RobotX 2026 Technical Design Report

National University of Singapore (Bumblebee Autonomous Systems)

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***Abstract*—Team Bumblebee presents BBASV 5.0, BBAUV 5.0 and Jellyfish 2.5 for RobotX 2026, a fleet of three new platforms built alongside our RoboSub 2026 campaign. With this much new hardware in one season, our approach is to make each vehicle reliable at its core tasks before asking the vehicles to work together. Where possible we reuse before we redesign. BBAUV 5.0 was proven at RoboSub first, and its electrical and software stacks were carried over to BBASV 5.0 so that effort could go into the problems our 2024 vehicles showed in the field. Thermal throttling is addressed at the enclosure on both new vehicles, holonomic control gives BBASV 5.0 the precision needed for docking and buoy navigation, and faster battery swaps give us more time on the water. Collaboration is built on top of these capabilities. BBASV 5.0 acts as the fleet hub, linking BBAUV 5.0 underwater and Jellyfish 2.5 in the air, and the messages between vehicles are kept to what each task needs. We target the Advanced tier across all four tasks, and will attempt Disruptive tiers where field testing supports them.**

I. Competition Strategy

A. Core Strategy

RobotX 2026 replaces isolated tasks with a single mission in which every task needs systems in more than one domain to cooperate [1]. This season Team Bumblebee is also commissioning three new platforms alongside RoboSub 2026, so our first objective is to field reliable vehicles. We target the Advanced tier in all four tasks, since each Advanced tier depends on one vehicle re-tasking another and this is where our investment in inter-vehicle communication pays off. To get there, we build the capabilities every tier relies on, which are perception, holonomic control, actuation and inter-vehicle messaging. Disruptive tiers are treated as stretch goals and attempted only where field testing shows they are repeatable.

B. Performance Assessment

Team Bumblebee clinched first place at RobotX 2024 and RoboSub 2026. Field operation of BBASV 4.0, Jellyfish 2.0 and BBAUV 5.0 across these campaigns validated several design decisions worth carrying forward, but also exposed specific limitations that motivate the platforms presented here.

Battery-Swapping Ergonomics: On BBAUV 5.0 the battery hot-swap was redesigned so that each battery is inserted and removed in a single straight motion. At RoboSub 2026 this cut the average swap from 1 minute on its predecessor to 30 seconds. BBASV 5.0's pontoons adopt the same approach.

Compute Form Factor: BBASV 4.0 carried a full PC stack which, although computationally sufficient, was bulky and heavy. The revised 2026 rules constrain the USV to a $2\,\mathrm{m}\times1\,\mathrm{m}\times1\,\mathrm{m}$ envelope and 60 kg [1], revealing a crucial need to downsize the compute stack without compromising computational ability. The Jetson Thor was deemed essential to meet this requirement; however, unlocking its full capability proved challenging with respect to its 130 W power envelope and its thermal design.

Thermal Dissipation Limitations: BBASV 4.0 and Jellyfish 2.0 both encountered thermal throttling of their compute at RobotX 2024, and



Fig. 1: BBASV 5.0 render.



Fig. 2: BBAUV 5.0 render.



Fig. 3: Jellyfish 2.5 render.

BBAUV 4.0 experienced the same during out-of-water staging at RoboSub 2025. In every instance the root cause was the enclosure rather than the compute module itself. Stripping the Thor of its stock cooling system to minimise mass only exacerbates this, and thus necessitates a dedicated, lightweight cooling solution for both BBASV 5.0 and Jellyfish 2.5.

C. Inter-Vehicle Communication

Since the Advanced tiers depend on re-tasking, we scoped inter-vehicle communication to the few one-shot messages those tiers require rather than continuous state sharing. These are the entry, exit and buoy positions for Task 1, a resource request for Tasks 2 and 3, and an incident position and keep-out radius for Task 4. BBASV 5.0 is the hub for this traffic because it is the only vehicle that can reach both BBAUV 5.0 underwater and Jellyfish 2.5 in the air. In Task 2, for example, it relays the pipeline sequence decoded by BBAUV 5.0 to Jellyfish 2.5. The network is shown in Fig. 4 and detailed in Sec. II-C.

