards Py Trees [7] for our behavior tree implementation. While Py Trees gives up the convenience of GUI editing found in BT.CPP, it retains core behavior tree functionality and comes with several compelling advantages: it is easier for newer members to learn, offers strong introspection support for debugging, is more readable and explicit, and boasts strong integration with ROS. This strategic change aims to enhance team productivity and simplify the development and debugging of complex mission logic. Figure 7 shows a render of a behavior tree defined in Py Trees.

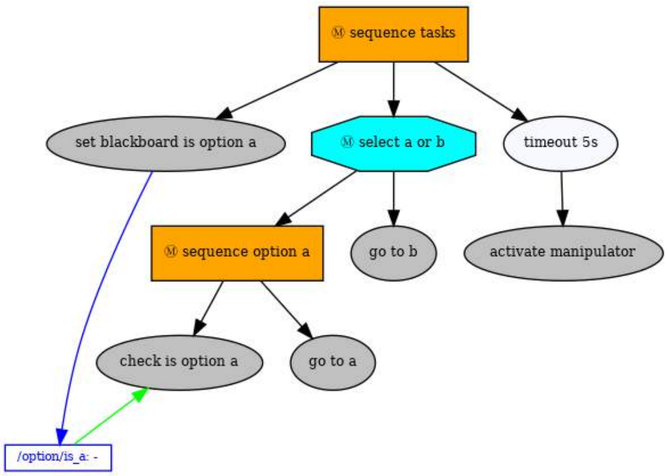

Fig. 7: Example of behavior tree specifying mission logic.

5) Network and Telemetry

Drawing on lessons learned from successes we enjoyed in RobotX 2024, we have brought our philosophy of high telemetry coverage from the BBASV 4.0 over to the BBAUV 4.5. The BBAUV 4.5 features a revamped Controller Area Network (CAN) standard with safeguards against errors [8] [9] and optimized custom message passing between the electrical and software subsystems, enabling the management of more messages for four times less computational cost. Furthermore, greater manipulator feedback is available to the software subsystem, facilitating more precise approaches to competition tasks. To improve operational efficiency during testing, BBAUV 4.5 sends automated telemetry reports and warning messages to team members via Telegram, ensuring timely communication, more eyes to monitor critical systems, and proactive problem solving.

D. Mini-AUV

Given the tight development timeline, the Mini-AUV was deliberately designed with simplicity and ease of use in mind to ensure it could be deployed in time for RoboSub 2025. Its small, modular size also makes it ideal as a validation platform for new sensors that we intend to deploy on future vehicles.

1) Mechanical Structure

The mechanical design of the Mini-AUV is centered around enabling the vehicle to execute a barrel roll maneuver, allowing it to earn “style” points when passing through the *Gate*. Weighing approximately 10 kg in air and measuring just 0.6 m × 0.4 m × 0.4 m, the Mini-AUV is compact, lightweight, and highly portable, making it ideal for rapid deployment and iterative testing.

Drawing inspiration from the BlueROV2 Heavy and ArduSub configurations [10], we adopted an 8-thruster layout to provide full 6-DOF control, enabling the precise maneuvers required for the vehicle’s core objective.

2) Electrical Design

The electrical design of the Mini-AUV prioritizes maintainability to minimize hardware stability issues especially given the shorter development timeline. The low-level control is done by an ESP-32 breakout module from Espressif instead of a bare-bone MCU chip that is traditionally found in past iterations of our BBAUV designs. This approach simplifies PCB routing and allows for rapid replacement in the event of electrical faults, which is an important consideration given the increased risk under accelerated development conditions.

The Thruster PCB is designed to mirror the shape of the end-cap for it to be mounted directly on it. This allows for quick-disconnect of cables to facilitate easy access to the internals and mounting trays, which is illustrated in Figure 22.

Similar to the BBAUV 4.5, a load balancer module was also added so that the Mini-AUV can be powered via an external battery connector. Thus, the onboard computer can remain powered when executing battery swaps, minimizing disruptions for the team’s use and testing.

3) Software Architecture

The Mini-AUV is designed to utilize the mission planner and perception stacks of BBAUV 4.5. MAVROS is used to bridge data from the sensors integrated in the Pixhawk 6X controller of the Mini-AUV into the ROS environment where it can be used for localization. Nav2 [11] is then used for trajectory planning before command velocities and thruster commands are fed back into the controller via the same MAVROS bridge. Overall, the Mini-AUV’s software architecture is minimal through code reuse, but focused on core capabilities for its role in RoboSub 25.

III. Testing Strategy

A. Compartmentalized Electrical Testing

During the conceptualization and design of our new backplane-based electrical architecture, it became evident that several PCBs in the system have inherent dependencies on one another. This posed significant challenges for unit testing and subsystem validation. In particular, the reliance of all daugther boards on each other for communication via CAN Bus created bottlenecks during validation, and limited the extent of what could be tested and debugged in early stages.

To address these issues and ensure a more robust development process, we designed and fabricated a series of simple, purpose-built test boards. For example, a ”mock” PSB was developed to mimic the backplane layout. This allowed the firmware and CAN Bus communication on the daughter boards to be validated independently, without requiring the actual PSB to be operational.

Individual debug boards were also fabricated, featuring critical electrical nets broken out to header pins and connectors. These boards are breadboard-compatible, thus providing a flexible platform for probing signals and validating individual subsystems during early-stage development.

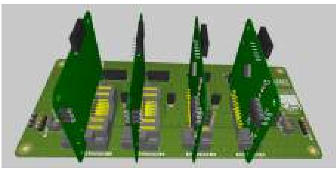

Fig. 8: “Mock” PSB.

Fig. 9: Individual debug boards that are breadboard compatible.

This approach significantly streamlined our development workflow by enabling parallel firmware testing and early-stage software validation. It was especially beneficial given the complexity and stability requirements of the actual PSB, which deals with high-current power switching. By decoupling firmware development from overall hardware readiness, we minimized integration delays and increased our overall development speed.

B. Integration Testing

To ensure that the software subteam retains access to a stable platform for task capability development, we opted to maintain BBAUV 4.1 for pool tests while developing and testing the hardware in parallel. To prevent premature system changes, all PCBs were subjected to a comprehensive load test, firmware validation, and subsystem tests before full system integration. The electrical subteam only initiated integration once full confidence in each PCB’s functionality was established. A dedicated weekend was then allocated to validate the new electrical stack using the compute units and sensors from BBAUV 4.1, ensuring compatibility before migrating these components into the new hull.

This rigorous testing strategy significantly reduced the risk associated with new hardware and minimized disruptions to software’s testing schedule. Additional details on our other design verification and testing procedures can be found in Appendix D to Appendix E.

C. Software Testing and Validation

To facilitate regression testing during the migration to ROS2 Humble, containerization was used to enable a hybrid setup with both ROS1 Noetic and ROS2 Humble components. The team utilized a bridge to allow each new ROS2 Humble component to interact with existing ROS1 Noetic components, thus enabling the team to verify that the new components can fully replace the old counterpart without error.

For individual software components, our team adheres to common code best practices including unit testing, static analysis, and peer review. For integrated systems and complex behaviors that are challenging to test conventionally, the software team employs heavy use of Gazebo simulations complete with competition elements. Simulations enable validation of task strategies and testing even when hardware is not available. This allows for preliminary checks on the safety and viability of our software logic, including perception and behavior, long before actual vehicle deployment. By testing in simulation, we identify bugs earlier, iterate faster, and free up valuable development time for the electrical and mechanical teams.

Before and after each in-water test, we formulate and review testing goals to ensure efficient use of deployment time. We also log the conditions during every in-water test run. This allows for thorough review and ensures the reproducibility of observed behaviors. Further details of the software team’s testing plan is summarized in Appendix F, while detailed in-water testing procedure, test observations of note, and resulting decisions are discussed in Appendix G .

