RoboSub 2026 Technical Design Report

National University of Singapore (Bumblebee Autonomous Systems)

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***Abstract*—Team Bumblebee presents the dual-vehicle deployment of BBAUV 5.0 and BBAUV 4.5 for the RoboSub 2026 competition. Building upon the multi-vehicle frameworks validated with our Mini-AUV platform last year, we have matured our strategies into a full-fledged cooperative paradigm. BBAUV 4.5 serves as a high-stability, heavy-manipulation specialist, while the newly developed BBAUV 5.0 acts as an agile platform optimised for rapid transit. To ensure reliable coordination of vehicles, we introduced a custom software-defined acoustic modem architecture for Inter-Vehicle Communication (IVC). Mission reliability and vehicle performance are maximised through advanced manufacturing for weight optimisation. Additionally, a wire-free backplane topology eliminates routing failure points, while an integrated multi-modal perception framework fuses cross-sensor data for accurate target localisation.**

I. Competition Strategy

A. Core Strategy

Our primary objective for RoboSub 2026 is to achieve 100% task accuracy with high repeatability through multi-vehicle collaboration. Under strict run-time constraints, the vehicles execute a task-splitting model to complete mission objectives in parallel. Advancing the dual-vehicle roadmap initiated during our 2025 campaign, our 2026 development directly delivers on our strategy through two pillars: the deployment of a custom software-defined Inter-vehicle Communication (IVC) architecture for real-time acoustic coordination, and the commissioning of BBAUV 5.0. This new platform is engineered to expand our operational envelope, introducing a larger yet agile vehicle.

B. Performance Assessment

In 2025, Team Bumblebee clinched first place utilising a dual-vehicle strategy with BBAUV 4.5 and the Mini-AUV. While an emphasis on modular behaviour tree logic and rigorous telemetry successfully met our goals of flexible execution and testability, field operations exposed specific limitations alongside opportunities to advance our long-term multi-vehicle roadmap.

Thermal Dissipation Limitations: During extended out-of-water staging, BBAUV 4.5 experienced compute throttling due to high temperatures. Although managed via a makeshift tub of water during the competition, telemetry isolated the root cause to structural heat-sink saturation within the sealed enclosure. This highlighted the need for a structural hardware redesign rather than addressing the symptoms.

Object Localisation Limitations: Although our multi-layered perception pipeline proved resilient, object pose estimation relied exclusively on a monocular camera. This camera-only approach was sensitive to lighting changes and overlapping visual features, degrading localisation accuracy and proving to be the bottleneck of the *Slalom* task as opposed to manoeuvrability as we had originally anticipated. This underscored the necessity for developing improved localisation strategies such as a multi-modal sensor fusion approach.

Deferral of IVC Development: To manage architectural complexity during the initial dual-vehicle deployment in 2025, an IVC bridge was intentionally omitted. The vehicles operated via decoupled, time-factored mission schedules. Having successfully validated parallel execution as a baseline, our 2026 strategy directly executes the next planned phase: transitioning to active, software-defined acoustic coordination.

C. Dual-Vehicle Strategy

Fig. 1: BBAUV 4.5 Render.

Fig. 2: BBAUV 5.0 Render.

Our 2026 deployment transitions to a cooperative fleet-based model featuring specialised roles for BBAUV 4.5 and BBAUV 5.0. Sustained by our custom IVC architecture, this cooperative ecosystem enables real-time decentralised state estimation and dynamic task allocation.

1) BBAUV 4.5 – High-Stability Manipulation

We continue to leverage the field-proven strengths of BBAUV 4.5, designating it for precise stationkeeping and manipulation-heavy tasks. It utilises specialised actuator mechanisms including a custom four-bar linkage gripper, and a Teflon-lined torpedo launcher. This payload configuration is optimised to execute high-precision manipulation tasks with minimal drift.

To address the thermal dissipation issues, we attempt a single-compute architecture to reduce sources of heat. Furthermore, we recommission the Oculus M750d Sonar of BBAUV 4.5 to complement the existing camera-only perception pipeline.

2) BBAUV 5.0 – Expanded and Versatile Flagship

BBAUV 5.0 is engineered as a versatile high-capability platform. Featuring an optimised hydrodynamic hull geometry and an upgraded power delivery system, it possesses the control authority necessary for rapid transit and continuous 360° spatial manoeuvrers. Additionally, its flexible sensor payload gives room to integrate and experiment with stereo cameras for new vision approaches tackling the updated RoboSub tasks. Our design also draws inspiration from peers and academia. Notably, Team *DesertWave* demonstrated last year that higher nominal hull speed significantly minimises odometry drift, maximising the window for task retries [1].

BBAUV 5.0 also represents an operational leap forward for the team's field strategy with improved hull capacity, mounting capacity, and improved ergonomics for battery replacement. This aligns with our team's understanding and emphasis on the importance of operational capability on top of vehicle performance in competition.

D. Capability-to-Task Alignment

Tasks are allocated to optimise scoring efficiency and minimise vehicle swaps during pool testing, as detailed in Table I. Notably as a full-featured platform, BBAUV 5.0 is not intended as a replacement of Mini-AUV. The *Slalom* task originally assigned to Mini-AUV has been reassigned to the sonar-fitted BBAUV 4.5 while BBAUV 5.0 takes over *Bins* as a result of our assessment that perception is the performance bottleneck for the *Slalom*.

TABLE I: 2026 Task-Requirement-Vehicle Matrix

Task	**Capability Requirement**				**Vehicle Assignment**
	Actuation	Manoeuvrability	Vision	Acoustics	
Gate & Barrel Roll	No	High	Yes	No	BBAUV 5.0
Gate (No Style)	No	Nominal	Yes	No	BBAUV 4.5
Slalom	No	High	Yes	No	BBAUV 4.5
Coin Flip	No	Nominal	Yes	Yes	BBAUV 4.5
Bins	Yes	Nominal	Yes	No	BBAUV 5.0
Torpedoes	Yes	Nominal	Yes	Yes	BBAUV 4.5
Octagon	Yes	Nominal	Yes	Yes	BBAUV 4.5
Return Home	No	Nominal	Yes	No	BBAUV 5.0

E. Risk Assessment

Concurrently developing BBAUV 5.0 while maintaining BBAUV 4.5 introduces critical timeline constraints and resource contention, where troubleshooting new hardware directly competes with autonomous software validation. To mitigate risk of performance degradation under these constraints, we draw on experience from developing Mini-AUV and our design strategy prioritised rapid prototyping and modular architectural decoupling to accelerate the hardware development cycle.

Additionally, while BBAUV 5.0 possesses the theoretical payload capacity to undertake complex manipulation tasks as well, we have deliberately constrained its initial operational scope to the *Bins* task. Actively limiting its scope during this introductory phase mitigates the risk of performance regression on a completely new platform. This allows the team to safely ease BBAUV 5.0 into live competition operations while leveraging the proven manipulation capabilities of BBAUV 4.5, maximising our probability of achieving 100% overall mission capability.

II. Design Strategy

A. Capability-Effort Matrix

Our vision of a heterogeneous multi-vehicle paradigm motivated us to map desired fleet capabilities directly to subsystem requirements. To ensure our engineering execution strictly prioritises these operational goals, every design choice was evaluated by how effectively it bridges high-level mission objectives with cross-functional implementation. These specific technical allocations across our mechanical, electrical, and software subteams are outlined in Table II.

B. In-house Acoustics Solution

For both IVC and acoustic pinger localisation, we developed an in-house acoustic modem mounted on both AUVs. We found that today's commercial modems portray a series of compromises: high cost, poor Doppler resilience, and reliance on proprietary, fixed-function signal processing [2] as seen in Table III. In the spirit of flexibility, we designed a software-defined modem stack operating in the 50–65 kHz band, where most of the signal processing is done in software using the open-source GNURadio toolkit [3].

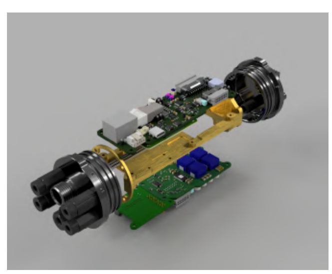

Fig. 3: Render of Bumblebee's custom software-defined modem stack.

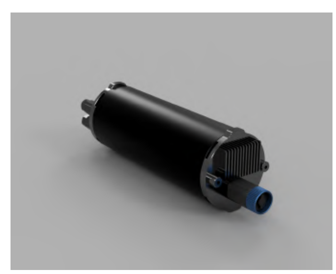

Fig. 4: Render of the Acoustic housing.

Our tuning this year focuses on reliability; we use a Frequency-Hopping Binary Frequency-Shift Keying (FH-BFSK) modulation scheme with Forward Error Correction (FEC). This design has been proven to be Doppler-resilient and reliable in environments with high multipath interference

TABLE II: 2026 Fleet Capability-Effort Matrix with Platform Design Allocations

Desired Capability	Mechanical Subteam Effort	Electrical Subteam Effort	Software Subteam Effort
Inter-Vehicle Comms (IVC)	Design a custom space-optimised and thermally efficient acoustic modem hull **[Both]**.	Tailor PCBs for transmit, receive and compute **[Both]**.	Develop signal processing, coordination behavior trees, and network-layer data links **[Both]**.
Speed & Search Logic	Increase usable internal volume without compromising overall dry weight **[v5.0]**.	Increase power delivery and refine electrical architectures **[v5.0]**.	Deploy multi-modal sonar–camera fusion over the vision baseline to accelerate object localisation **[Both]**.
Agility	Restructure vehicle architecture to minimise Centre-of-Gravity-to-Centre-of-Buoyancy offset **[v5.0]**.	Manage high transient current draw from thrusters and compute **[v5.0]**.	Adapt agile localisation frameworks to manage high rotational instability **[v5.0]**.
Thermal Management	Integrate cooling measures to main hull to improve Design For Assembly **[v5.0]**.	Fabricate copper-core PCBs and route direct stack thermal bonds **[v5.0]**.	Optimise computationally intensive perception networks and inference models **[Both]**.
System Stability	Ruggedise vehicle sensor and actuator mounts **[v4.5]**.	Redesign backplane routing and ensure proper cable harnessing **[Both]**.	Enforce thread-safe routines; migrate stack to a centralised single Jetson Orin compute node **[Both]**.
Accelerated Development	Leverage low-cost manufacturing processes e.g. 3D printing for development and deployment **[v5.0]**.	Design custom test boards and leverage Printed Circuit Board Assembly (PCBAs) **[Both]**.	Deploy SAM3-aided annotation tooling to accelerate vision training and model bring-up **[Both]**.
Future Readiness	Standardise hole patterns across hulls and frame and modularise camera tunnels **[v5.0]**.	Implement backplane topology with hot-swappable daughter cards **[Both]**.	Develop modular, platform-agnostic autonomy frameworks **[Both]**.

(such as pools) [4], [5]. Some aspects of higher-level communications such as packet acknowledgement and error detection have also been developed [6]. Field testing confirms reliable half-duplex 12 bits per second transmission across Olympic-sized pools, even when both vehicles are in motion. Pinger localisation also runs concurrently with IVC. More hardware details are available in Appendix B.

C. Mechanical Design

In line with BBAUV 5.0's role as our next generation vehicle, provision must be made for bigger and more capable internal components while minimising impacts in our mechanical requirements such as mass and hydrodynamics. Underpinning these gains is a systematic weight-reduction campaign and a redesigned thermal architecture, each validated through Finite Element Analysis (FEA) to ensure that improvements in *Speed* and *Thermal Management* do not compromise *System Stability*. BBAUV 5.0 also needs to adapt to new design requirement, notably a new eight-thruster configuration that delivers substantially greater vertical thrust and a large overhaul of vehicle layout to bring the centre of gravity closer to centre of buoyancy.

1) Weight Optimisation

To achieve BBAUV 5.0's *Speed* objective, we have aggressively reduced its mass, bringing the vehicle's overall dry weight below that of BBAUV 4.5, from 35 kg to 30 kg, without sacrificing structural integrity. The reduced dry weight along with increased internal volume also allows the vehicle to attain neutral buoyancy without supplementary floats. This simplifies our design and reduces our cost significantly.

External Frame: A lightweight external frame made from 2 mm Aluminium 5052 surrounds the main hull. It secures the side battery hulls, hides inter-hull cabling, and provides mounting points for peripherals. FEA shows that the frame remains stiff enough under thruster loads.

Main Hull: BBAUV 5.0's main hull was redesigned from its predecessor with a tighter FEA-driven design loop. This reduced weight and increased internal volume. It also retains pressure resistance at the 15 m operating depth with a 2× safety margin.

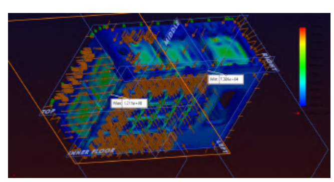

Fig. 5: BBAUV 5.0 Hull FEA.

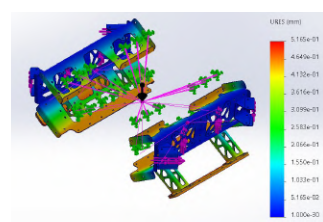

Fig. 6: BBAUV 5.0 Frame FEA.