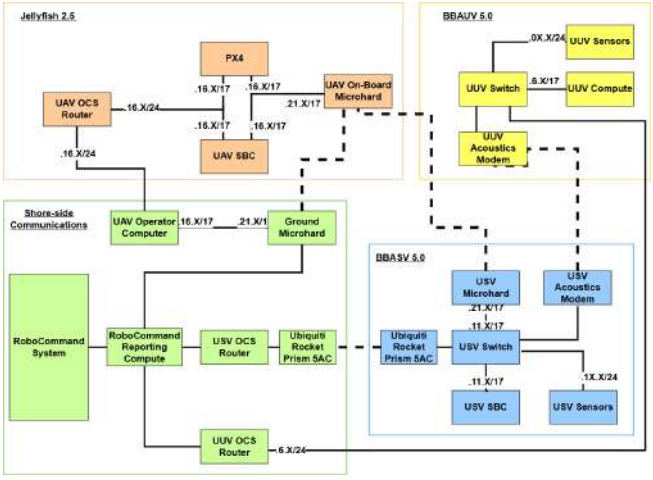


Fig. 4: Team Bumblebee Fleet Network.

D. Complexity–Reliability Trade-offs

Commissioning BBASV 5.0 and Jellyfish 2.5 while maturing BBAUV 5.0, across two competitions in one season, places new-hardware troubleshooting in direct competition with autonomous software validation. Our answer was to reuse before redesigning. BBAUV 5.0 was fielded at RoboSub 2026 as a deliberate shakedown, and its electrical backplane and ROS 2 software stack, conceived as platform-agnostic from the outset [2], were ported to BBASV 5.0 with only power-delivery modifications for the Thor. This removed an electrical bring-up cycle of several months from the ASV schedule, at the cost of inheriting the AUV stack's limitations.

II. Design Strategy

A. Requirements Capture

Before development began, we broke each mission task down into requirements for each vehicle. These covered what the vehicle must perceive, actuate, communicate and manoeuvre, and which of its existing subsystems had shown limitations in the field. Table I summarises the result.

B. Platform-Specific Changes

1) Autonomous Surface Vehicle 5.0

Due to the revised vehicle envelope, we decided to iterate on BlueRobotics' Blueboat Hull by heavily refurbishing it with our own custom designs to fulfil the competition requirements.

a) Compute Stack

The Jetson Thor was selected to replace the full PC stack of BBASV 4.0 within the smaller 2026 envelope as mentioned in Table I, and to give the team compute headroom to begin exploring Vision-Language-Action models and other

TABLE I: 2026 Fleet Platform Task Requirement Allocation

	AUV 5.0	ASV 5.0	Jellyfish 2.5
Improvements	- Adjustable sonar angle for easier testing - Improved PMB for longer battery life	- Heat exchanger for Jetson Thor - Holonomic Control - Proper cable harnessing	- Improved airflow within shell
Task 1	N.A.	- Perception of buoys - Obstacle detection	- Perception of buoys - Search pattern and Path planning - Localisation with ASV
Task 2	- Detection of Pipeline - Ability to decode colour sequence	N.A.	- Ability to pick up and drop tins - Drop site colour recognition
Task 3	N.A.	- Actuated Water Cannon - Target board recognition - Ability to strafe - Ability to decode colour sequence	- Ability to pick up and drop tins - Drop site colour recognition
Task 4 and Inter-Vehicle Communication	- Transmission of Pipeline Colour Sequence to ASV via Acoustic	- Transmission of Dock Colour Sequence to UAV via Microhard - Ability to act as repeater between AUV and UAV for Pipeline Colour Sequence	- Transmission of path route to ASV via Microhard

learning-based approaches to autonomy in future seasons. Fitting it into BBASV 5.0 required changes to the hull, the cooling and the power supply. A standard watertight case could not dissipate enough heat, so we built our own hull, with a bent aluminium sheet base that conducts heat away from the electronics and carbon fibre walls that keep the weight down. The design was refined through FEA to keep mass low without losing stiffness.