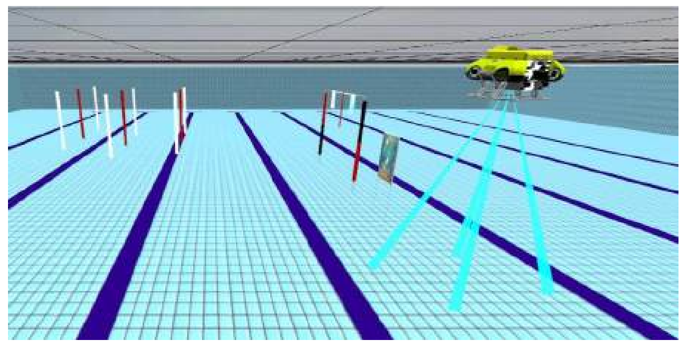

Fig. 10: Gazebo simulation pool environment with competition elements (from left to right: Slalom, Gate, Torpedoes, BBAUV 4.5).

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Fig. 11: Team Bumblebee 2025.

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APPENDIX A
SPONSORS

A. *Title Sponsors*

NUS (College of Design and Engineering, Innovation & Design Programme and School of Computing) — For their crucial cash support, equipment procurement, and academic assistance for our project.

B. *Platinum Sponsors*

Altium — For providing software licenses vital to our PCB design.

DHL — For sponsoring the logistics and shipment of our cargo from Singapore to the United States for RoboSub 2025.

DSO National Laboratories — For cash support.

Future Systems Technology Directorate (FSTD) — For cash support.

Republic of Singapore Yacht Club — For providing a testing location and wet berth for our Autonomous Surface Vessel.

ST Engineering — For providing the Ouster OS0 LiDAR on our Autonomous Surface Vessel and for offering our members valuable Final-Year Project opportunities.

C. *Gold Sponsors*

Fugro, MacArtney, SBG Systems and Würth Electronik.

D. *Silver Sponsors*

Avetics, Festo, Jane Street, MEDs Interconnect, Samtec, Solidworks, Southco

E. *Bronze Sponsors*

Blue Trail Engineering, Bossard, Kraus & Naimer, LionsForge, Pololu, Rohde & Schwarz, TGN Technology and Waterlinked.

The following initialisms are specific to our internal usage and may be useful for elucidation of the appendices:

- **ESC**: Electronic Speed Controller
- **PMB**: Power Monitoring Board
- **PDB**: Power Distribution Board
- **PSB**: Power Switching Board
- **OCS**: Operator Control Station

Appendix B
Torpedo CFD Analysis

The Torpedo CFD results of the old model 12 and the new model 13 are presented below. The drag profile was carefully balanced against the torpedo's volume and mass. While minimizing surface drag remained a priority, some increase in overall mass was accepted to preserve momentum and ensure stable travel at the target speed. This trade-off enables effective propulsion without requiring excessive force at launch, resulting in a more efficient and predictable trajectory.

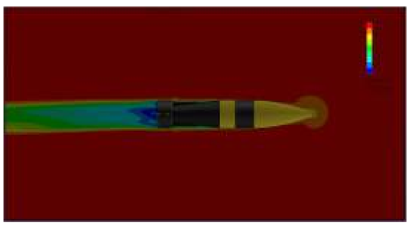

Fig. 12: CFD results of the old Torpedo.

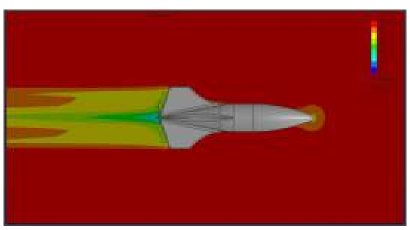

Fig. 13: CFD results of the new Torpedo.

The figures below summarizes the convergence metrics from the CFD simulation used in evaluating the torpedo's aerodynamic and hydrodynamic properties. Key goals include net force (F_1), frictional force (F_{friction}), and center of pressure locations (CoP1 and CoP2).

Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence	Delta	Criteria
F 1	[N]	0.043	0.043	0.042	0.043	100	Yes	2.401e-05	0.001
F friction	[N]	0.015	0.015	0.015	0.015	100	Yes	8.213e-06	3.412e-04
CoP1	[mm]	-84	-84	-86	-83	100	Yes	2e-01	8e-01
CoP 2	[mm]	84	83	82	85	100	Yes	2e-01	8e-01

Fig. 14: Old Torpedo data.

Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence	Delta	Criteria
F 1	[N]	0.032	0.032	0.031	0.032	100	Yes	1.018e-04	2.686e-04
F friction	[N]	0.017	0.017	0.017	0.017	100	Yes	3.351e-06	7.356e-05
CoP 1	[mm]	-35	-36	-39	-33	100	Yes	1	2
CoP 2	[mm]	34	36	32	40	100	Yes	1e+00	1

Fig. 15: New Torpedo data.

Appendix C
PSB Design and Validation

While the previous version of the PSB does support power control capabilities, we expanded on it to include power monitoring features so the overall power subsystem is more robust and resilient to faults. The current version utilises active power cycling via an on-board MCU, which allows power sequencing and board status updates to the compute stack via CAN. The positions of the daughter board on the PSB were also readjusted for ease of access and mounting of the daughter boards.

The PSB controls and monitors power rails for 12 V and 24 V via load switches LM5060, and for 5 V via a synchronous buck converter LMR51450. There is also an unisolated power rail taken directly from the battery dedicated for powering the lights board. These chosen power components feature enable status and power good status indicators, and will turn off completely in user-defined over-current fault conditions. The board's architecture can be found in Figure 23.

To verify each feature, comprehensive tests were carried out on the PSB with a dual channel load tester. Key metrics such as load tester current, voltage drop, and maximum board temperature.

To illustrate the verification process, the results of the load tests conducted on the 12 V power channels for 5 minutes can be found in Table II.

Component	**GPU**	**SBC**	**Cameras**
PSU Current (A)	9.1	9.1	7.1
Voltage (V)	11.20	11.28	11.30
Temp. (°C)	46	38.5	39.0

TABLE II: PSB Load Test Results for 12 V Channels.

Based on these load tests, we concluded that the 12 V power channels are capable of reliably supporting both step loads from 0 to 9 A and sustained loads at 9 A. This capability is particularly critical for components such as the Single Board Computer (SBC) and the Jetson, which can exhibit transient current spikes that exceed their maximum datasheet values during the boot-up sequence. In earlier tests using a bench power supply, boot failures were observed when the current limit was set too low, highlighting the importance of accommodating these startup transients in the final power design.

The successful completion of these tests provides the electrical subteam with high confidence in the board's ability to safely and reliably power high-value components. Similarly, tailored validation checklists and processes ensure that each individual PCB can be connected to actual hardware with minimal risk during the final integration phase.

APPENDIX D
ELECTRICAL INTEGRATION TEST PLAN

Category	**Items**
Power	1) Able to power entire system with one battery 2) Turning off one battery does not turn off the other battery or the system entirely 3) Able to load balance with vastly different voltages 4) Able to output stable 12 V & 24 V on PDB 5) Able to output stable 12 V on PSB for all daughter boards 6) Able to power and control LEDS 7) Able to power compute components (e.g., Jetson Orin) 8) Able to run all seven thrusters and three acutuators simultaneously 9) Able to power cycle all channels 10) Power good status received
Thruster and Kill System	1) Removing the kill switch stops all thrusters within 1 s 2) Replacing the kill switch enables power to the thrusters 3) All systems remain alive after transitioning from a killed state
Telemetry	1) Working PCB heartbeats 2) Status updates accordingly (e.g., heartbeats appear and disappear correctly) 3) Telemetry screen minimally displays internal pressure and heartbeats 4) Working OCS telemetry 5) Able to receive and display statistics from compute stack (e.g., CPU temperature)
Sensors	1) Able to send critical sensor data over CAN (e.g., external pressure) 2) Able to read button status and provide buzzer feedback 3) Able to publish temperature probe readings
CAN	1) SBC able to forward msgs to SBC-CAN 2) SBC-CAN able to forward to SBC 3) Able to control thruster movement through ESCs from SBC
Acoustics	1) Working filter board 2) Working MUSIC algorithm 3) Able to publish direction of arrival and elevation readings

TABLE III: Integration phase testing feature checklist.