2) Multi-Jet Fusion (MJF) Battery Hull

While BBAUV 4.5's CNC-machined aluminium battery hulls contributed significantly to its stability, this also impedes dynamic manoeuvrers such as barrel-rolls, motivating the redesign of a new battery hull for BBAUV 5.0. Compared to aluminium machining, MJF technology allows for geometric freedom in design due to its additively-layered manufacturing process and uses nylon, a lighter material. Produced entirely via MJF 3D printing, the new battery assemblies contribute significantly to BBAUV 5.0's weight reduction. While MJF-printed nylon is significantly weaker, the flexibility of 3D

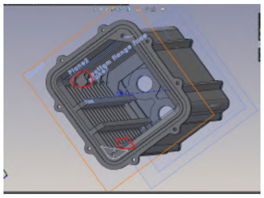

Fig. 7: BBAUV 5.0 Battery Hull CAD.

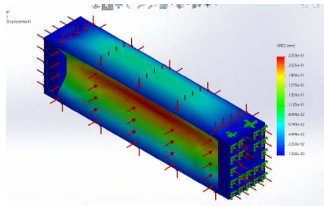

Fig. 8: BBAUV 5.0 Battery Hull FEA.

printing allows us to design complex geometry that is still capable of bearing pressure within our requirements without being heavier than aluminium. However, MJF inherently produces porous parts. As such, the hull is additionally treated with a Dichtol Sealant to achieve water-tightness [7]. Despite its reduced strength, the design of the hull is verified through FEA to ensure it adheres to safety factor as seen in Appendix C.

This novel MJF-based approach unlocks endless possibilities for our mechanical team, allowing us to design components more compact and lightweight than ever before, for any pressure hulls we might need in the future.

3) *Thermal Management*

Thermal throttling of the internal stack outside of water was a significant operational inefficiency of BBAUV 4.5, curtailing between-run readiness during competition. BBAUV 5.0 addresses this with a 2-part solution.

Firstly, we designed a special compute mount with integrated copper heat pipes to rapidly draw heat away from our compute into the hull.

Secondly, the hull has a finned heatsink to dissipate heat to its surroundings. Such fins also exist on other heat conducting surfaces, such as the underside of the main hull. This resolves the previous enclosure's limited heat dissipation, enabling sustained compute performance across consecutive deployments and securing the *Thermal Management* capability. A detailed thermal study is presented in Appendix D.

D. *Electrical Design*

The electrical subteam matures the clean-slate backplane established on BBAUV 4.5 into a high-power, wire-free platform, targeting the following two coupled objectives for BBAUV 5.0.

1) *Power Architecture for Maximum Power Delivery*

To support the fleet's target *Speed* and *Agility* benchmarks, the electrical architecture of BBAUV 5.0 was redesigned for increased power requirements. The addition of an eighth thruster, an elevated thruster duty cycle, and power-heavy peripherals as the custom acoustic modem substantially raise the vehicle's peak current draw. Consequently, the battery and power management systems were re-engineered to maximise capacity and endurance while respecting air-transport limits, discharge rates, and the vehicle's weight ceiling. Load switches, protection circuits, and converters were re-specified for the increased current draw without thermal or spatial compromise. In collaboration with the mechanical subteam, the stack is also thermally coupled to the main hull, using it as a distributed heat sink for *Thermal Management*. As higher power brings higher noise in equal proportion, we added additional filtering circuits and designed the backplane to segregate noisy rails from the clean lines that power our sensitive sensor suite. The change in architectures are illustrated in Figure 40 and 41.

2) *Optimised Backplane System*

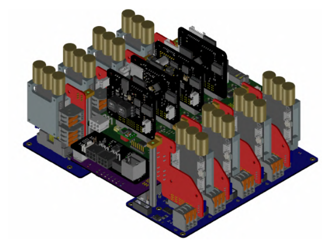

Fig. 9: BBAUV 5.0 Electrical Stack Isometric View.

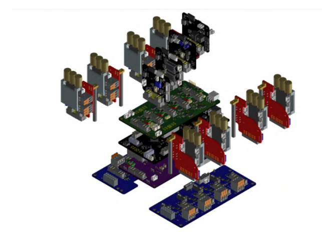

Fig. 10: BBAUV 5.0 Electrical Stack Exploded View.

Power and communications are unified through a central backplane architecture that features standardised board-to-board connectors. Power rails enter the base and are distributed identically across each slot with signal lines. Five standardised slots are provided, allowing specialised daughter boards covering sensor interfacing, lighting, and actuator control to be integrated in a "plug-and-play" manner. A new board-identification scheme, using DIP-switch IDs, is resolved by the central microcontroller on insertion, identifying the board inserted into each slot. This localises a faulty daughter board instantly, supporting *System Stability*. The ESC backplane enforces separation of concerns by relocating the actuation board to a dedicated daughter-board slot, leaving the noisy ESC backplane isolated with its eight VESCs. Similar to the daughter boards, the ESCs can be installed in any order and self-configurable via CAN. Together, these design choices yield a fully integrated electrical stack with no external inter-board wiring, eliminating cable-induced failure points and improving resilience under the high-dynamic motion key to BBAUV 5.0's role. The degree of modularity achieved even allows the entire stack to be ported to a different vehicle wholesale, a property that directly underpins *Future Readiness*.

E. *Software Design*

Our 2026 software architecture adopts a top-down systems engineering approach, starting with our prioritised capabilities. Software milestones align with core fleet metrics: *Speed* through multi-modal state estimation, *System Stability* via reduced communication overhead, and *Future Readiness* through automated machine learning pipelines. The stack introduces three key architectural upgrades detailed below.

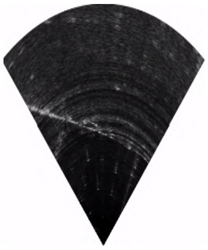

Fig. 11: Acoustic forward-looking sonar image.

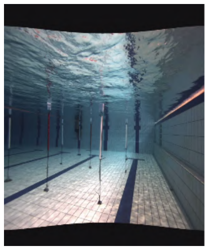

Fig. 12: Optical camera frame feed.

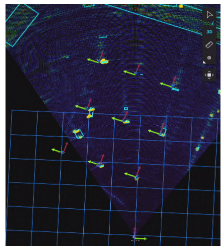

Fig. 13: Cross-modal fused projection output.

1) Sonar-Camera Fusion

To improve target localisation robustness and reduce search drift, we extend our 2025 vision-only perception baseline with forward-looking acoustic sonar processing. The baseline preserves YOLO11 [8] for object detection, while preserving XFeat [9] for feature matching and pose estimation, supplemented by PnP solvers, HDBSCAN clustering, and monocular depth estimation [10]. To enhance this baseline, we integrate acoustic sonar with the primary visual feed to provide accurate target range and depth estimates, enabling faster object localisation under visually cluttered or low-visibility conditions.

As visualised in Fig. 11, Fig. 12, and Fig. 13, the software maps the acoustic return intensity array onto undistorted optical camera coordinates through extrinsic calibration. This allows acoustic detections to be projected onto localised pixel regions, supporting immediate target tracking even beyond standard illumination ranges. This optimisation directly enhances the fleet's *Speed* capability.

2) SAM3-Aided MLOps Labelling Pipeline

To accelerate development and keep pace with the concurrent build of multiple vehicles, the software team required a faster way to train machine learning models. To address this, we developed an in-house annotation tool powered by the Segment Anything Model 3 (SAM3) zero-shot engine [11]. Instead of relying on manual coordinate assignment, this pipeline uses foundation models to automate masking and bounding-box generation for novel underwater targets. This reduces our data compilation time from days to hours, lowers manual data engineering overhead, and allows the subteam to focus on validating task logic. In this way, the pipeline supports our *Accelerated Development* and *Future Readiness* goals. Comprehensive details are provided in Appendix J.

3) Single-Compute Architecture

To improve *System Stability* and reduce internal network overhead, both BBAUV 4.5 and BBAUV 5.0 adopt a centralised single-compute model. This replaces the earlier single board computer and NVIDIA Orin setup in BBAUV 4.5, removes inter-node communication delays, and allows perception, mission logic, and control loops to run more deterministically on a single Jetson AGX Orin.

III. Testing Strategy

To validate our designs, we adopt a multi-tiered testing framework throughout development, as shown in Fig. 14. We begin with isolated unit tests to validate each subsystem, followed by bench-level hardware integration and full system integration. This progressive approach prepares the vehicle for in-water testing while minimizing compounded failures.

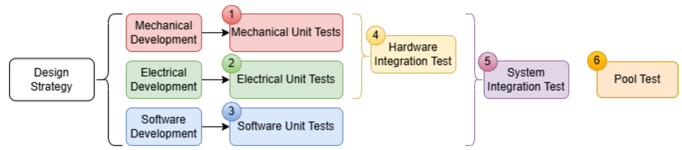

Fig. 14: Team Bumblebee Testing-Framework

A. Subsystem Unit Testing

Each subteam implements unit testing methodologies tailored to its domain to verify that mechanical, electrical, and software components meet their design specifications. Early validation at the subsystem level enables effective fault isolation and provides a reliable foundation for subsequent hardware and system-level integration.

1) Mechanical FEA, Simulations, 3D-Printed Mockups

By adopting a simulation-driven verification and low-fidelity prototyping methodologies, the mechanical team verifies its designs efficiently for cost and time effective developments. FEA is pivotal for critical structural elements (main hull, MJF-printed battery hulls) to validate our weight optimisation efforts while maintaining a desirable Factor of Safety (FoS) metrics under operational hydrostatic pressures. Thermal solutions are drastically improved by observing effective heat dissipation through thermal simulations.

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Fig. 15: Full 3D Printed Mockup of BBAUV 5.0

Desktop 3D printing was heavily used for rapid prototyping of form factors and tolerances. Prototype hull sections and internal chassis brackets enabled physical verification of O-ring compression seals, wire routing, and spatial clearances before committing to CNC machining. The printed hull also provided a practical platform for the electrical team to plan wiring and for the software team to optimise sensor placement.

2) Electrical Stack Test Plan

The electrical subteam produced a new test plan (Appendix E) that details sequential stages of testing with a Standard Operating Procedure (SOP):

- **Isolated tests using Custom Test Boards:** The team quickly validates specific circuit implementations using test boards, such as the load switches on the back planes as shown in Fig 16. Professional tools such as oscilloscopes profile voltage ripples while logic analysers test signal integrity. We also improved our Breadboard-Compatible Debug Boards developed last year [12] to a *Universal Daughter Testboard* as shown in Fig 17 to test any daughter boards, with its CAN interface exposed. Custom Python scripts are also developed to perform thruster profiling to test VESCs on our backplane.

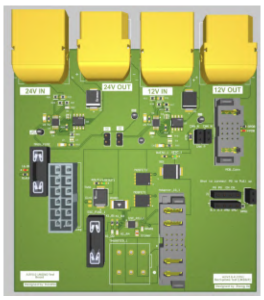

Fig. 16: Backplanes Circuit Implementation Testboard.

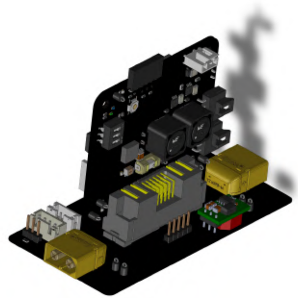

Fig. 17: Universal Daughter Testboard.

- **Incremental Integration Tests:** By integrating boards one at a time, we are able to quickly identify point of failures at every step of the integration process.
- **Full Integration Test:** Once the electrical stack is fully integrated, upon any migration of platform, such as from the bench into the AUV, the team has carried out the same SOP to check for system-level functionalities, such as publishing CAN commands from a daughter board to run thrusters. This test is independent of environment, as the procedures and tools are fixed, allowing us to stress test our electrical stack's capabilities anywhere at anytime. Appendix F details the team's process and test results.

3) Software Feature Testing Workflow

Software changes are developed on isolated branches and validated through a GitHub Actions CI pipeline to enforce linting, formatting, and successful builds to catch early errors.

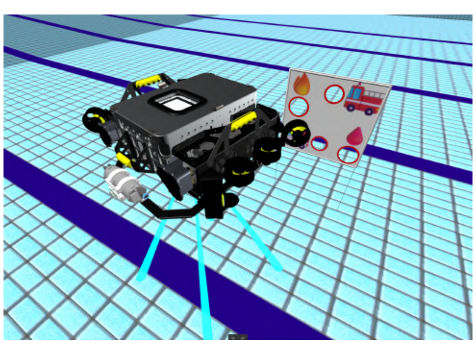

Fig. 18: Gazebo simulation pool environment with competition elements.

After passing CI, testing depends on the type of change. Mission logic and control systems are validated in a high-fidelity Gazebo simulation that replicates vehicle dynamics and operating conditions. Sensor-level modifications are tested separately using physical hardware in isolation to ensure accurate performance.

B. Hardware Integration into Systems Integration Test

To mitigate risk to high-value compute units and delicate sensor payloads, both the mechanical and electrical subteam enforced strict assembly of physical components, by wiring up the various peripherals from mechanical mountings to the integrated electrical stack, to ensure optimal fitting into the vehicle chassis with no issues on the hardware level. The software team then ensures that the compute unit can access sensor data, controlling thrusters and actuators such that it is ready for in-water testing.

C. Pool Test

The final stage of the validation pipeline is a full-system in-water testing at the National University of Singapore University Sports Centre swimming pool. Pool deployments are focused on validating cross-subsystem interactions under real operating conditions, including vehicle dynamics, acoustic localisation, and perception robustness in the underwater environment. These tests also expose environment-specific edge cases, such as lighting variability and hydrodynamic disturbances, which cannot be fully captured in simulation. A detailed breakdown of pool testing procedures and evaluation metrics is provided in Appendix I.