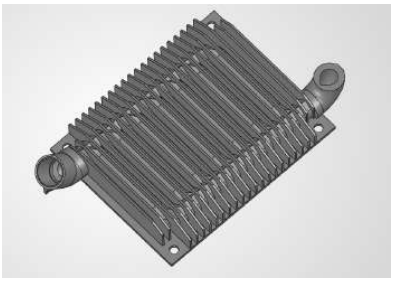


Fig. 5: CAD model of the heat exchanger.

A heat exchanger sits beneath the hull directly under the Thor. It is printed in AlSi10Mg by Selective Laser Melting, which allows for internal channels that CNC machining cannot produce, and a pump drives seawater through these channels to keep the Thor from throttling even at full load.

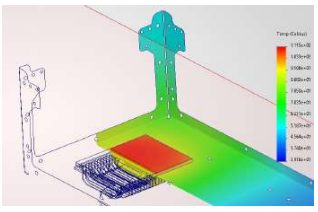


Fig. 6: Thermal simulation of the heat exchanger without seawater.

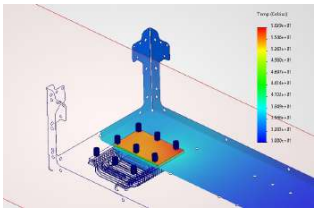


Fig. 7: Thermal simulation of the heat exchanger with seawater.

The 24 V power line was upgraded from 150 W to 500 W to handle the Thor's peak current draw, with added filtering to keep the supply clean during sudden load changes.

b) Propulsion

Entering the dock and weaving through the buoy field both need BBASV 5.0 to translate in any

direction without changing heading. To achieve this holonomic control, as determined necessary in Table I, we mounted four T200 thrusters on a carbon fibre tube frame at approximately 45° to the vehicle axes. The two stern M200 thrusters of the original BlueBoat are retained for efficient surge during long transits, where the angled T200s would waste thrust.

The thrusters are driven by BEESC, our own electronic speed controller, which we developed to understand the technology behind the commercial Flipsky ESCs we previously used. Its six-layer PCB with custom routing fits in a smaller form factor, and a USB-C debug port allows any ESC on the backplane to be diagnosed directly. Because BEESC is tuned to our thrusters' profile, it trades a lower current ceiling for more accurate current sensing, giving finer and more efficient thrust control.

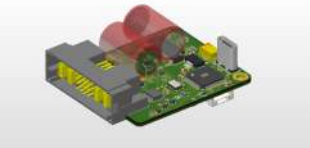


Fig. 8: CAD model of BEESC.

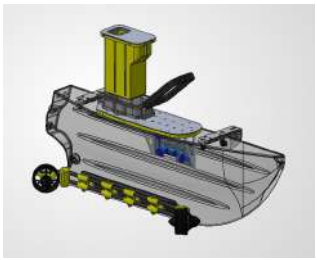


Fig. 9: CAD model of the pontoon hull set-up.

c) Battery Hot-Swap System

Building on the hot-swap system developed for BBAUV 5.0, we replaced the original BlueBoat pontoon end caps and face seals with custom end caps and O-ring face-seal adapters, which also provide mounting for the ESC backplanes. Each end cap has an open flange that compresses an O-ring as the battery is inserted, sealing the pontoon from the outside. Batteries can therefore be swapped at the wet berth without removing the end caps or compromising the pontoon seal, which maximises testing time and simplifies our standard operating procedures.