APPENDIX E
HARDWARE TESTS

Test/Simulation	Description
Preliminary Leak Test	Upon receiving the newly refurbished hull, we performed a preliminary leak test by assembling the AUV in its bare-minimum configuration and sealing all penetrator holes with blank plugs. Our initial plan was to send the hull to an external vendor for pressure testing in a pressure chamber. However, due to difficulties in obtaining a timely response, we proceeded with in-house leak testing. Using our custom-built Pressure Monitoring Board, which provides real-time internal pressure readings via an onboard OLED display, we vacuum-tested the hull to 10 kPa. After 12 hours of monitoring, the pressure remained stable with no signs of leakage. Based on these results, we concluded that the hull is watertight and meets the design specification for operational depths of around 10 meters.
Actuators System Test	The mechanical and electrical members responsible for actuator development work closely with each other to test each actuator before they are deployed on the vehicle for pool tests. Using spare actuator boards, the new actuator designs can be tested in the lab when the BBAUV 4.5 is out for pool tests. The electrical team also developed firmware that enables actuation commands to be triggered directly from the command line. This functionality provides flexibility for the mechanical team, as it removes the need for an electrical member to be physically present during actuator testing.
Bench Test	Prior to every pool test, a routine check is performed to ensure that all AUV subsystems are functioning correctly. The software team executes a bench test script, which sequentially runs each of the seven thrusters in-air for a few seconds to verify the SBC to electrical stack communication. Key sensor outputs—such as the camera feed and inertial measurement unit (IMU) data—are also checked to verify that they are working. The final step involves pressurizing the sealed hull to 130 kPa using an external air pump. The internal pressure is monitored via the vehicle's telemetry display for a few minutes. If any pressure drop is observed, the team performs a leak check by applying soap solution to potential leak points and inspecting for air bubbles, which indicates a leak. This process helps ensure the vehicle remains watertight and safe during the pool test.

TABLE IV: Descriptions of hardware-related tests.

APPENDIX F
SOFTWARE TEST PLAN

Component/Capability	**Description**	**Methodology**	**Timeline**
Sensor Drivers	Drivers needed validation and integration testing after migration to ROS2.	Docker containers and a bridge was used to create hybrid ROS1 and ROS2 setup, each new ROS2 component was tested with the other components being ROS1 to ensure that it is a seamless replacement before all ROS2 components are tested together in-water.	By the end of February 2025.
Localization and Movement	The localization and control system also required validation and integration testing after migration to ROS2. New quality of life features of control system also needs to be tested to ensure that it does not break existing functionality.	Test scripts were used to simulate high-level planning systems and send various low-level movement commands for BBAUV 4.5 to execute in simulations and in-water. Sensor data was logged to quantify the quality of movement.	Requires sensor drivers to be ready, complete testing by end of March 2025.
Perception	The new combined vision pipeline mixed old approaches with new ones, requiring fine-tuning to ensure that it performs on par or better than just the old approach.	Old recordings were used to gauge the effectiveness of the vision pipeline. Props were set up in-water to simulate the competition environment and the vision pipeline was validated under different environmental conditions such as dim or bright lighting.	March to April 2025.
Mission Plans	Testing of high-level behavior control and competition task approaches.	Initial approaches were discussed early on and trialed in simulations. In-water testing happened as soon as hardware capabilities were ready and evolved the plan over time. Test conditions were logged to ensure reproducibility of behaviors.	All throughout the development timeline.
Network and Message Standards	Mostly innovative optimizations to match the new electrical stack and allow the vehicle to keep up with the demands of new approaches.	New optimizations were prepared as toggle-able options in advance. Verification of functionality is performed along with the integration of the new electrical stack.	April to June 2025.
Actuation	New droppers, torpedoes, and grabbers needed testing and fine-tuning for precise manipulation.	Initial approaches were trialed in simulations before moving to in-water testing with manually inputted movement commands. Fully autonomous testing is to occur after a few iterations of hardware to ensure the best possible performance.	Requires all other components to be ready along with the mechanical and electrical teams, testing by end of July 2025.

TABLE V: Software testing plan.

APPENDIX G
POOL TESTS AND STRATEGY ADJUSTMENTS

Our in-water testing is done in the Olympic size swimming pools of the National University of Singapore University Sport Centre (USC). Logistics include replicas of competition elements built by our mechanical team (e.g., see Figure 16 below), power apparatus, network reel and OCS, miscellaneous network equipment (e.g., network switch), tables and chairs, and hand tools.

Fig. 16: Torpedo board used for pool tests.

Fig. 17: Software team members in a pool test at USC.

Before arrival at the USC pool, the team meets to align the testing goals for the day and perform necessary preliminary checks such as bench testing (see the preceding Appendix E). The conditions at the pool, such as lighting conditions and temperature of the water (very hot days affect DVL readings) are noted along with which software components and electrical components are active for later review and reproducibility. An individual pool test will span most of the day, with electrical members on standby to deliver battery replacements, so that smaller scale issues can be worked through and ironed out on the spot.

Beyond validation of individual software components (as in Appendix F), pool tests crucially reveal blind spots in our development plan through problems that only arise in full in-water deployments. Major examples of significant findings from pool tests to date that have broadly affected our overall strategy are as follows:

- Need for a more accurate torpedo: Early pool tests showed that our old torpedoes were precise but not sufficiently accurate. The consistent spread pattern formed a ring shape, which we deemed too risky given the reduced target size and increased firing distance compared to previous RoboSub competitions. This directly spurred the development of our BBAUV 4.5 torpedo. Subsequent validation through similar tests confirmed its significantly improved performance.

- Difficulty in stationkeeping close the bottom of the pool: During tasks like *Bins* or *Octagon*, the DVL can struggle to report accurate linear velocities due to close proximity, leading to poor localization. Through a series of refinements developed during rigorous pool tests, our software team has devised an approach to minimize the occurrence of this limitation. Furthermore, feedback from these tests is directly informing the mechanical team's design of an improved grabber, ensuring a more robust solution for these tasks.

- Embracing error resistance and graceful degradation: Through task approach testing, we recognize that errors from unexpected circumstances are inevitable. Our strategy has shifted from solely striving for error avoidance to embracing error resistance and graceful degradation. We're building systems that are inherently resilient, incorporating comprehensive fallbacks and recovery protocols, such as our upgraded perception pipeline. This doesn't negate the importance of good practices and quality code, which remain our strong foundation. This philosophy also guided the software team's decision to adopt Py Trees, valued for its explicitness, readability, powerful debugging utilities, and native support for fallback mechanisms.

To ensure safety and mitigate risks, known dangers and identified risks are communicated broadly across the entire team. We've established standard operating procedures for managing pool test equipment and handling BBAUV4.5, promoting routine operations and minimizing unsafe practices. Crucially, the software team's testing intentions are communicated in advance to a designated standby team member who is ready to activate the kill switch in case of any unforeseen circumstances.

The upgraded telemetry of BBAUV4.5 also serves to support all operations. Through automated reports sent via Telegram, team members not at the pool can also monitor vital measurements like internal pressure, adding an additional layer of safety. This also boosts testing efficiency by reducing dependence on software team members to report key metrics and alert for battery changes.

APPENDIX H
ARCHITECTURE BLOCK DIAGRAMS

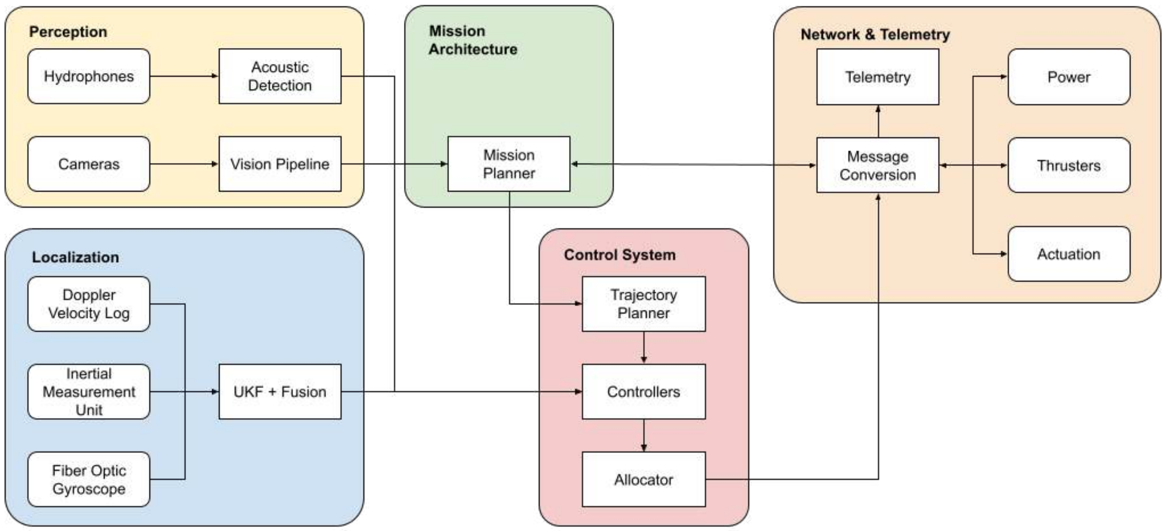

Fig. 18: High-level Overview of BBAUV 4.5's Software Architecture.