ACKNOWLEDGEMENTS

Team Bumblebee's achievements would not be possible without the incredible support from various organisations and individuals. We are deeply grateful to Patrick Tan Shoong Chin, Tan Annie, and Cheah Kok Keong for their unwavering administrative assistance. Our sincere thanks also go to Dr. Marcelo Ang, Graham Zhu and Dr. Sriram Sami for their invaluable guidance as our technical advisors. We thank the Satellite Technology and Research (STAR) Centre for providing apparatus for gyroscope calibration. We also acknowledge Zhu Yunsong and Neo Jun Hao for their assistance in filming and producing this year's team video. Finally, Team Bumblebee extends its deepest gratitude to our sponsors, who are listed in Appendix A.

Fig. 19: Team Bumblebee 2026.

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APPENDIX A
SPONSORS

A. Title Sponsors (1)

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 (9)

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

DSO National Laboratories — For cash support.

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 2026.

Singapore Maritime Foundation (SMF) — For providing direct financial stipends to support Singaporean members.

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

ST Engineering — For providing various sensors that are deployed on our vehicles, and for offering our members valuable Final-Year Project (FYP) opportunities.

BeeX Autonomous Systems — For providing financial cash support to procure sensors for validation, and for offering our members valuable FYP opportunities.

MacArtney — For providing specialised underwater connectors critical to our vehicle's waterproofing.

C. Gold Sponsors (3)

SBG Systems, Waterlinked, and Würth Elektronik

D. Silver Sponsors (3)

Avetics, Samtec, and Solidworks

E. Bronze Sponsors (9)

Aquarian Audio, Blue Trail Engineering, Bossard, Espressif, Pololu, Rohde & Schwarz, Southco, TGN Technology, and TOYOGO.

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

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

APPENDIX B
IN-HOUSE ACOUSTIC MODEM AND IVC ARCHITECTURE

Running complex signal processing with the flexibility of software requires a high-speed data-processing frontend coupled with powerful compute.

Our modem stack consists of the following PCBs:

- TX Board: Features an DAC and Class D amplifier to drive our piezoelectric transducer. Includes an impedance matching circuit to maximise power transfer
- RX Board: Features a high-speed 4-channel ADC and hydrophone preamplifier circuits
- Compute Board: Features a Raspberry Pi Compute Module 5 (CM5) for digital signal processing, interfacing with host AUV and locating the pinger

However, the modem is also placed under heavy mechanical constraints; we needed to package the acoustics modem in a form factor which would be practical to mount onto our AUVs (and future vehicles). Hence, all boards were miniaturised to fit in a compact 58 mm OD, 150 mm long hull.

Each modem is potted to 4 hydrophones and 1 transducer, along with an 8-pin Cobalt connector for power and data. To ensure that the CM5 and Class-D amplifier do not overheat, the boards are mounted to a custom tray which transfers heat to an endcap's integrated heatsink for passive dissipation.

Table III presents a review of commercial acoustic modems not mentioned in [2]. Resillience to the Doppler effect was important to us after our experience with the Popoto S1000RP in 2024, where the communication link degraded significantly when the AUV was moving. The Subnero modem was the only option where Doppler resillience was precisely quantified, but it also operated in the banned 25–40 kHz pinger band. When tuning our modem, we focused on achieving reliable transmissions across the pool even when moving.

Our solution approximately matches the Waterlinked M16 Modem in feature set and slightly undercuts it in price, with the downside of being less compact. The key difference is that since our software-defined acoustics modem is now stable, opportunities for future refinement are aplenty; we intend to explore more modulation schemes, such as Orthogonal Frequency Division Multiplexing (OFDM) [13]. Modems could negotiate a shift to higher-speed protocols when conditions are ideal (e.g. low movement, short range). Other potential future directions include packet confidence estimation and relative localisation (angle and distance) between AUVs to improve reliability.

TABLE III: Comparison Study of Commercial Acoustic Modems

Modem	Price	Freq. Band	Modulation	Data Rate	Range	Doppler Resilience	Software-Defined
Popoto S1000RP (Tested by us in 2024) [14]	$3,995	22–35 kHz	FSK, PSK	80bps (FSK)–10kbps (PSK)	1,000 m	Poor (from pool testing)	No
Subnero WNC-M25MSO4 [15]	N/A	20–32 kHz	OFDM, FSK	Up to 15kbps	5,000m	Rated for high speeds at ± 4 knots	Yes (propietary UnetStack software)
Waterlinked M16 (used by various RoboSub teams) [16]	$2,650	54–62 kHz	N/A	10bps	1,000 m	Unknown	No
In-house Modem	**$\approx$$2,800 (with 4 hydrophones)**	**50–65 kHz**	**FSK**	**12bps**	**Works across 50m pool**	**Good (from pool testing)**	**Yes (GNU Radio)**

APPENDIX C
BATTERY HULL STRESS ANALYSIS

The structural integrity of the Multi-Jet Fusion (MJF) battery hull was evaluated under operational pressure conditions, as shown in Figure 20. The simulation analyses the resultant displacement across the enclosure walls to ensure the geometry can withstand external loading without compromising the internal electronics.

While weight reduction remains a priority for maintaining vehicle buoyancy and trim, a baseline wall thickness was preserved to limit material deflection. The maximum displacement is concentrated along the unsupported center spans of the long lateral faces, peaking at approximately 0.225 mm. This minor deflection confirms that the structural stiffness of the MJF material is sufficient to prevent geometric buckling or seal failure at the target operational depth.

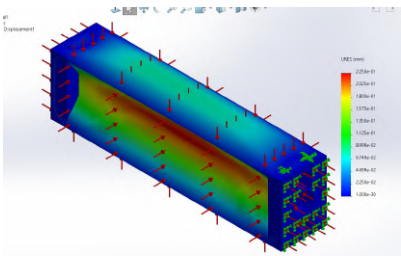

Fig. 20: Stress Analysis of MJF Battery Hull.

APPENDIX D
COMPUTE MOUNT THERMAL STUDY

To prevent thermal throttling of the NVIDIA Jetson compute module during long autonomous runs, a passive cooling system was integrated into the internal chassis. As shown in the thermal simulation in Figure 21, the custom compute mount is designed to maximize conductive heat transfer away from the processor. This thermal path also enables extended testing on land without risking thermal shutdown; when the vehicle is out of the water, ambient airflow beneath the hull provides enough convective cooling to keep temperatures stable.

The primary heatsink maintains full contact with CNC-machined aluminum blocks. These blocks interface with copper heat pipes to quickly draw heat away from the electronics bay and transfer it to the main vehicle hull. To efficiently dissipate this heat into the water during deployment, the underside of the aluminium hull features integrated cooling fins, as shown in Figure 22. This setup keeps peak junction temperatures well within safe limits, even under heavy sensor fusion workloads.

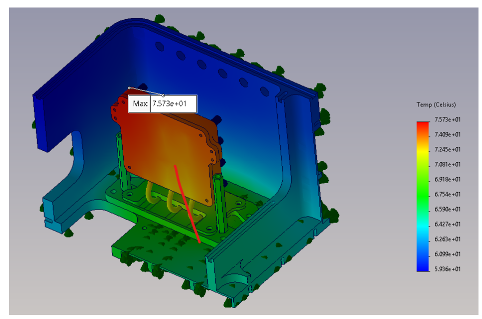

Fig. 21: Thermal simulation of the Jetson compute mount.

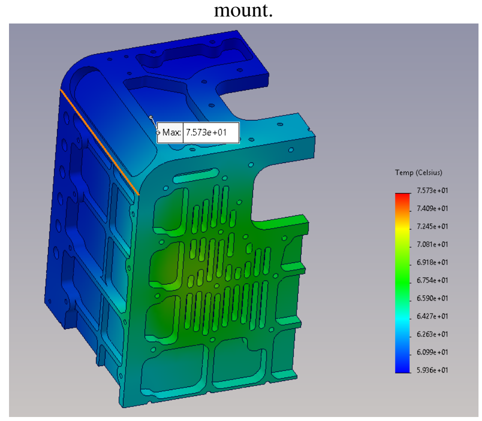

Fig. 22: Thermal simulation of the hull underside.

APPENDIX E
ELECTRICAL INTEGRATION TEST PLAN

Our electrical validation philosophy is built on a single principle: a fault must be localisable to the smallest possible unit before it is allowed to propagate into a larger assembly. To this end, the electrical subteam developed a structured, multi-stage test plan governed by a Standard Operating Procedure (SOP), progressing from isolated single-board tests, through sequential sub-assembly integration, to a full-stack integration test. Each stage has explicit, pre-defined pass criteria, and a board (or substack) is only promoted to the next stage once every criterion is unambiguously met. This disciplined gating is what allows us to compress development time without sacrificing reliability: when an anomaly appears at integration, the incremental integration tests tells the point of failure immediately i.e. which board or board-to-board integration introduced it, rather than the fault surfacing only when the stack is fully assembled and the fault search space is large. Test results are detailed in Appendix F.

ISOLATED BOARD TESTING

Before any board enters the stack, it is validated in isolation against a dedicated, board-specific test plan, such as the two examples tabulated below. Each plan follows a common escalation ladder, from solder and continuity inspections to powered sanity checks, MCU/firmware bring-up, device-level verification, and finally AUV-specific functionality test with a documented "criteria to clear" at every stage. Isolation is achieved using purpose-built test boards (such as the "Universal Daughter Testboards in Appendix N), together with standard bench equipments: a bench power supply, electronic load, oscilloscope, logic analyser, thermal camera, and a CANbus-to-serial interface to read CAN message outputs from electrical boards. Custom Python scripts automate repetitive procedures such as VESC thruster profiling.

TABLE IV: Isolated test plan for the ESC Backplane (ESCBP).

KPI: Load performance and heat **Manpower:** 3 (1 executing, 2 monitoring)

Equipment: Bench PSU, CANnable, oscilloscope, FLIR thermal camera, computer with VESC-Tool

Safety: High current and voltage: secure thrusters and clear the work area before firing

#	Stage	Procedure	Criterion to Clear
1	**Configuration**		
1.1	Per-slot CAN ID	Assign and verify each VESC's individual CAN ID	All eight IDs unique and addressable
1.2	Visual inspection	Eyeball all solder joints, wiring, and capacitors	No cold joints, bridges, or defects
2	**Communications**		
2.1	VESC-Tool comms	Connect to each VESC via USB; confirm VESC-Tool link	Tool connects to all slots
2.2	CANnable comms	Confirm CAN communication over the backplane	Bus communication established
2.3	VESC power kill	Verify power-kill behaviour on the ESCBP side	Kill removes power to all VESCs
3	**Load Test**		
3.1	Directionality	Fire each VESC at ± 0.1 duty cycle (PSU at 16.8 V)	Correct, commanded direction of spin
3.2	Stable load	Fire at ± 0.7 duty cycle; soak $\sim$10 min until temperature stabilises	Stable current draw (PSU), heatsink temp (FLIR), and supply-line ripple (scope) within limits
3.3	Impulse	Step $0 \rightarrow 0.7$ duty for 3 s, then drop to 0	Current spike, voltage drop, and noise within limits; no instability
4	**Backside Load Test**		
4.1	Continuous	Drive backplane at full 0.7 duty (PSU 16.8 V); soak $\sim$10 min	Stable current draw, heatsink temp, and ripple within limits
4.2	Burst	Full 0.7 duty for 3 s, then drop to 0	Supply-line voltage spike within limits; no fault

TABLE V: Isolated test plan for the Lights Control daughter board

KPI: Controllable lumen output **Board ID:** 7 **Manpower:** 1

Equipment: Test board, CANnable, terminal, two flood lights, lights-indicator board

Data collected: Lights-indicator temperature after 10 min of continuous RGB flashing

Safety: Flood and indicator lights must point away from people, toward the ceiling, before power-on

#	Stage	Procedure	Criterion to Clear
1	**Initial Verification**		
1.1	Power-on (test board)	Power board on a test board; confirm all daughter-board LEDs illuminate (initial supply check)	All LEDs on
1.2	Board ID	Verify physical DIP-switch board ID	Reads ID 7
1.3	Connect flood lights	Connect two flood lights (pre-aimed at ceiling)	Connections correct
1.4	Power on	Power on via Universal Daughter Testboard	Flood lights flash twice on power-up
2	**MCU Verification**		
2.1	Intensity control	Via CANnable, confirm light intensity is controllable	Intensity responds to CAN command
2.2	Terminal readout	Check terminal output for heartbeat and board ID	Heartbeat present; ID matches DIP switches
3	**Lights Indicator**		
3.1	Connect indicator	Connect lights-indicator board; verify polarity (LED+/LED−), current limit 2 A	Correct polarity, within current limit
3.2	CAN check	Repeat Stage 2 CAN check on indicator board	CAN responds
3.3	Thermal check	Measure indicator temperature after 10 min continuous RGB flashing; allow cooldown before re-power	Temperature within safe limit
4	**AUV Verification**		
4.1	Connect daughter board	Mount into stack; confirm all LEDs on when battery powers on	All LEDs on
4.2	CAN control	Confirm control over CAN; if unresponsive, verify CAN bus is up	Controllable over CAN bus

Incremental into Full Integration Testing

Once each board clears isolation, boards are integrated incrementally rather than all at once: the stack is built up one board at a time, and the relevant subset of the feature checklist is re-run at every step before the next board is added. This sequential approach ensures that any fault arising from inter-board dependency is caught at the moment the offending interface is introduced, rather than surfacing only once the complete stack is assembled and the search space is large. The full integration test then exercises the complete stack against the feature checklist in Table VI, verifying power, kill-chain, telemetry, sensing, CAN routing, and acoustics end to end. Critically, this SOP is environment-independent: because the procedure and tooling are fixed, the identical validation can be executed on the lab bench, when integrating into the main hull of the AUV, or even outside the lab, as shown in Appendix F, alongside our test results from conducting the test plan in the table below. This portability lets us stress-test the electrical stack anywhere, at any time, keeping development moving regardless of facility access.