Task 1 - Safe Passage:

d) Obstacle Avoidance

Safe Passage places BBASV 5.0 in a randomised buoy field with the possibility of hazards changing mid-transit, so avoidance must be reactive rather than pre-planned. Building on RobotX 2024, navigation remains on the Nav2 framework [3] with obstacles maintained in a Spatio-Temporal Voxel Layer (STVL) [4] rather than a conventional occupancy grid. STVL was chosen because surface returns are noisy due to wave crests, spray and thruster wash and would persist in a static costmap. STVL time-decays each voxel, so transient returns clear on their own while real obstacles are continually refreshed, and the three-dimensional voxel representation lets a buoy's hull be distinguished from the water surface beneath it.

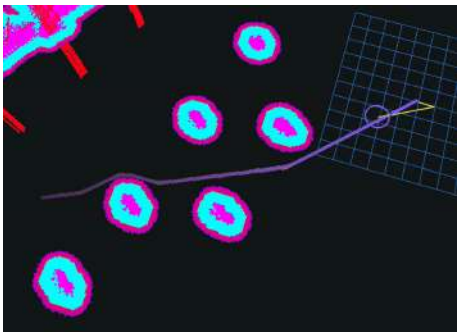


Fig. 10: Planned trajectory through the obstacle field.

Nav2 sits above our own controls stack. Its controller server outputs a body-frame velocity setpoint in surge, sway and yaw. Our holonomic controller tracks this setpoint, and the thrust allocator resolves it into commands for the four T200s and two M200s, sent over CAN to the BEESCs. This split keeps the dynamics-aware part of control in code we tune and test ourselves, while Nav2 provides planning, costmap maintenance and recovery behaviours. The same stack also serves Task 4. A RoboCommand keep-out zone or moving contact is added to the costmap as an obstacle, and the planner routes around it with no change to mission logic.

Task 3 - Coordinated Logistics:

e) Dock Detection and Entry

Coordinated Logistics requires BBASV 5.0 to identify the GREEN bay among three and enter it without contacting the bay walls, in a space only marginally wider than the vehicle. Two sensors divide this work by what each measures well. The OAK-D's depth stream is processed with the Point Cloud Library (PCL) to segment the planar

dock face and the rectangular opening of each bay. Plane fitting on the face yields the dock's orientation, and the opening's centroid gives the approach axis, while bay colour is read from the co-registered RGB frame. The Ouster LiDAR, mounted higher with a wider field of view, resolves the bay's side walls as the vehicle enters, where the OAK-D's forward view no longer covers them. These wall returns are inserted into the local costmap so that the planner treats them as hard obstacles, and holonomic sway control corrects lateral offset during the final approach without altering heading. Fig. 12 shows the segmented dock face and bay opening from the OAK-D point cloud.

f) Water Cannon

In RobotX 2024, targeting relied on fusing LiDAR with a monocular camera, which required the host to search tens of thousands of LiDAR points to isolate the target. This capped pose estimation below 5 Hz, so wave surge and thruster wash moved the vehicle faster than the targeting loop could respond, and tracking lagged.

For RobotX 2026, BBASV 5.0 aims the water cannon using a Luxonis OAK-D stereo camera. Depth and noise filtering run on the camera's onboard vision processor rather than the main compute, and depth is extracted only around the detected target instead of across the full scene. This frees the host from point cloud processing and raises the targeting update rate to 12 Hz, keeping the cannon on target as the vehicle moves.



Fig. 11: CAD model of the water cannon.



Fig. 12: Dock face and bay opening segmented from the OAK-D point cloud.

2) Autonomous Underwater Vehicle 5.0

Following its successful inaugural run at RoboSub 2026, our focus for RobotX was to maintain the capabilities of BBAUV 5.0 while extending its ability to execute the RobotX tasks.

a) Overhauled Battery Stack

BBAUV 5.0 became our primary vehicle from RoboSub 2026 onwards. Its power subsystem was resized for the higher current requirements. We retained 21700 Li-Ion cells for their mechanical robustness and dimensional stability, but arranged 6 in parallel to raise both discharge current and capacity to 48 Ah at 14.4 V, while keeping each pack under the 160 Wh limit for air transport to overseas competitions. The custom Power Monitoring Board (PMB) was upgraded to match, with its power MOSFETs thermally coupled to the finned metallic battery-hull cap so that the hull itself dissipates the additional heat.