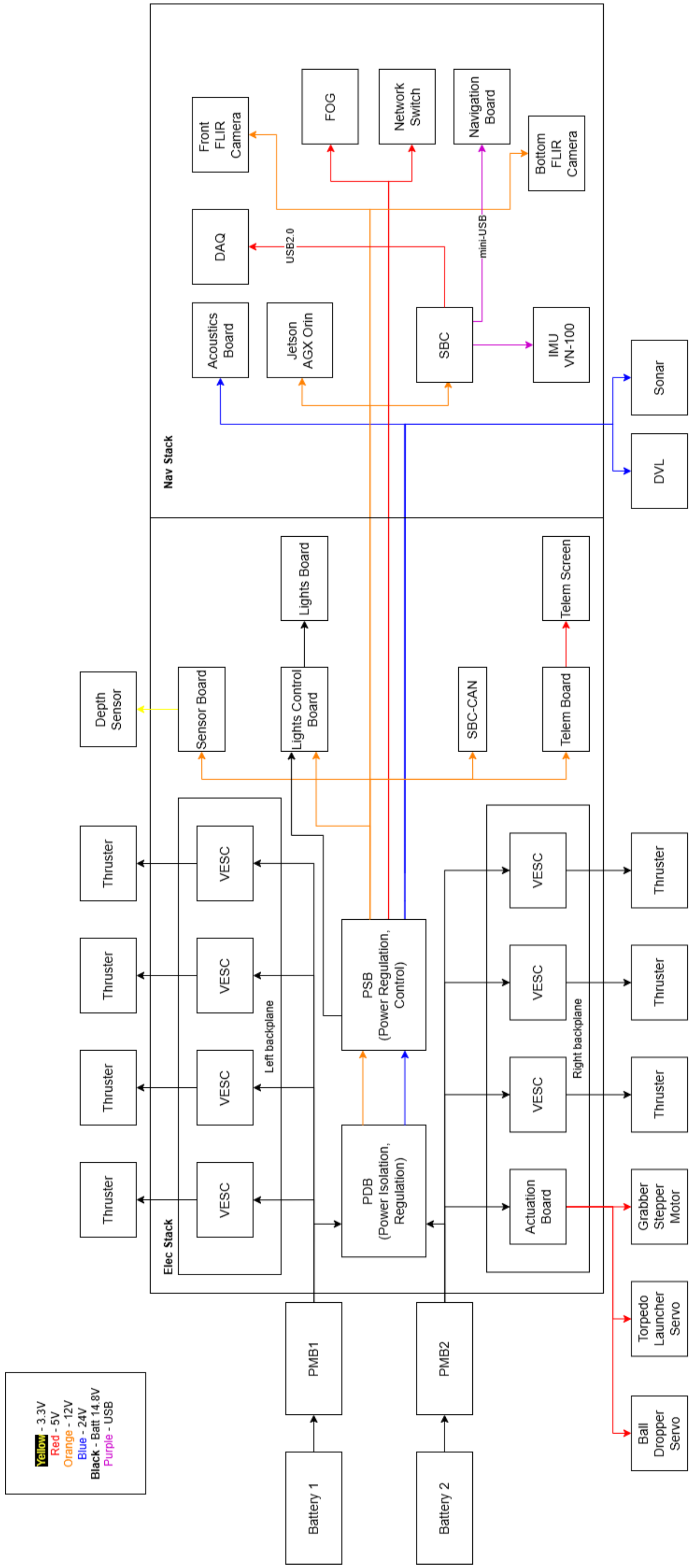

Fig. 19: BBAUV 4.5 Power Architecture.

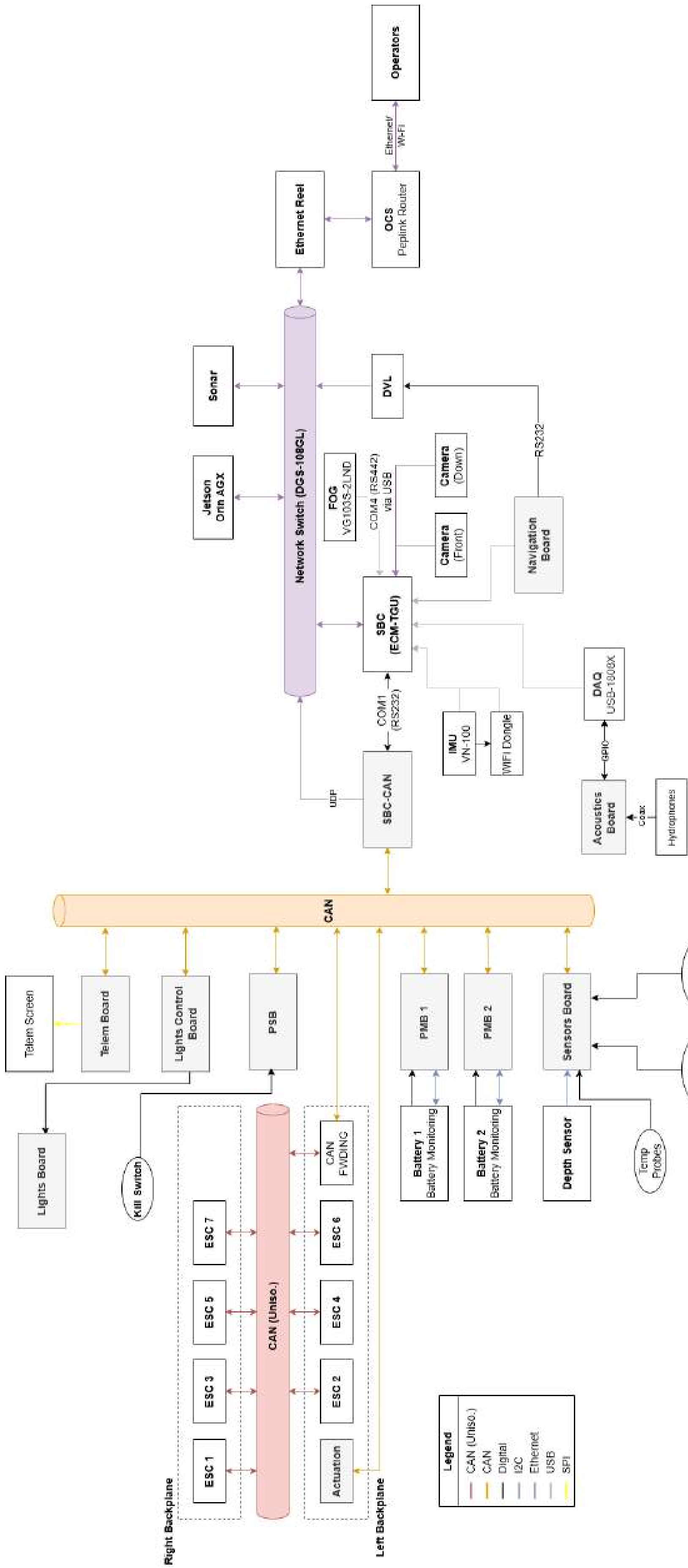

Fig. 20: BBAUV 4.5 Communication Architecture.