TABLE VI: Incremental full-stack electrical integration test plan, executed in order. Each block is validated before the next is introduced.

KPI: End-to-end stack functionality and power integrity **Manpower:** 6–7 **Equipment:** Full electrical stack, batteries, electronic load, oscilloscope, FLIR thermal camera, OCS

Safety: High current and voltage; secure all thrusters before firing and keep the kill switch within reach throughout

#	Procedure	Expected Result
1	**Comms + Power**	
1.1	Power entire system from a single battery; then verify dual-battery load balancing across vastly different voltages	System powers up on one battery; turning off one battery does not down the other or the system; balancing holds under mismatched voltages
1.2	Telemetry screen power-on	Telem screen turns on; minimally displays internal pressure and PCB heartbeats
1.3	Verify per-board heartbeats and board-ID resolution over CAN	All expected heartbeats present; each board ID resolved to the correct slot; heartbeats appear/disappear correctly on insertion/removal
1.4	OCS telemetry and compute statistics	OCS receives and displays stats from the compute stack (e.g., CPU temperature)
2	**Sensors**	
2.1	CANnable observes sensor messages on the bus	Critical sensor data (e.g., external pressure) published over CAN
2.2	Button and buzzer feedback; temperature probes	Button status read with correct buzzer feedback; temperature-probe readings published
3	**Lights + Actuation**	
3.1	With lights connected, actuate via CANnable	Lights respond to CAN commands
3.2	Grabber responds by CANnable	Grabber actuates as commanded
3.3	Torpedo fires by CANnable	Torpedo launcher fires
3.4	Dropper drops by CANnable	Dropper releases
4	**Thrusters and Kill Chain**	
4.1	Command all thrusters at 0.1 duty cycle via CANnable	All thrusters spin in the correct direction
4.2	Command all thrusters at 0.5 duty cycle via CANnable	All thrusters sustain commanded thrust
4.3	Hard kill while thrusters running	All thrusters stop within 1 s of kill-switch removal
4.4	Soft kill, then restore	Motors stop on soft kill; all systems remain alive and recover after transitioning out of the killed state
4.5	Power-cycle all channels	Every channel power-cycles cleanly; power-good status received
5	**Maximal Load Test (per board)**	
5.1	PSB maximal load: record V_{drop}, load-balancer / isolator / MOSFET temperatures, 12 V and 24 V ripple, current cutoff	All metrics within limits; current cutoff triggers at the configured threshold
5.2	PDB maximal load: same metric set as 5.1	All metrics within limits
5.3	ESCBP-L maximal load: MOSFET temp, V_{drop}, voltage ripple	All metrics within limits
5.4	ESCBP-R maximal load: MOSFET temp, V_{drop}, voltage ripple	All metrics within limits
6	**Functionality Test (compute + sensors)**	
6.1	Jetson power-on test	Jetson boots and is reachable
6.2	Camera power-on and ping test	Camera powers on and responds to ping
6.3	DVL A50 power-on test	DVL powers on and streams data
6.4	3D sonar & 3-axis FOG bring-up	Sonar & FOG powers on and streams data

Appendix F
Electrical Integration Process and Test Results

Following the validation methodology described in Section III-A2 and the test plans mentioned in Appendix E, the electrical subteam has performed Full Electrical Stack Integration Test at various points of BBAUV 5.0's electrical stack development, especially after fixes and additions of new boards. The integration test setup can be run anywhere by bringing equipments such as an oscilloscope, probe, electrical load and power supply with the team. Together with the custom test boards and test cables, any member of the electrical subteam is prepared to execute the detailed and clear step by step Standard Operating Procedure for the Full Electrical Stack Integration Test. The following images shows part of the process and the test results from the electrical subteam in their development of the new electrical stack for BBAUV 5.0.

Fig. 23: Full Electrical Stack Integration Test by Electrical Team: fixed SOP and portable toolset allow the electrical stack to be tested anywhere.

One of our initial concerns with the electrical stack was its thermal management, due to the increased power delivery requirement desired for BBAUV 5.0. Each board (and then the electrical stack) needs to be able to handle this increased current draw, where some boards may have heat sensitive components. Adopting our electrical testings methodology, each board needs to be tested on its thermal performance during the initial isolated testing phase. This is done by pulling a full load on them and using a thermal camera to observe the temperatures of specific components (e.g. the isolator on the Power Distribution Board (PDB), shown in the left thermal image of Fig 24). For our Indicator Lights Board, which powers 15 high power LEDs, its thermals are also stress tested during its isolated testing phase. To test whether our design using Direct Copper Core technology helped with thermal dissipation, we performed a similar test by firing the maximum brightness for a prolonged period of 10mins, to observe its thermal performance, as shown on the right thermal image in Fig 25. The individual thermal profiles shown confirm that every electrical board and its components are operating within expected and managed temperatures, before we move on to integrate the entire stack.

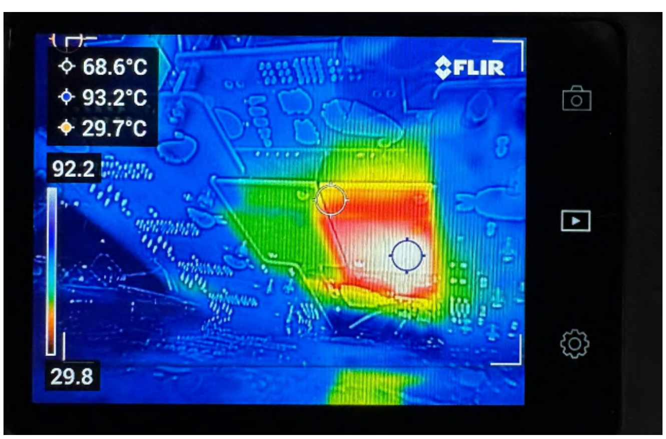

Fig. 24: Thermal image of the Power Distribution Board (PDB)

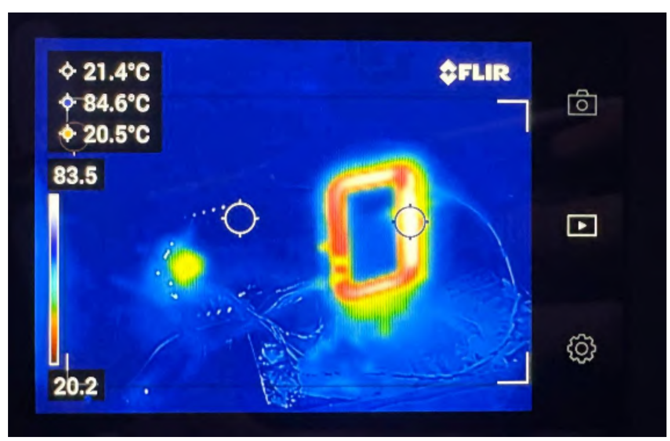

Fig. 25: Thermal image of Lights Indicator Board

Fig. 26: Thermal images from integration testing

Our next concern is related to power stability during transient currents. BBAUV 5.0 is planned to accommodate power hungry components, such as our in-house acoustics solution, our compute stack, and the VESCs that will run with dramatically increased duty cycles. While our isolated testing phase can confirm that the load switches on the Power Switching Board and the ESC backplanes are able to handle the increased power draw, putting the stack together may not guarantee such performance due to inter-board dependencies, such as in the power chain. Hence, the incremental integration and full stack integration test is pivotal in ensuring that the end-to-end power delivery is clean and stable. One of the test we run is illustrated below. With the entire stack integrated together, we test the power delivery stability to sensitive sensors by scoping the voltage output from those channels using an oscilloscope. For example, the voltage for power channel for Sonar with no load and no thrusters is shown in Fig 27, with peak-to-peak voltage (Vpp) of 171mV. We then test its performance by using an electrical load to load the channel with a maximum rated power draw of 2.7A, barely increasing Vpp to 124mV (as shown in right image of Fig 28. We stress test it further by running thrusters at maximum rate of change (from 0 to 0.9 duty cycle), which shows a transient current spike of 17.5A per thruster based on the VESC Tool Software (left graph of Fig 30). The resulting voltage ripples shown in the corresponding right image shows lower Vpp and a similar voltage profile. Hence, the electrical team can confidently conclude that even under increased loads or transient conditions, power stability is maintained for all power channels.

Through the electrical team's elaborate test plans and methodology of isolated tests and incremental to full electrical stack test, the electrical stack is stress tested in a systematic and hence efficient and effective manner.

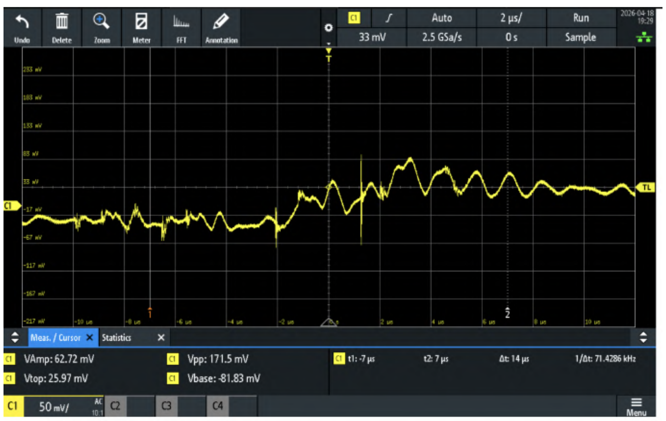

Fig. 27: Sonar power channel with no load and no thrusters (Vpp = 171 mV)

Fig. 28: Sonar power channel with full load (2.7 A, Vpp = 124 mV)

Fig. 29: Power stability of sonar power channel: left shows no-load condition, right shows full-load condition

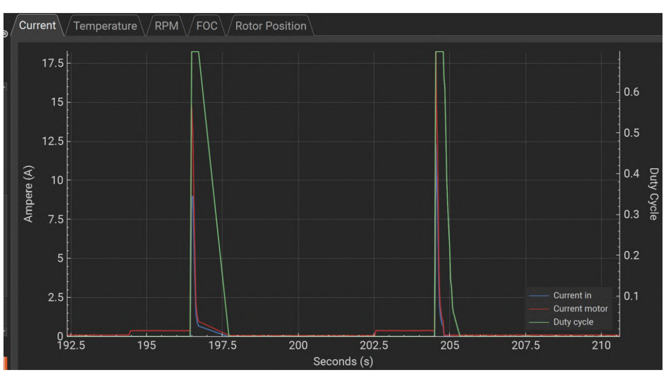

Fig. 30: Transient current spike of 17.5 A per thruster from VESC Tool Software

Fig. 31: Sonar power channel voltage ripples under full load and full thrusters

Fig. 32: Power stability of sonar power channel under maximum thruster operation: left shows VESC current draw, right shows voltage ripples

APPENDIX G
PRE-DEPLOYMENT TEST

TABLE VII: Descriptions of hardware-related pre-deployment 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 AUV 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 thrusters in-air for a few seconds to verify the Jetson 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 pressurising 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.

APPENDIX H
SOFTWARE TEST PLAN

TABLE VIII: General software verification and testing plan across vehicle platforms.

Component/ Capability	Description	Methodology	Timeline (2026)	
			BBAUV4.5	**BBAUV5.0**
Sensor-Level Drivers	Verification of low-level driver execution and spatial coordinate frame conventions prior to main compute integration.	Isolated unit testing of drivers is conducted on localised workstations and personal compute machines. Utility configuration scripts are developed to streamline parameter tuning, frame offsets, and message publishing before deploying onto the central vehicle compute stack.	Jan – Feb	Mar
Localisation & State Estimation	Validation of state estimation accuracy, sensor noise propagation modeling, and odometry drift tracking.	Trajectory reconstruction tests are performed by executing a closed-loop path over a 30-minute duration, verifying that the final estimated position converges with the known starting datum. Angular precision and orientation drift are quantified by rotating the vehicle in precise 90-degree increments.	Feb – Mar	Apr
Perception Pipelines	Validation of the hybridised vision architecture blending legacy vision techniques with deep learning approaches.	Historical dataset recordings are leveraged to benchmark and compare pipeline iterations. The combined pipeline is subjected to rigorous in-water validation utilising physical competition props under varying environmental factors, such as extreme bright and dim lighting conditions.	Apr – May	Apr
Mission Planning	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.	Continuous	Continuous
Actuation & Manipulation Control	Fine-tuning and validation of new physical manipulation subsystems including robotic droppers, torpedo mechanisms, and pneumatic grabbers.	Kinematic profiles and closed-loop control laws are initially trialed in simulation before transitioning to physical in-water testing via manual command-line execution interfaces. Fully autonomous task-space integration is slated to execute following final hardware mechanical iterations.	Jan – Jun	May – Jun

APPENDIX I
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 33 below), power apparatus, network reel and Operator Control Station (OCS), miscellaneous network equipment (e.g., network switch), tables and chairs, and hand tools.