Task 2 - Infrastructure Survey and Repair:

b) Magnet Plate

To activate the pipeline light box, a plate of square neodymium magnets is mounted on the underside of BBAUV 5.0's forward base and triggers the box's reed switch as the vehicle passes over it. The magnets are arranged in a variant of the Halbach array, so the field is concentrated towards the light box and cancelled to near zero towards the hull. This matters beyond trigger range. BBAUV 5.0's own battery hulls use reed switches to toggle power, and an unshielded plate could switch them off and shut down the vehicle.

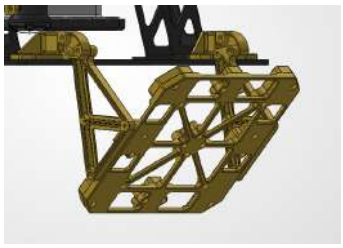


Fig. 13: CAD model of the magnet plate.

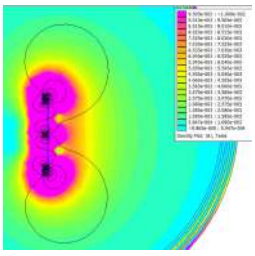


Fig. 14: Simulated field distribution of the Halbach array.

The light-box panel faces upwards, and the vehicle triggers it from directly above. The panel is therefore below the hull, outside the forward camera field of view. The flashing colour sequence is therefore decoded from the bottom-facing camera, reusing the bottom-camera de-

tection pipeline developed for the Bins task at RoboSub 2026 [2].

c) Sonar

BBAUV 5.0 must perceive the pipeline in the Singapore River, whose turbidity is unlike the clear water of the Woollett Aquatics Center at RoboSub 2026. Acoustic pinger localisation brings the vehicle to the vicinity of the pipeline start, but a reliable heading towards the pipeline is needed before the camera can acquire and track it, and at Marina Bay visibility that heading cannot be derived optically. A forward-looking imaging sonar fills this gap. Two candidates were evaluated on a pipeline mock-up, the Blueprint Oculus M750d and the Water Linked Sonar 3D-15, judged on whether the pipeline could be distinguished in the sonar image at the ranges needed to establish an approach heading. Neither resolved the pipeline cleanly at range, but the M750d degraded more gracefully: at 5 m the 3D-15 returned too little pipeline structure to derive a heading, whereas the M750d still did (Appendix K).

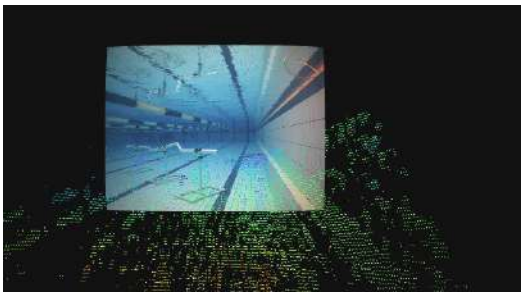


Fig. 15: 3D-15 Sonar Points Overlaid on Front Camera Feed.

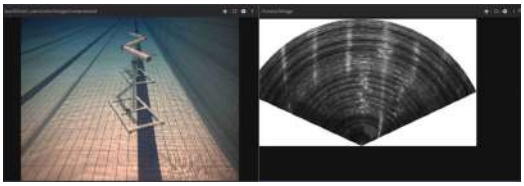


Fig. 16: Front camera feed alongside the M750d Cartesian sonar image.

3) Jellyfish 2.5

Learning from RobotX 2024, we carried over the Jellyfish 2.0 design with one significant problem in mind. As we develop Jellyfish 2.5, we aim to eliminate these design problems to unleash the full potential of Jellyfish and to introduce our own actuation for RobotX.

a) Thermals

In RobotX 2024, Jellyfish 2.0 ran into severe thermal issues due to the lack of convection within the UAV's shell. Hot air recirculated within the shell, so the onboard compute's temperature rose steadily until it throttled. This caused the computational capacity of the onboard compute to be significantly hampered, resulting in less efficient operational performance.