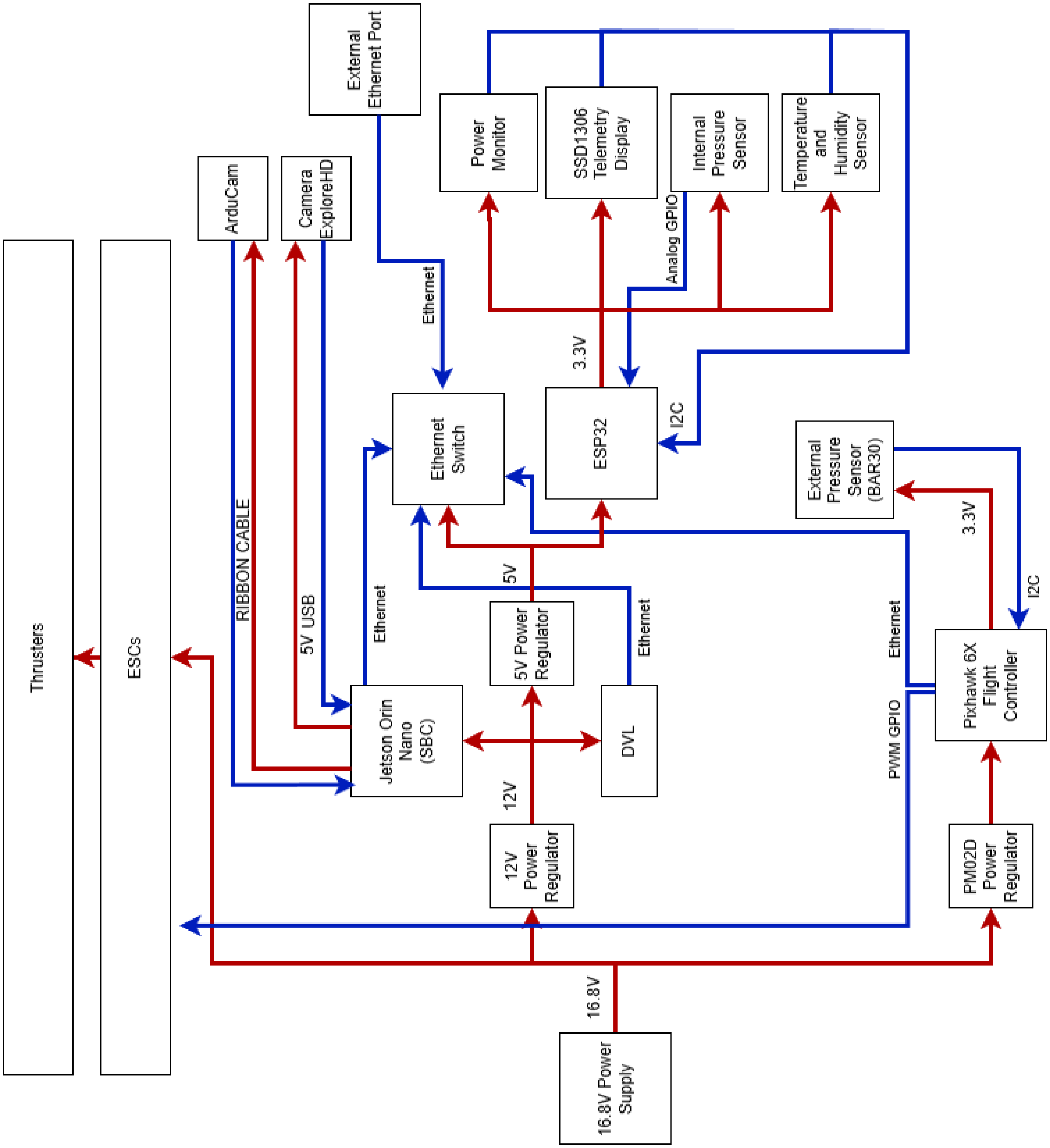

Fig. 21: Mini-AUV Architecture Diagram.

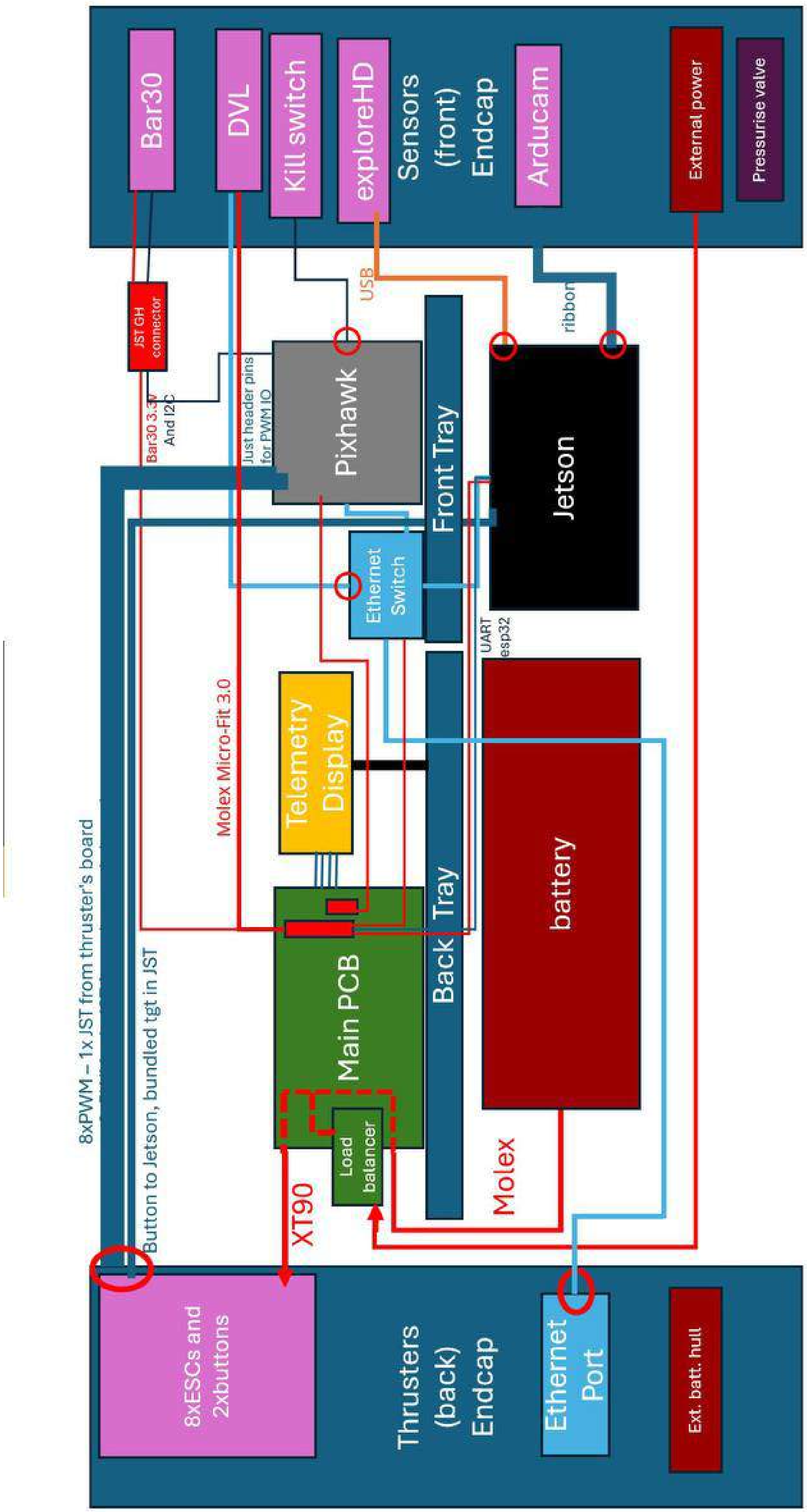

Fig. 22: Mini-AUV Connection Diagram.