Fig. 33: Torpedo board used for pool tests.

Fig. 34: 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 G). 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 spans 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 H), pool tests reveal crucial 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:

- **Transition to Sonar-Camera Fusion for Robust Object Localization:** Relying solely on optical perception pipelines posed a significant operational risk under varying lighting and turbidity conditions underwater. To achieve reliable and efficient target detection, we developed a multi-modal sensor fusion framework integrating forward-looking sonar and camera feeds. This year's validation focused heavily on cross-modal target state-estimation, ensuring high-accuracy object localisation even when visual tracking degrades at longer ranges or in low-visibility competition environments.
- **Addressing State Estimation Degradation During Dynamic Maneuvers and Surface Proximity:** Maintaining precise stationkeeping and odometry continuity remains a challenge during aggressive localised maneuvering. Specifically, during and immediately following high-rate angular maneuvers such as a barrel roll, or when operating in close proximity to pool bottoms and walls (e.g., during object grasping or bin tasks), the Doppler Velocity Log (DVL) experiences acoustic beam reflections and temporary data dropouts. Through iterative pool testing, the software team refined our state estimation filtering and dead-reckoning fallbacks to bridging these sensor dropouts, while providing critical feedback to the mechanical team to optimise sensor placement and manipulator clearances.

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 BBAUV 4.5 and BBAUV 5.0, promoting routine operations and minimising 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 standardised telemetry architecture deployed across both BBAUV 4.5 and BBAUV 5.0 utilises automated reporting pipelines routed directly to dedicated vehicle Telegram channels. This enables off-site team members to continuously monitor critical internal vitals for each platform, such as enclosure pressure and battery status. Furthermore, this decentralised monitoring framework enhances field-testing efficiency by eliminating the need for software operators to manually report metrics, allowing the team to preemptively coordinate battery hot-swaps without disrupting active testing loops.

APPENDIX J
SAM3-AIDED MLOPS LABELLING PIPELINE

We developed an in-house MLOps labelling and dataset generation pipeline accelerated by the Segment Anything Model 3 (SAM3). The pipeline converts recorded mission data into structured training datasets by extracting ROS bag files into video, sampling image frames, and generating segmentation masks and bounding box proposals using SAM3. These outputs are refined through a human-in-the-loop interface and converted into YOLO-compatible segmentation labels.

Instead of fully automated labelling, SAM3 is used as a prompt-driven annotation assistant. Operators provide text prompts and optional exemplar boxes for underwater targets such as torpedoes, bins, and gates. SAM3 generates candidate masks, which annotators can quickly refine through a lightweight interactive interface. This approach reduces manual effort while maintaining label quality in challenging underwater conditions.

The pipeline is integrated with the YOLO training workflow. Refined annotations are automatically formatted, organised into training and validation sets, and linked to dataset configuration files. This enables rapid dataset bootstrapping for new tasks without requiring changes to the overall annotation framework.

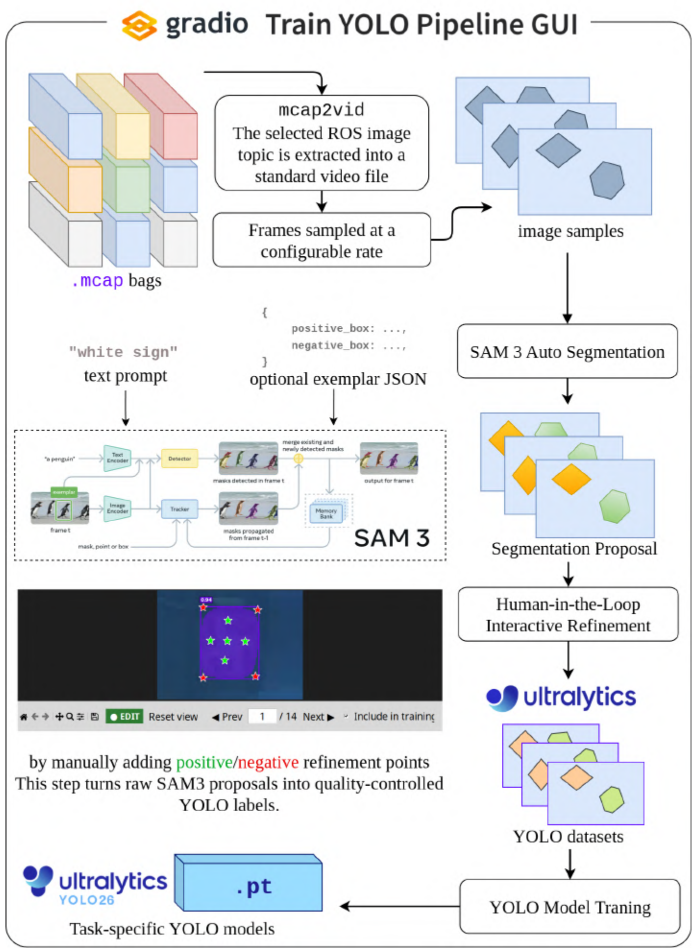

Fig. 35: Block Diagram of the SAM3-Aided MLOps Labelling Pipeline.

APPENDIX K
ARCHITECTURE BLOCK DIAGRAMS

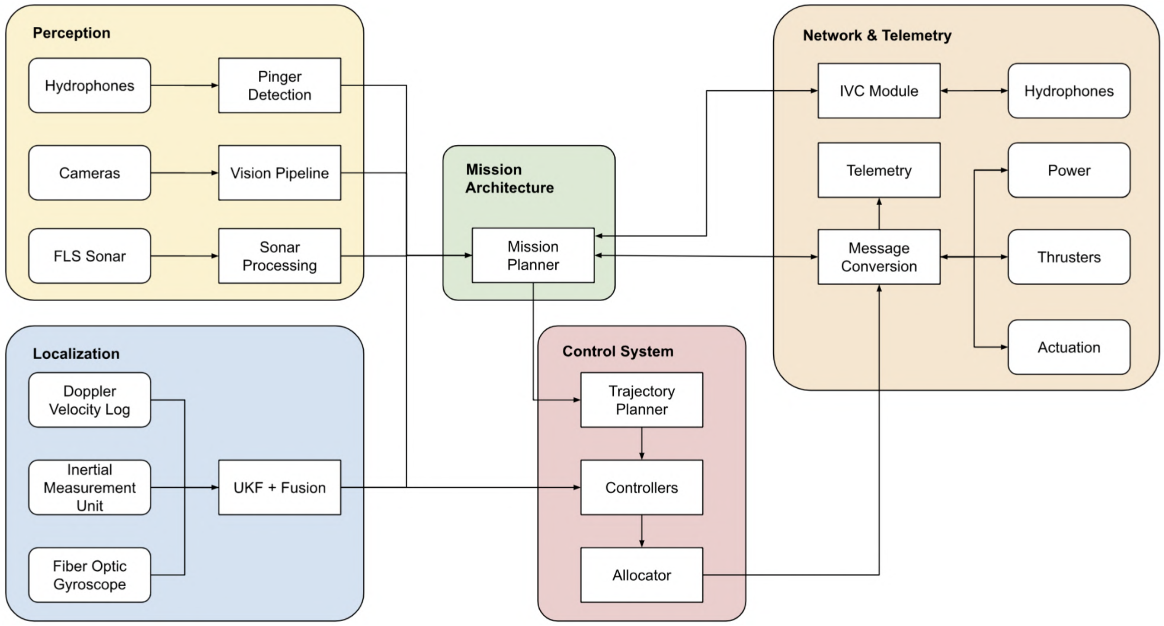

Fig. 36: High-level Overview of BBAUV 4.5's Software Architecture.

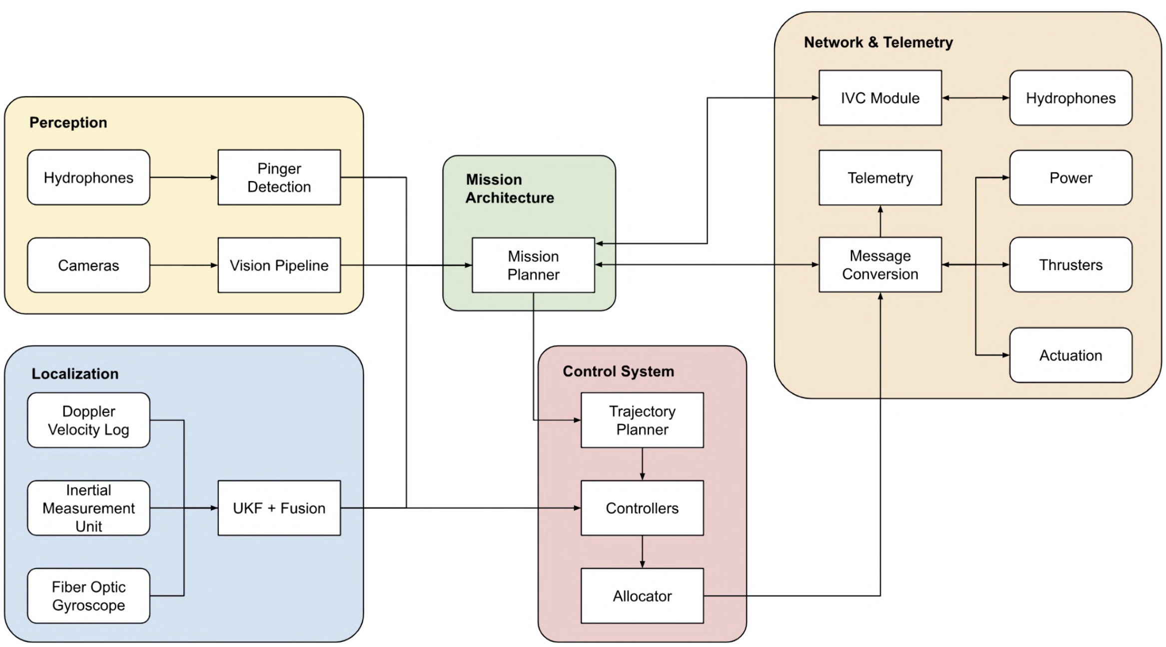

Fig. 37: High-level Overview of BBAUV 5.0's Software Architecture.

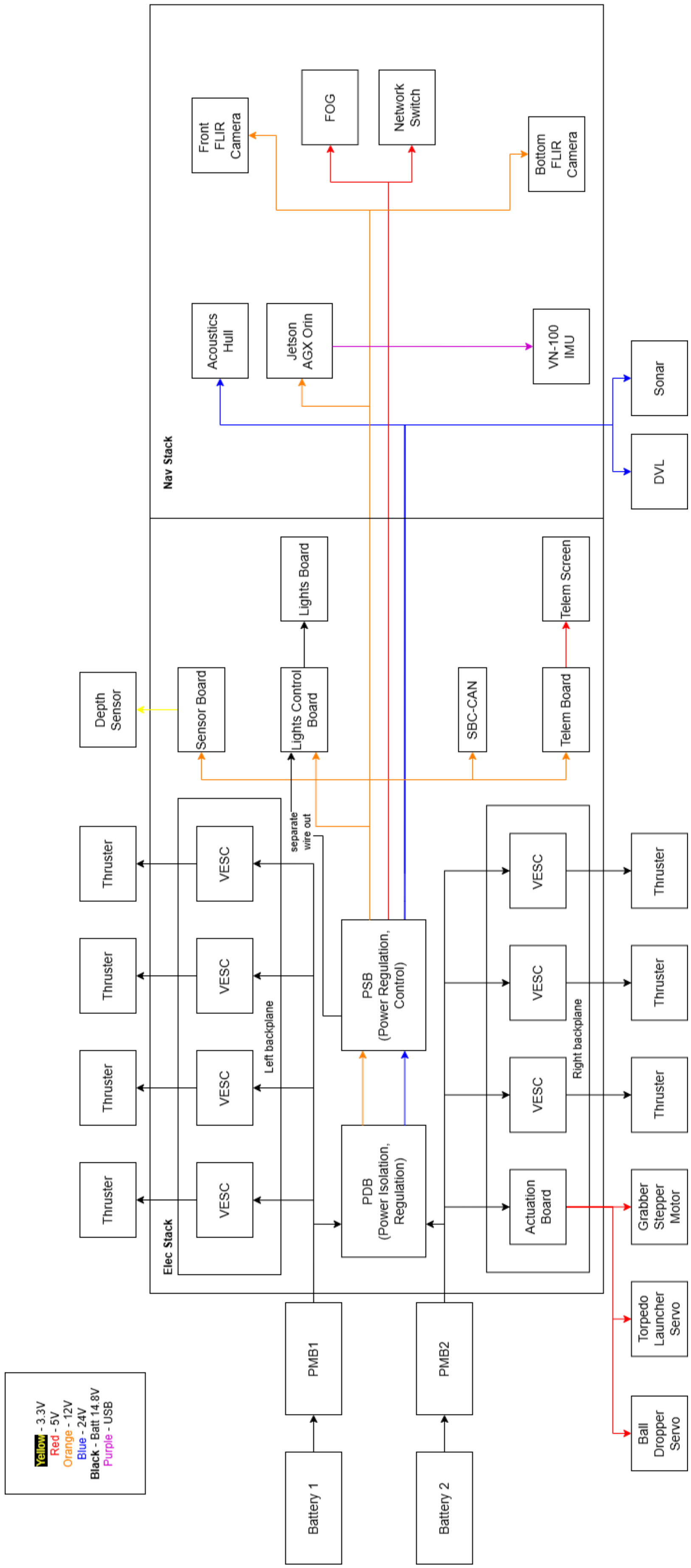

Fig. 38: BBAUV 4.5 Power Architecture.