To resolve this issue for RobotX 2026, the Jellyfish 2.5 enclosure cap was redesigned with thermal dissipation in mind. Inlet and outlet air ducts were strategically placed along the outer surface of the enclosure cap, and simple CFD simulations were carried out to ensure that proper flow of air can be achieved through the shell.

Task 1 - Safe Passage:

b) Search Pattern and Buoy Detection

At the higher tiers of Safe Passage the beacons marking the safe route are visible only from above, so Jellyfish 2.5 surveys the field before BBASV 5.0 enters. It flies a fixed-altitude lawnmower pattern over the known boundary, which guarantees full coverage of a small, bounded field in a predictable time. Beacons are detected with YOLO26 in the downward camera and projected to world positions using the drone's RTK GNSS pose. Their state is classified over a short window of frames, since flashing and steady lights look identical in any single image. Positions and states are sent to BBASV 5.0 as one message, and Jellyfish 2.5 then holds over the field to broadcast any change so that BBASV 5.0 can re-plan.

c) ASV Guidance

To stay with BBASV 5.0 during the transit, Jellyfish 2.5 needs the vehicle's position and heading relative to itself. We chose visual fiducials over sharing GNSS positions across the link because the relative pose is measured directly in the drone's camera frame, so it is not affected by GNSS error on either vehicle or by link latency. Four AprilTag markers are fixed at the corners of BBASV 5.0 (Fig. 17). Using four markers also means at least one remains visible from most viewpoints, and the spread between them gives a reliable heading estimate.

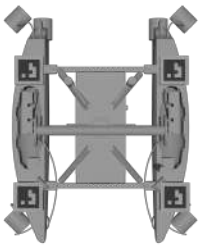


Fig. 17: AprilTag layout on BBASV 5.0.

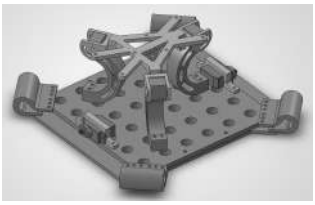


Fig. 18: CAD model of the Jellyfish 2.5 actuation payload.

Task 2 - Infrastructure Survey and Repair:

d) Actuation

For Tasks 2 (and 3), Jellyfish 2.5 carries a magnetic payload beneath the airframe, mounted on TPU spacers that absorb shock and allow the assembly to tilt so it can sit flat on tins resting at different angles. The mechanism consists of an upper plate holding the magnets and a lower pusher plate with cutouts that let the magnets make direct contact with the tin, giving a more reliable pickup. To release a tin, two servos drive the pusher plate downward until the tin is pushed far enough from the magnets to break their hold. Because every part is 3D-printed, the payload is inexpensive and can be quickly reproduced or replaced after a hard landing.

C. Inter-Vehicle Communication

1) Communications Design

Each vehicle uses the link that suits its environment, and BBASV 5.0 sits at the centre because it is the only vehicle that can reach all three (Fig. 4). Radio does not travel underwater, so BBAUV 5.0 communicates only through the acoustic modem on BBASV 5.0. Jellyfish 2.5, BBASV 5.0 and the shore station share a Microhard mesh network. Any message between BBAUV 5.0 and either Jellyfish 2.5 or shore is therefore relayed through BBASV 5.0.

The ASV–shore link carries most of the telemetry and sensor data, and keeps the 5.8 GHz Ubiquiti Rocket Prism 5AC pair from 2024. The UAV link had to change because the 900 MHz RFD900x we used in 2024 is not permitted in Singapore. We replaced it with the 2.4 GHz Microhard pMLTE, whose higher throughput and Ethernet interface let ROS 2 messages pass across the network directly. Remote kill for BBASV 5.0 and BBAUV 5.0 and pilot control for Jellyfish 2.5 run on a separate 2.4 GHz ELRS link from a single Radiomaster TX16S.