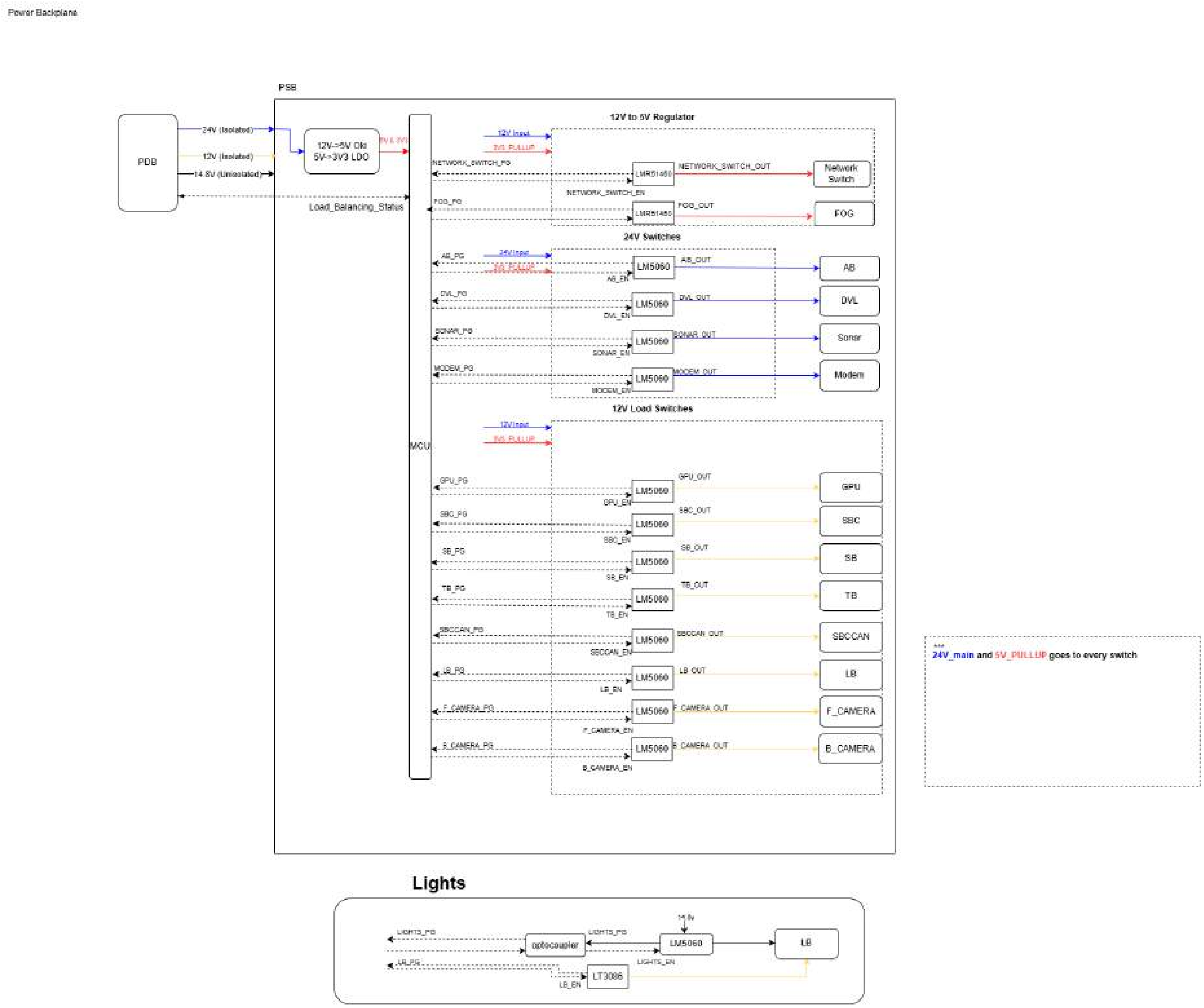

Fig. 23: PSB Design Architecture.

APPENDIX I
COMPONENT SPECIFICATIONS (BBAUV 4.5)

Component	Vendor	Model / Type	Specifications	Custom / Purchased	Cost	Year of Purchase
AUV Hull	JLCCNC	Custom Aluminium Milling	Aluminum 6061	Custom	$1,500	2025
Frame	Brown Metal Engineering	Custom Aluminium Milling	—	Custom	$400	2025
Floats	Admiralty International	Diab HCP30	—	Custom	$4,650	2022
Nylon Shell	3D Print Singapore	—	HP MJF	Custom	$1,000	2022
Waterproof Connectors	MacArtney Group	Assorted Micro & Low-Profile SubConn Series	—	Purchased	Sponsored	2019
Penetrators	Bluerobotics	Assorted Wetlink Penetrators	—	Purchased	$300	2025
Waterproof Servos	Blue Trail Engineering	SER20XX	—	Purchased	$500 ea	2024
Thrusters	Blue Robotics	T200 Thrusters	—	Purchased	$260 ea	2025
Thruster Control	Flipsky	MINI V6 MK5	—	Purchased	$100 ea	2025
Stepper Motor	StepperOnline	NEMA 17	—	Purchased	$175 ea	2022
Actuators/ Manipulators	In-House	ABS/HP MJF	—	Custom	—	2025
Battery Hull	JLCCNC	Custom Aluminium Milling	—	Custom	$270 ea	2025
Battery	Raitan	Molicel INR-21700-P42A	115.2Wh, Custom-made 2x2S4P Pack	Purchased	$330 ea	2025
Battery Monitoring System	JLCPCB	In-house Custom-made Circuit Board	—	Custom	$200 ea	2025
Microcontrollers	STMicroelectronics	STM32F103C8T6	-	Purchased	$2 ea	2025
	-	STM32F407VET6	-	Purchased	$2 ea	2025
Power Isolator	Murata	UWQ-12/10-Q12PB-C	120W Wide-range Isolated DC-DC to 12V	Purchased	$52	2025
		UWE-24/3-Q12PB-C	72W Wide-range Isolated DC-DC to 24V	Purchased	$67	2025
Single Board Computer	AValue	ECM-TGU	Intel Core i7-1185GRE, 1 TB SSD	Purchased	$1,000	2023
GPU	Seeed Studio	Nvidia Jetson Orin AGX	32 GB	Purchased	$2,500	2022
FOG	Fizoptika	VG103S-2LND	—	Purchased	$3,060	2021
IMU	VectorNav	VN-100	—	Purchased	$1,500	2023
Doppler Velocity Log	Teledyne Marine	Pathfinder DVL	600KHz Phased Array	Purchased	$16,000	2019
Camera(s)	Teledyne Vision Solutions - FLIR	BlackFly S PoE Gigabit Camera	BFS-PGE-31S4C-C	Purchased	$594	2019
Sonar	Oculus	M750d	Dual Frequency Multibeam Sonar (750KHz / 1.2MHz)	Purchased	$21,300	2019
Hydrophones	Teledyne Reson	TC-4013	—	Purchased	Legacy	2017

Data Acquisition Module (DAQ)	Digilent	MCC USB-1808X	OEM	Purchased	$1,200	2024
Acoustics Filter Board	JLCPCB	In-house Custom-made Circuit Board	14th-order Filter Stage	Custom	$300 ea	2025
Power Switching, Lights Control, Internal Sensors, Telemetry Display, Actuation Interface, Comms. Conversion Boards	JLCPCB	In-house Custom-made Circuit Board	—	Custom	$4,000	2025
Internal Comm. Network	—	CAN Bus / Ethernet	1000Kbps / 1000Mbps	Custom	—	—
External Comm. Interface	—	Ethernet	1000Mbps, Cat5e Ethernet Reel	Custom	—	—
Algorithm: Acoustics Localization	—	—	Multiple Signal Classification (MUSIC), Short-Time Fourier Transform (STFT) based Ping Extraction	—	—	—
Algorithm: Vision	—	—	OpenCV, YOLO11, DepthAnything, XFeat	—	—	—
Algorithm: Localization	—	—	Unscented Kalman Filter (UKF)	—	—	—
Software: Autonomy	—	—	Py Trees	—	—	—
Software: Framework	—	—	ROS2 Humble, PyTorch	—	—	—
Team size	—	—	55	—	—	—
Hardware/ Software Expertise Ratio	—	—	3:2	—	—	—
Testing time: Simulation	—	—	100 hours	—	—	—
Testing time: In-water	—	—	300 hours	—	—	—

APPENDIX J
COMPONENT SPECIFICATIONS (MINI-AUV)