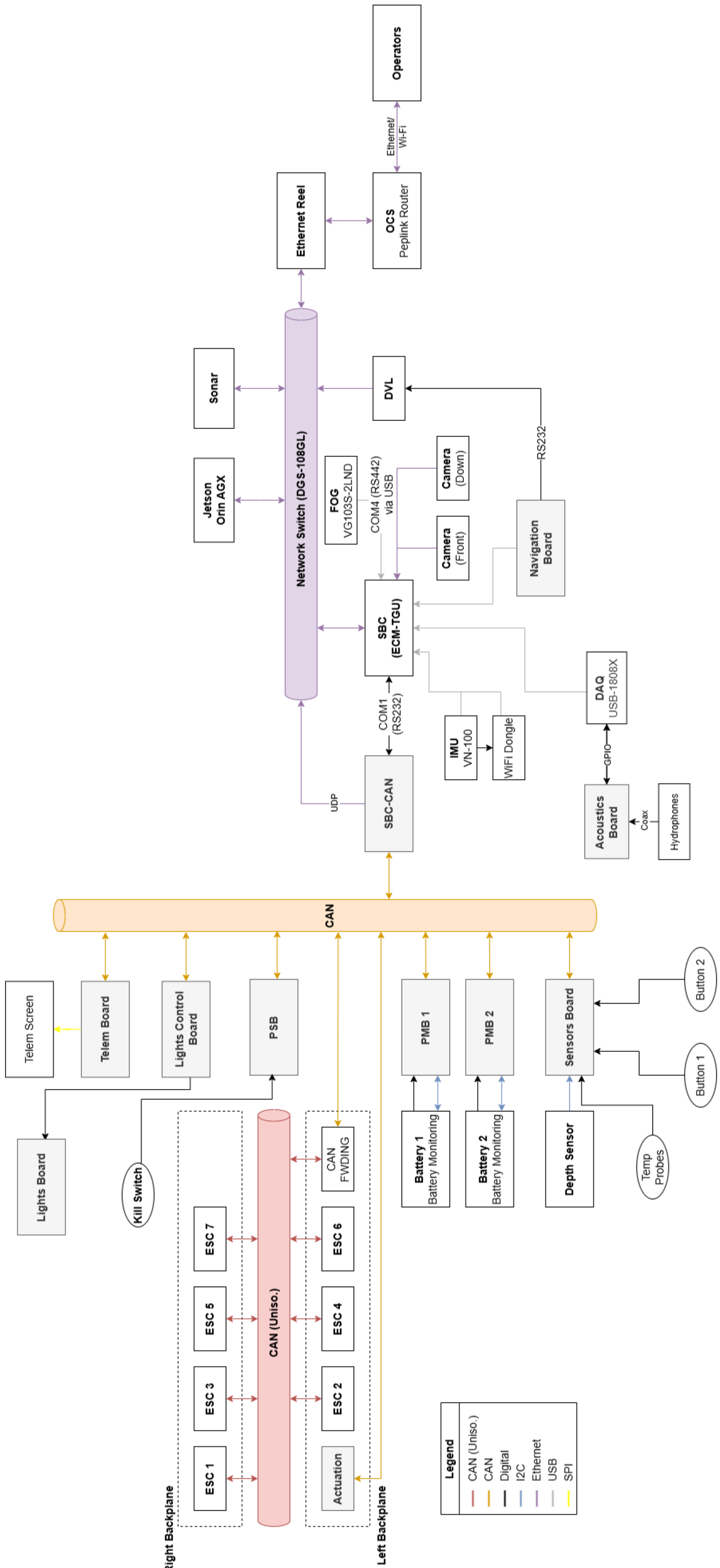

Fig. 39: BBAUV 4.5 Communication Architecture.

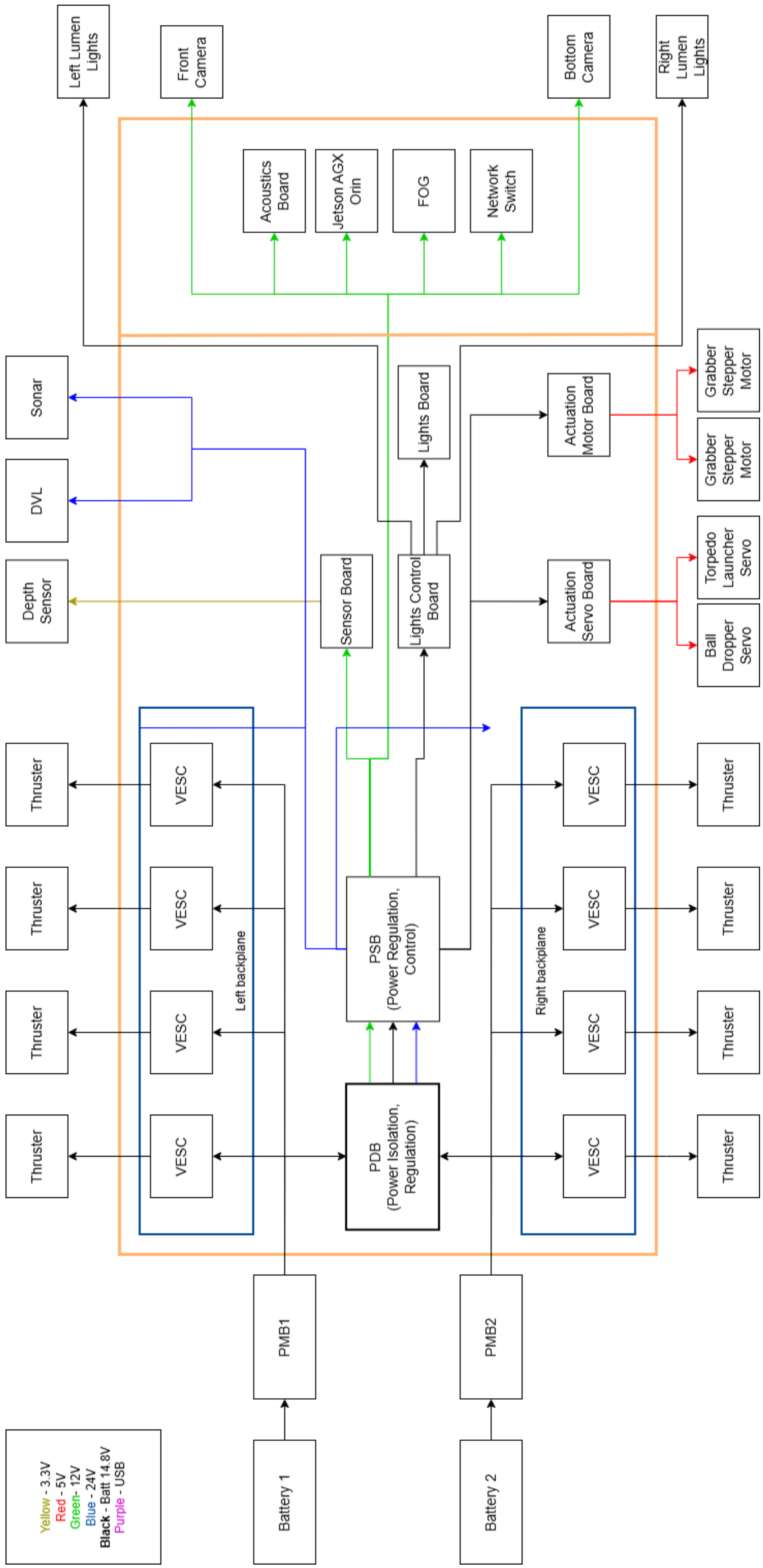

Fig. 40: BBAUV 5.0 Power Architecture.

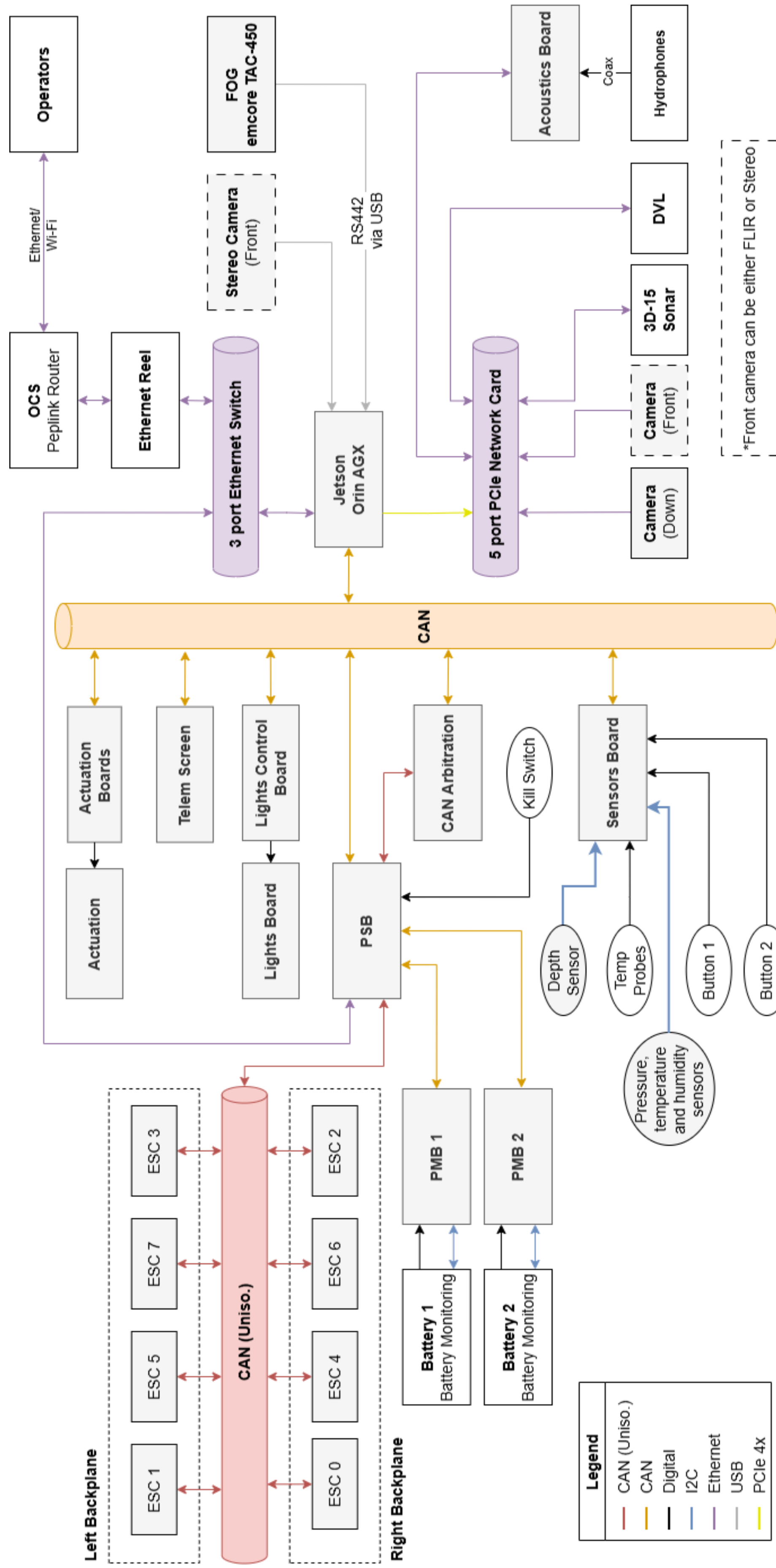

Fig. 41: BBAUV 5.0 Communication Architecture.