2) RoboCommand Integration

Operator Control Station (OCS) 4.0, developed for RoboSub 2026, is extended with a RoboCommand bridge. A single shore-side process subscribes to the fleet's ROS 2 status topics, serialises them as Protocol Buffer messages and publishes them to RoboCommand over the wired connection [1]; incoming tasking messages are parsed and republished as ROS 2 topics that each vehicle's mission tree subscribes to. Centralising this on shore means no vehicle carries a RoboCommand dependency, and a change to the RoboCommand schema touches one process rather than three vehicles.

3) In-house Acoustics Solution

For both IVC and acoustic pinger localisation, we developed an in-house acoustic modem mounted on BBAUV 5.0 and BBASV 5.0. 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 [5] as seen in Table II. 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 [6].

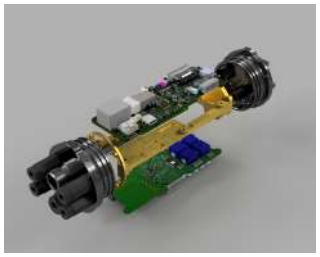


Fig. 19: Render of Bumblebee's custom software-defined modem stack.



Fig. 20: 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 (such as pools) [7], [8]. Some aspects of higher-level communications such as packet acknowledgment and error detection have also been developed [9]. 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.

III. Testing Strategy

To validate our designs, we adopt a multi-tiered testing framework throughout development, as shown in Fig. 21. 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 minimising compounded failures.

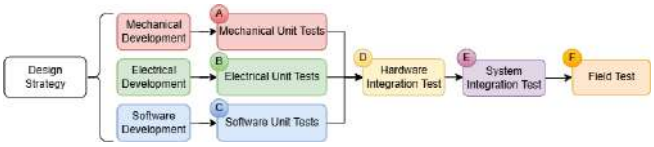


Fig. 21: Team Bumblebee testing framework.

A. Sensor Rig Integration

Before the hull of BBASV 5.0 was built, its LiDAR, cameras, dual-antenna INS and compute were mounted on a workshop trolley and powered from a portable station (Fig. 22). This let the software team bring up drivers and networking without waiting on hull fabrication. On the rig we confirmed that all sensors could share the network, measured real data rates and profiled the combined perception load. It also gave us a platform to tune the GNSS–LiDAR fusion before the vehicle ever reached the water. When the hull was ready, the sensor stack went in as a validated module, so the first pool session was spent tuning the controller rather than fixing drivers.

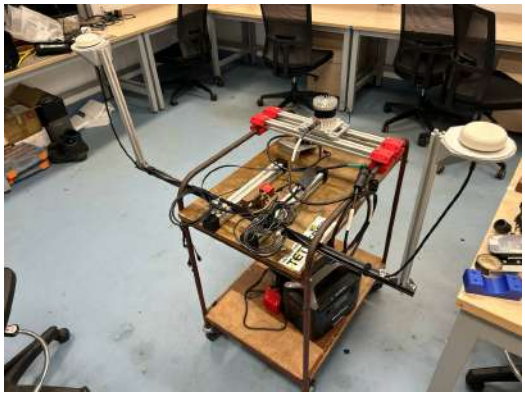


Fig. 22: Sensor rig: OS0 LiDAR and dual GNSS antennas on a workshop trolley.

B. 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 and FDM Rapid Prototyping

Initial concepts of the mechanical design were translated into CAD models and evaluated through regular design reviews, allowing concerns regarding component layout, accessibility and assembly to be addressed early. FEA was conducted on critical structural components across both vehicles, including the ASV main hull cap and pontoon hull lid, along with AUV frame, caps, main hull and battery connector hull. This allowed structural performance to be verified before manufacturing.

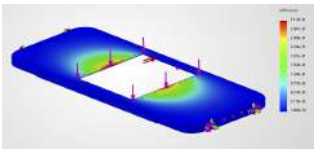


Fig. 23: FEA Simulation of BBASV 5.0 main hull cap.