Component	Vendor	Model / Type	Specifications	Custom / Purchased	Cost	Year of Purchase
AUV Hull & Mounting Trays	NUS Central Workshop	Custom Aluminium Milling	—	Custom	$300	2025
AUV Frame	Brown Metal Engineering	Custom Aluminium Milling	—	Custom	$600	2025
Waterproof Connectors	MacArtney Group	Assorted Micro & Low-Profile SubConn Series	—	Purchased	Sponsored	2019
Penetrators	Bluerobotics	Assorted Wetlink Penetrators	—	Purchased	$300	2025
Thrusters	Blue Robotics	T200 Thrusters	—	Purchased	$260 ea	2025
Thruster Control	Bluerobotics	Basic ESC	—	Purchased	$50 ea	2025
Battery	Raitan	Molicel INR-21700-P42A	115.2Wh, Custom-made 2x2S4P Pack	Purchased	$330 ea	2025
Single Board Computer	Waveshare	Nvidia Orin NX 16GB	1 TB SSD, 16 GB 128-bit LPDDR5 DRAM	Purchased	$1,014	2024
Motor Controller	Holybro	Pixhawk 6X	STM32H753	Sponsored	$300	2024
Camera(s)	Arducam	IMX219	—	Purchased	$900	2024
	DWE	ExploreHD 3.0	—	Purchased	$400	2024
Doppler Velocity Log (DVL)	Waterlink	A50	—	Purchased	$3,500	2024
Microcontroller	Espressif	ESP32-S3-DevkitC-1	—	Purchased	Sponsored	2025
Power Distribution, Regulation, and Sensors Boards	JLCPCB	—	Custom In-house Design	Custom	$500	2025
Algorithm: Vision	—	—	OpenCV, YOLO11, DepthAnything	—	—	—
Algorithm: Localization	—	—	Unscented Kalman Filter (UKF)	—	—	—
Software: Autonomy	—	—	Py Trees	—	—	—
Software: Framework	—	—	ROS2 Humble & MAVROS, PyTorch	—	—	—
Testing time: Simulation	—	—	100 hours	—	—	—
Testing time: In-water	—	—	30 hours	—	—	—

APPENDIX K
3D MODELS OF ELECTRICAL BOARDS

Fig. 24: 3D model of Power Monitoring Board.

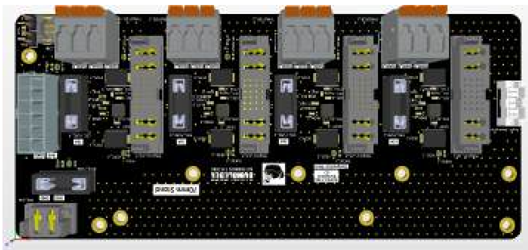

Fig. 25: 3D model of Left Backplane.

Fig. 26: 3D model of Right Backplane.

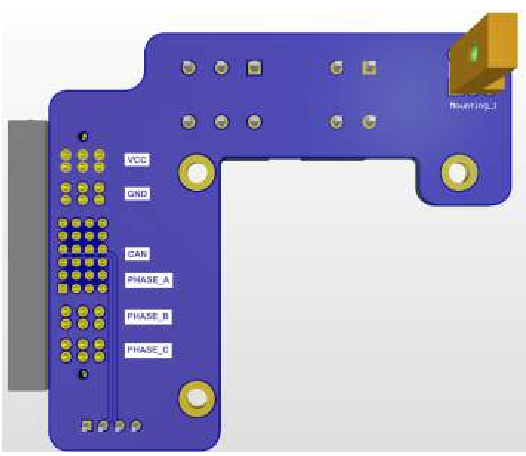

Fig. 27: 3D model of ESC Adaptor Board.

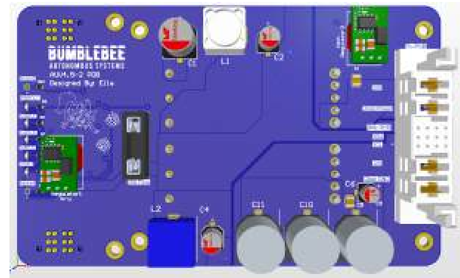

Fig. 28: 3D model of Power Distribution Board.

Fig. 29: 3D model of Power Switching Board.

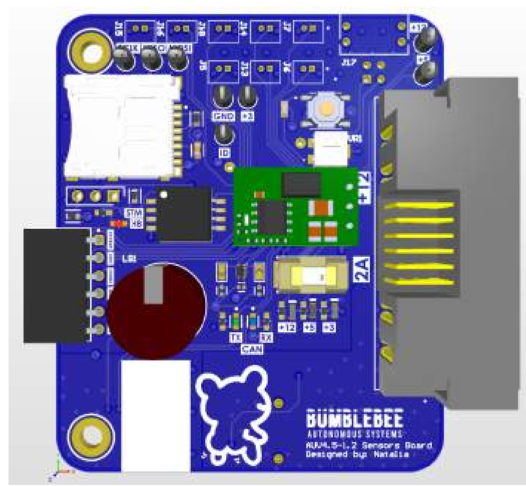

Fig. 30: 3D model of Sensors Board.

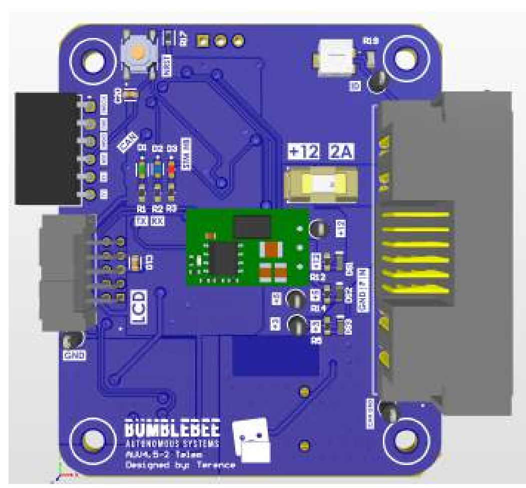

Fig. 31: 3D model of Telemetry Board.

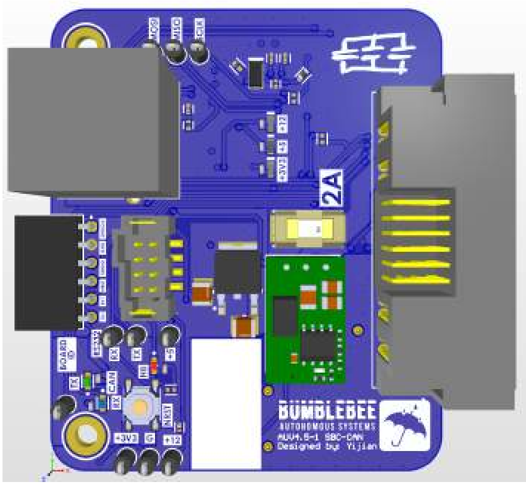

Fig. 32: 3D model of SBC-CAN Board.

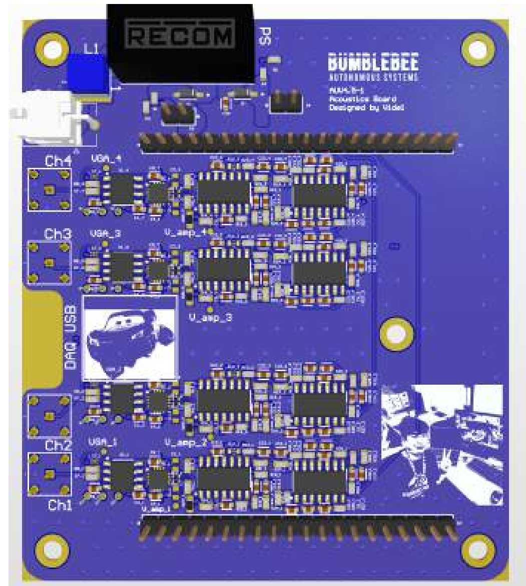

Fig. 35: 3D model of Acoustics Board.