APPENDIX L
COMPONENT SPECIFICATIONS (BBAUV 4.5)

Component	Vendor	Model / Type	Specifications	Custom / Purchased	Cost	Year of Purchase
AUV Hull	JLCCNC	Custom Aluminium Milling	Aluminium 6061	Custom	$1,500	2025
Frame	Brown Metal Engineering	Custom Aluminium Milling	—	Custom	$400	2025
Buoyancy Floats (Shell)	Shenzhen Full Depth Technology Co., Ltd.	—	—	Custom	$1,500	2025
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
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	115.2 Wh, 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	120 W Wide-range Isolated DC-DC to 12 V	Purchased	$52	2025
		CQB150W-24S24	15 W Wide-range Isolated DC-DC to 24 V Output	Purchased	$67	2025
Single Board Computer (with GPU)	Seeed Studio	Nvidia Jetson Orin AGX	64 GB	Purchased	$2,500	2022
Fibre Optic Gyroscope	MostaTech Ltd.	VG103S-2LND	Single-Axis FOG	Purchased	$3,060	2025
IMU	VectorNav	VN-100	—	Purchased	$1,500	2023
Doppler Velocity Log	Teledyne Marine	Pathfinder DVL	600 KHz 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 (750 KHz / 1.2 MHz)	Purchased	$21,300	2019
Hydrophones	Aquarian Audio	AS-1	—	Purchased	$530 ea	2026

Acoustics Modem Stack	JLCPCB	In-house TX Board	DAC and Class-D Amplifier	Custom	$300	2026
		In-house RX Board	4-channel ADC & Pre-amplifier circuits	Custom	$300	2026
	Raspberry Pi	Compute Module 5	—	Purchased	$80	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	1,000 Kbps / 1,000 Mbps	Custom	—	—
External Comm. Interface	—	Ethernet	1,000 Mbps, Cat5e Ethernet Reel	Custom	—	—
Algorithm: Acoustics Localisation	—	—	Multiple Signal Classification (MUSIC), Short-Time Fourier Transform (STFT) based Ping Extraction	—	—	—
Algorithm: Vision	—	—	OpenCV, YOLO11, DepthAnything, XFeat	—	—	—
Algorithm: Localisation	—	—	Unscented Kalman Filter (UKF)	—	—	—
Software: Autonomy	—	—	Py Trees	—	—	—
Software: Framework	—	—	ROS2 Humble, PyTorch	—	—	—
Team size	—	—	54	—	—	—
Hardware/ Software Expertise Ratio	—	—	3:2	—	—	—
Testing time: Simulation	—	—	100 hours	—	—	—
Testing time: In-water	—	—	300 hours	—	—	—

APPENDIX M
COMPONENT SPECIFICATIONS (BBAUV 5.0)

Component	Vendor	Model / Type	Specifications	Custom / Purchased	Cost	Year of Purchase
AUV Main Hull	Feimus Engineering	Custom Aluminium Milling	Aluminium 6061	Custom	$2,800	2026
Frame	Brown Metal Engineering	Custom Aluminium Milling	Aluminium 5052	Custom	$600	2026
Waterproof Connectors	MacArtney Group	Assorted Micro & Low-Profile SubConn Series	—	Purchased	Sponsored	2019
Penetrators	Bluerobotics	Assorted Wetlink Penetrators	—	Purchased	$500	2026
Waterproof Servos	Blue Trail Engineering	SER20XX	—	Purchased	$500 ea	2026
Thrusters	Bluerobotics	T200 Thrusters	—	Purchased	$260 ea	2026
Thruster Control	Flipsky	MINI V6 MK5	—	Purchased	$100 ea	2026
Battery Hull	JLCCNC	MJF and Aluminum	—	Custom	$620 ea	2026
Battery	Raitan	Molicel INR-21700-P42A	86.4 Wh, 2x Custom-made 1S6P Pack	Purchased	$330 ea	2026
Battery Monitoring System	JLCPCB	In-house Custom-made Circuit Board	—	Custom	$300 ea	2026
Microcontrollers	STMicroelectronics	STM32F103C8T6	—	Purchased	$2 ea	2026
		STM32F407VET6	—	Purchased	$2 ea	2026
Power Isolator	Cincon	CQB150W-24S12	150 W Wide-range Isolated DC-DC to 12 V	Purchased	$170 ea	2026
		CQB150W-24S24	150W Wide-range Isolated DC-DC to 24 V	Purchased	$170 ea	2026
Compute Unit	RS Components	Nvidia Jetson Orin AGX	64 GB	Purchased	$3,180	2026
Fibre Optic Gyroscope	Emcore	TAC-450-320	3-axis Photonic Inertial Measurement Unit	Purchased	Sponsored	2024
Doppler Velocity Log (DVL)	Waterlinked	A50	—	Purchased	$4,500	2024
Camera(s)	Teledyne Vision Solutions - FLIR	BlackFly S PoE Gigabit Camera	BFS-PGE-31S4C-C	Purchased	$594	2019
	Luxonis	OAK-D Pro W	Stereo Camera	Purchased	$680	2026
Hydrophones	Aquarian Audio	AS-1	—	Purchased	$530 ea	2026
Acoustics Modem Stack	JLCPCB	In-house TX Board	DAC and Class-D Amplifier	Custom	$300	2026
		In-house RX Board	4-channel ADC & Pre-amplifier circuits	Custom	$300	2026
	Raspberry Pi	Compute Module 5	—	Purchased	$80	2025
Telemetry Display Screen	Riverdi	RVT50HQSNWC00-B	5-inch TFT LCD screen controlled by STM32U5A9NJH6Q	Purchased	$170	2025

Power Switching, Lights Control, Internal Sensors, Actuation Interface	JLCPCB	In-house Custom-made Circuit Board	—	Custom	$4,000	2026
Internal Comm. Network	—	CAN Bus / Ethernet	1,000 Kbps / 1,000 Mbps	Custom	—	—
External Comm. Interface	—	Ethernet	1,000 Mbps, Cat5e Ethernet Reel	Custom	—	—
Algorithm: Acoustics Localisation	—	—	Multiple Signal Classification (MUSIC), Short-Time Fourier Transform (STFT) based Ping Extraction	—	—	—
Algorithm: Vision	—	—	OpenCV, YOLO11, XFeat	—	—	—
Algorithm: Localisation	—	—	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	—	—	50 hours	—	—	—
Testing time: In-water	—	—	120 hours	—	—	—

APPENDIX N
3D MODELS OF ELECTRICAL BOARDS

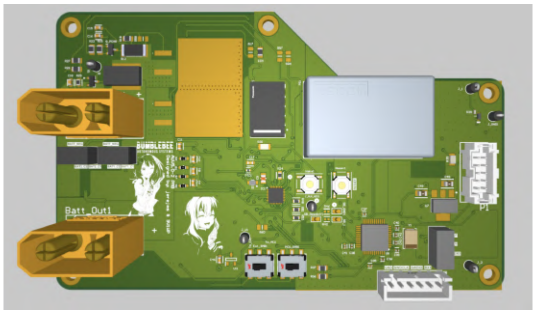

Fig. 42: 3D model of BBAUV 5.0 Power Monitoring Board.

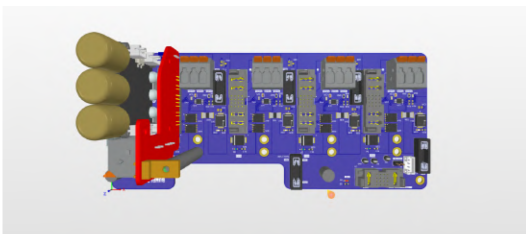

Fig. 43: 3D model of BBAUV 5.0 Left Backplane.

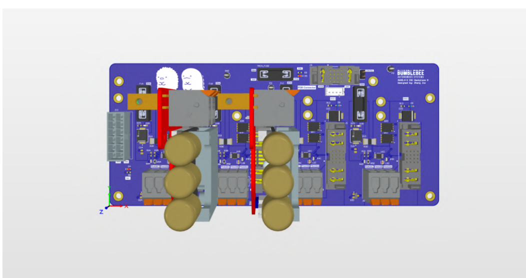

Fig. 44: 3D model of BBAUV 5.0 Right Backplane.

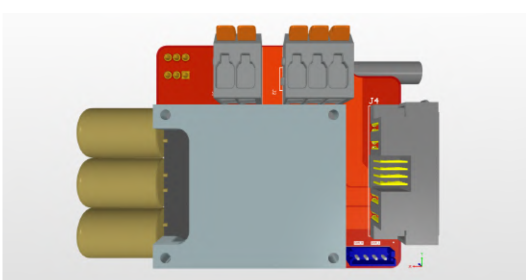

Fig. 45: 3D model of BBAUV 5.0 ESC Adaptor Board.

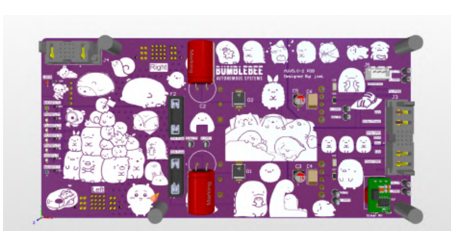

Fig. 46: 3D model of BBAUV 5.0 Power Distribution Board.

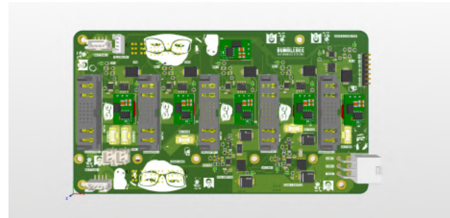

Fig. 47: 3D model of BBAUV 5.0 Power Switching Board (Top).

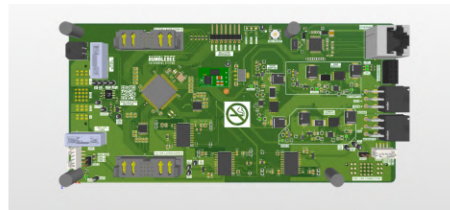

Fig. 48: 3D model of BBAUV 5.0 Power Switching Board (Bottom).

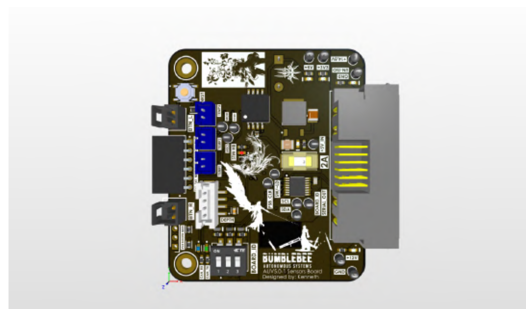

Fig. 49: 3D model of BBAUV 5.0 Sensors Board.

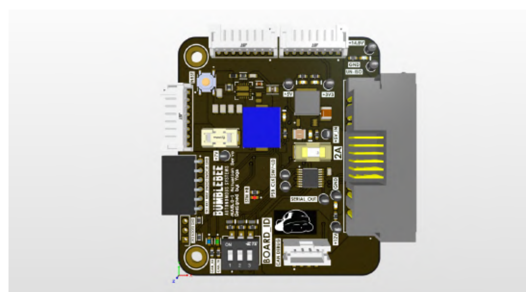

Fig. 50: 3D model of BBAUV 5.0 Actuation-Servo Board.

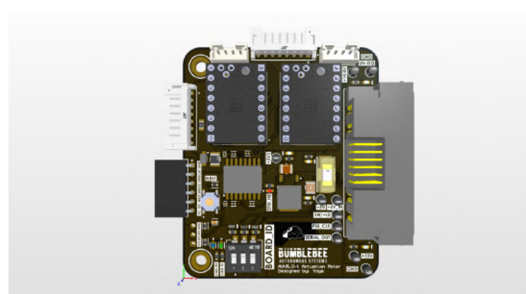

Fig. 51: 3D model of BBAUV 5.0 Actuation-Motor Board.

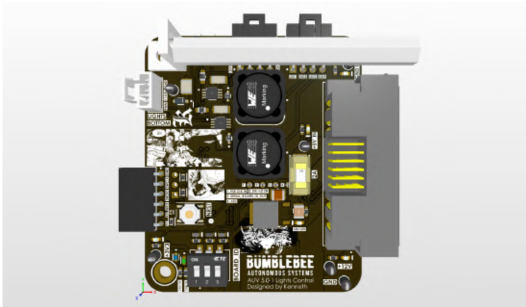

Fig. 52: 3D model of BBAUV 5.0 Lights Control Board.

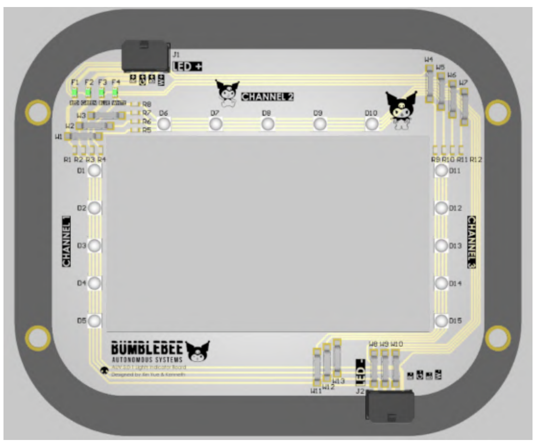

Fig. 53: 3D model of BBAUV 5.0 Lights Indicator Board.

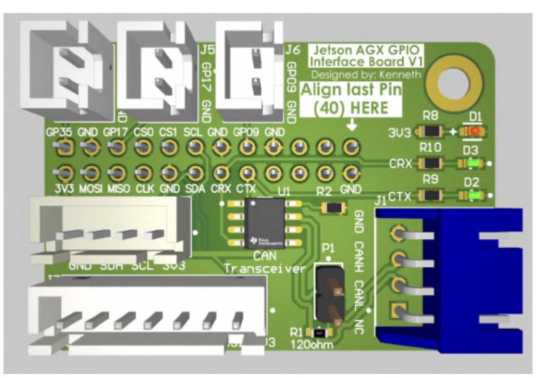

Fig. 54: 3D model of Jetson Interface Board.

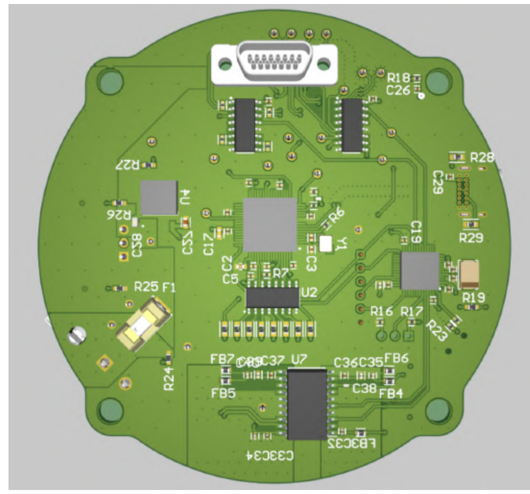
Fig. 55: 3D model of FOG Board.

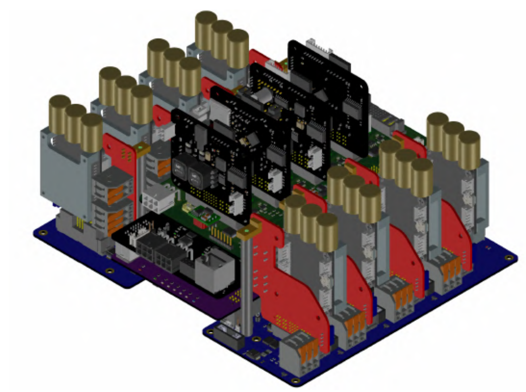
Fig. 56: 3D view of BBAUV 5.0 Electrical Stack.

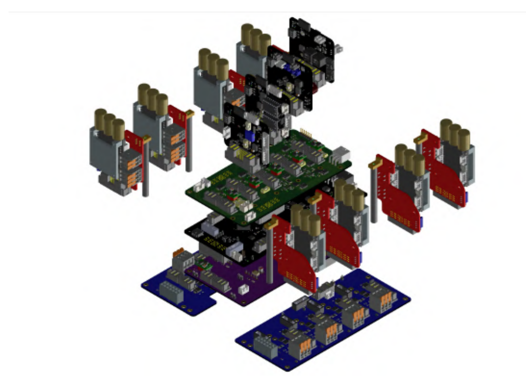
Fig. 57: 3D view of BBAUV 5.0 Electrical Stack (Exploded View).

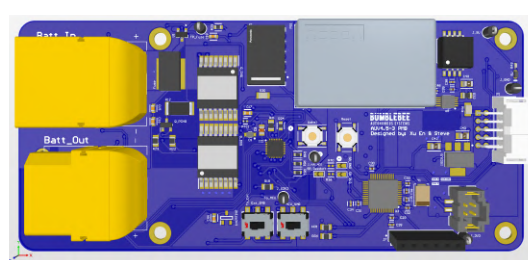

Fig. 58: 3D model of BBAUV 4.5 Power Monitoring Board.

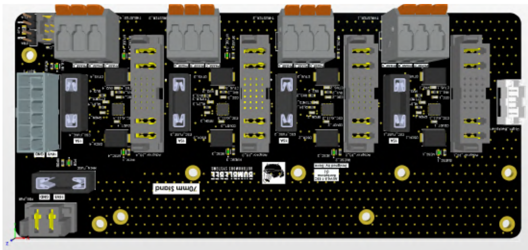

Fig. 59: 3D model of BBAUV 4.5 Left Backplane.

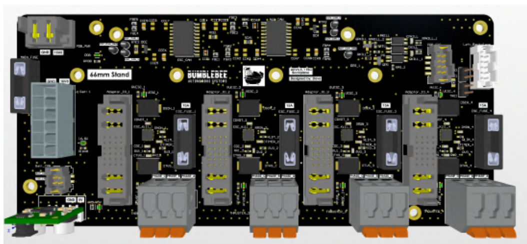

Fig. 60: 3D model of BBAUV 4.5 Right Backplane.

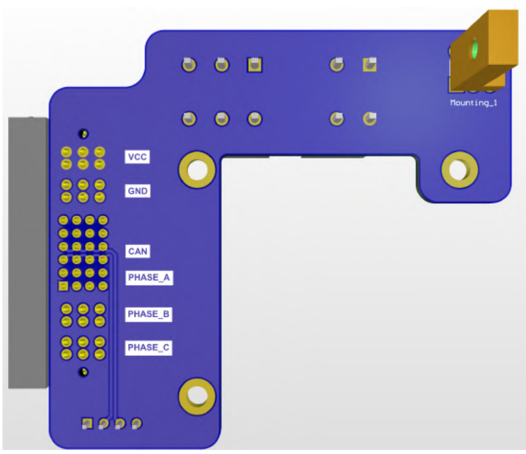

Fig. 61: 3D model of BBAUV 4.5 ESC Adaptor Board.

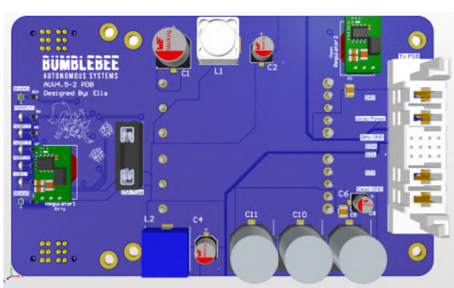

Fig. 62: 3D model of BBAUV 4.5 Power Distribution Board.

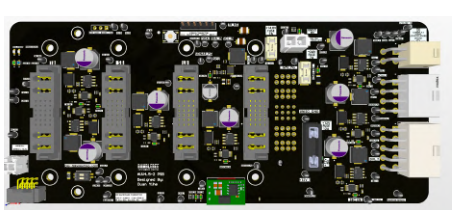

Fig. 63: 3D model of BBAUV 4.5 Power Switching Board.

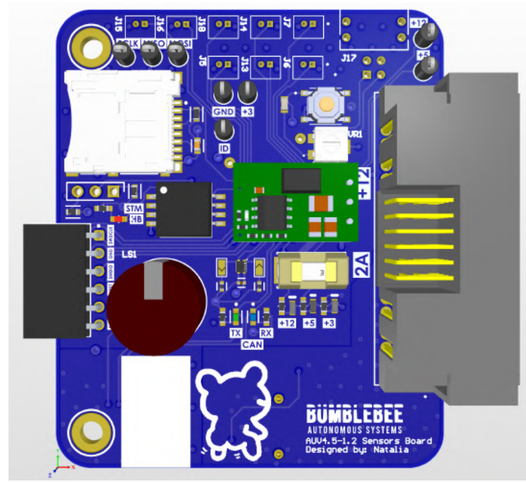

Fig. 64: 3D model of BBAUV 4.5 Sensors Board.

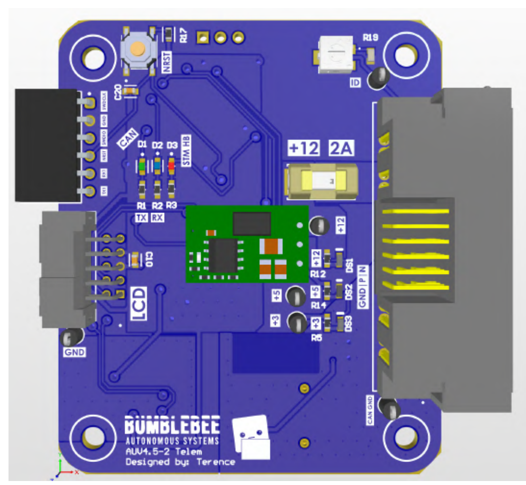

Fig. 65: 3D model of BBAUV 4.5 Telemetry Board.

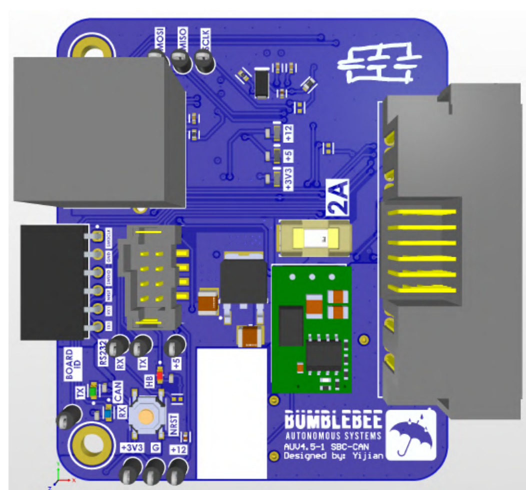

Fig. 66: 3D model of BBAUV 4.5 SBC-CAN Board.

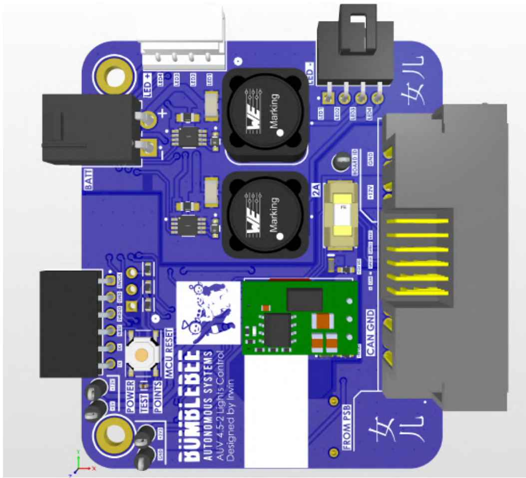

Fig. 67: 3D model of BBAUV 4.5 Lights Control Board.

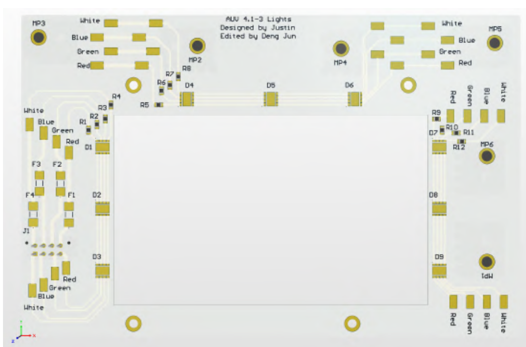

Fig. 68: 3D model of BBAUV 4.5 Lights Board.

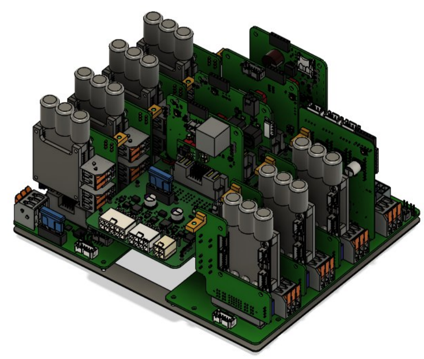

Fig. 70: 3D view of BBAUV 4.5 Electrical Stack.

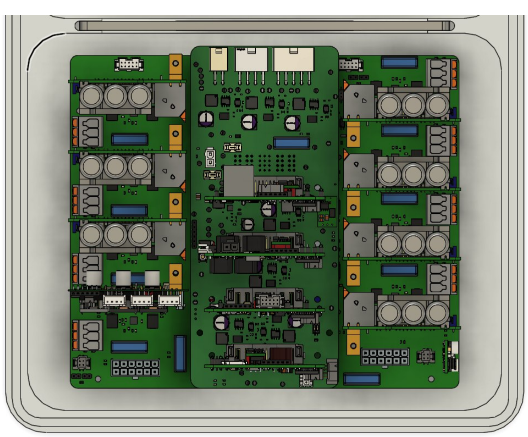

Fig. 69: 3D view of BBAUV 4.5 Electrical Stack (top view).

APPENDIX O
OUTREACH ACTIVITIES

Since our inception in 2012, Team Bumblebee has steadily grown, becoming a recognisable 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

Team Bumblebee regularly hosts student teams and researchers to foster connections and share technical knowledge. Following recent successes, we welcomed renowned expert Professor Oussama Khatib alongside local and international school and research teams to our lab. These visits serve as a vibrant platform for international technical exchange, building strong relationships within the global robotics community.

Fig. 71: Lab visit by Professor Oussama Khatib.

Fig. 72: 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 better understand real-world maritime challenges, we organise frequent site visits. This year, we were highly honored

Fig. 73: Our 2025 Sponsor Appreciation Event.

to accept an invitation from the Singapore Chief of Navy to tour their Naval Base and experience the Republic of Singapore Navy's advanced unmanned capabilities.

Fig. 74: Visit to RSN.

C. Hornet Training Programme

The Hornet Training Program is our hands-on engineering initiative for new students interested in joining Team Bumblebee. Participants design, build, and test a low-cost Autonomous Underwater Vehicle (AUV) for the Singapore AUV Challenge. The eleventh iteration (Hornet XI) welcomed 20 new members and is now officially recognised as a university elective course (CDE1301B), awarding module credits for their year-long dedication.

Fig. 75: Hornet XI in action during Pool Test in 2026.

D. Academic Research

We actively collaborate with academic researchers to advance the field of underwater robotics. Beyond hosting Professor Oussama Khatib for technical discussions, we participated in a high-profile public showcase alongside Stanford's OceanOneK team at the Singapore Oceanarium. We also regularly host various research groups across Singapore, including Republic Polytechnic, to share insights and discuss emerging robotic trends.

Fig. 76: Technical sharing with Republic Polytechnic Researchers.

E. Collaboration with Local Schools

Dedicated to inspiring the next generation of engineers, Team Bumblebee conducts engaging sharing sessions with local high school students. We share our firsthand experiences competing globally in RoboNation's RoboSub and RobotX competitions. By providing insights into the design, development, and rigorous testing of autonomous vehicles, we hope to spark early interest in maritime robotics and engineering careers.

Fig. 77: Sharing with local high school students for their project work.

F. Public showcases

Team Bumblebee actively participates in public exhibitions to bridge the gap between complex engineering and the local community. These public showcases allow us to educate audiences of all ages, raising awareness and excitement for the future of maritime robotics technology.

Fig. 78: Public showcase at Funan Mall Singapore.

Fig. 79: Joint public showcase with OceanOneK at Singapore Oceanarium.