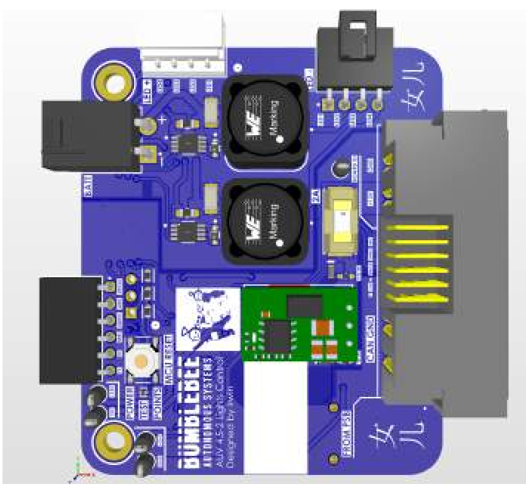

Fig. 33: 3D model of Lights Control Board.

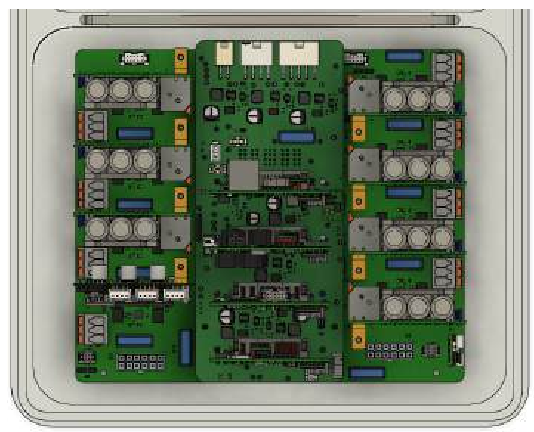

Fig. 36: 3D view of Electrical Stack (top view).

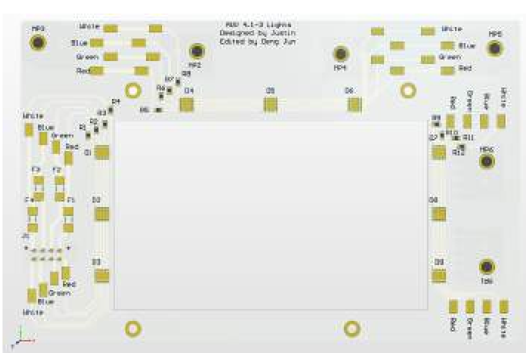

Fig. 34: 3D model of Lights Board.

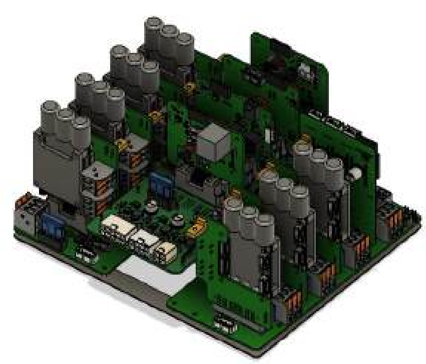

Fig. 37: 3D view of Electrical Stack.

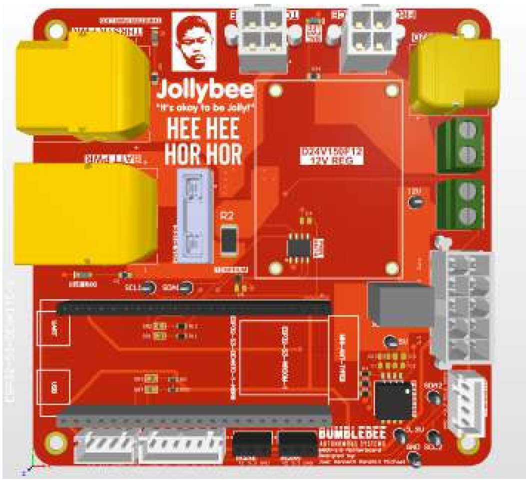

Fig. 38: 3D model of Mini-AUV's motherboard.

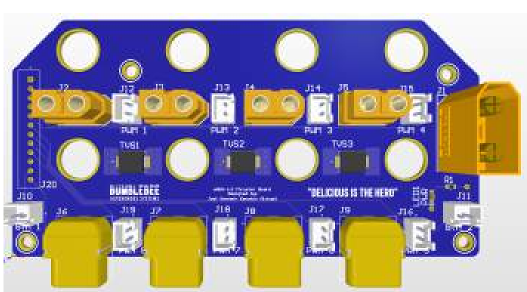

Fig. 39: 3D model of Mini-AUV's thruster board.

APPENDIX L
OUTREACH ACTIVITIES

Since our inception in 2012, Team Bumblebee has steadily grown, becoming a recognizable student team in the maritime robotics community. We remain deeply grateful to this community and our sponsors for their unwavering support over the years. We firmly believe in fostering new relationships and are committed to sharing our knowledge and experiences as a way of giving back.

A. Lab Visits

As part of Team Bumblebee's public relations efforts, we regularly host lab visits for fellow robotics teams and marine robotics enthusiasts from around the world. Following last year's success, we continued to welcome several international teams who traveled to Singapore for the Singapore AUV Challenge. Through these visits, we aim to exchange knowledge and build lasting connections with equally passionate teams.

Fig. 40: Lab visit by Team Offset from Plaksha University, India.

Fig. 41: Lab visit by CityUHK Underwater Robotics and PolyUHK Engineering Entrepreneurship Club teams from Hong Kong.

B. Industrial Partnership and Appreciation

Team Bumblebee is incredibly grateful to our industrial partners and sponsors whose support is fundamental to our continued excellence.

To deepen our understanding of real-world challenges, we also regularly organize visits with these partners. This year, we were honored to receive an invitation from the Singapore Chief of Navy to experience the Republic of Singapore Navy's unmanned capabilities and tour the Maritime Security Unmanned Surface Vessel (USV) at their Naval Base.

Fig. 42: Our 2024 Sponsor Appreciation Event.

Fig. 43: Visit to the Republic of Singapore Navy at a Naval Base.

C. Hornet Training Programme

Team Bumblebee is dedicated to fostering students' passion for maritime robotics. This objective is accomplished through the implementation of the Hornet Training Program and its recruitment drive. Our team actively engages new students by conducting sharing sessions during orientation camps and setting up booths at freshman welcome talks.

Fig. 44: Hornet X in action during SAUVC 2025.

The Hornet Training Program serves as a hands-on introduction to engineering and robotics. In this program, students are tasked with designing, building, and testing a low-cost Autonomous Underwater Vehicle (AUV) for the Singapore

AUV Challenge (SAUVC). This initiative encourages students to explore and experiment with novel designs, fostering a vital spirit of innovation and creativity.

We recently concluded the tenth iteration of the Hornet Training Program (Hornet X), which culminated in the team's participation at SAUVC 2025. Following its completion, we've welcomed 20 eager new members into Team Bumblebee. We're also actively working with the university to incorporate the Hornet Program as an unrestricted elective course (CDE1301B), allowing members to gain modular credits in recognition of their year-long efforts.

A key motivation behind the development of the Mini-AUV is for it to serve as a dedicated training platform for the Hornet Program. Feedback from previous Hornet batches highlighted a critical need for a ready-made vehicle. This addresses a significant bottleneck, particularly for the software team, by allowing new members to gain early exposure to the internal systems and operations of an AUV without being constrained by hardware development timelines.

By providing a stable and accessible base vehicle, the Mini-AUV aims to accelerate the learning process, enabling new team members to understand AUV architecture from the very start of the program. We believe this approach will not only build technical competence more quickly but also help sustain engagement and interest across all subteams throughout the training program.

D. Academic Research

Team Bumblebee is committed to engaging with researchers in their academic work, offering advice and support whenever possible. Recently, we collaborated with the NUS Soft Robotics Lab, led by Professor Cecilia Laschi, on their research into soft robotic arms. As part of this partnership, we conducted several pool tests where our BBAUV 4.5 served as a mobile platform to film and demonstrate the capabilities of their soft robotic arm. These tests directly contributed to a research publication by the Soft Robotics Lab, which is set for future release.

Fig. 45: Testing of a 2 DOF arm with a gripper underwater to benchmark against their research product.

E. Collaboration with Local Schools

Team Bumblebee is dedicated to inspiring the next generation. We conducted sharing sessions with local high school students to encourage them to pursue engineering in their undergraduate studies and to spark their interest in maritime robotics. During these sessions, we shared our experiences competing in RoboNation's competitions (RoboSub, RobotX), along with insights into the development and rigorous testing of our autonomous vehicles.

Fig. 46: Sharing with local high school students for their project work.