Fig. 24: Full 3D Printed Mockup of BBAUV 5.0

FDM printing was used to rapidly prototype the AUV frame and hull, as well as the ASV pontoon

hull. These mockups allowed verification of component fittings, assembly, clearances and overall design before final manufacturing. 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 F) that details sequential stages of testing with a Standard Operating Procedure (SOP):

Isolated Testing and Load Testing: Individual circuits are validated using custom test boards before full-stack integration. Our *Universal Daughter Testboard* [2] allows daughter boards to be rapidly tested and debugged through exposed interfaces such as CAN. This proved especially useful with the addition of a new ASV daughter board for Radio Control, Actuation and Light Indicator. It is load tested to verify power stability and operation under representative loads to ensure it behaves as intended before it is placed with the rest of the stack.

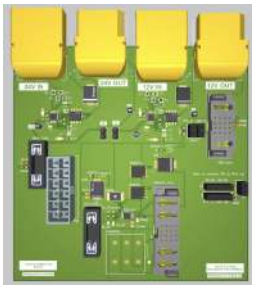


Fig. 25: Backplane circuit test board.

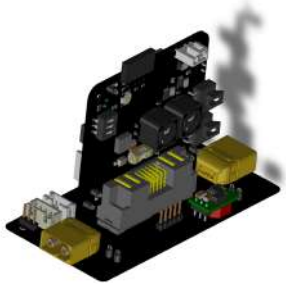


Fig. 26: Universal Daughter Testboard.

Integration of Electrical Stack: Each board that has undergone individual testing is progressively integrated into the electrical stack. The combined stack is tested after each addition, allowing faults to be isolated before the next board is introduced. Once fully assembled, it is ready to be integrated with the Vehicle.

Full Integration Test: After any platform migration, e.g. from bench to ASV, a standardised SOP verifies system-level functionality and stress tests the electrical stack. The process and results are detailed in Appendix G.

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.

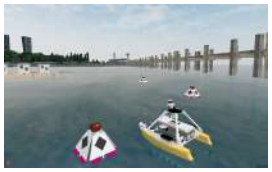


Fig. 27: Gazebo simulation of the Singapore River.

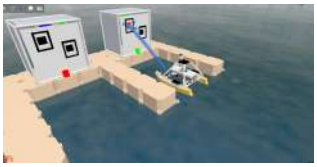


Fig. 28: Gazebo simulation of the docking bays.

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.

C. Hardware Integration into Systems Integration Test

To mitigate risk to high-value compute units and delicate sensor payloads, subteams enforce strict assembly of physical components, by wiring up the various peripherals from mechanical mountings to the integrated electrical stack, to confirm fit within the vehicle chassis before installation. The software team then ensures that the compute unit can access sensor data, and command thrusters and actuators, so that the vehicle is ready for in-water testing.

D. Field Testing

1) Sites and Competition Props

BBAUV 5.0 and BBASV 5.0 are tested in the Olympic-size pools at the National University of Singapore University Sports Centre (USC), and BBASV 5.0 is also tested in open water at our wet berth at the Republic of Singapore Yacht Club (RSYC). Jellyfish 2.5 is flown at West Coast Park. To test against realistic targets, the mechanical team built replicas of the competition elements, including a pipeline with switchable RED/GREEN segments and the docking-bay window.

2) Pool Testing

Each pool session follows a fixed procedure of briefing, pre-deployment checks and condition logging (Appendix K). For BBAUV 5.0, sessions concentrated on the Task 2 critical path, covering pinger localisation, sonar-guided approach to the pipeline replica and camera tracking along it, as well as colour-sequence decoding on the mock light box. For BBASV 5.0, the pool was first used to tune the holonomic controller and to validate localisation from GNSS-RTK fused with DLIO [10]. Docking against the window replica and cannon targeting followed, and an open-water session at RSYC then added wind and current.

3) Flight Testing

Flight testing progresses from manual to autonomous flight, first over land and then over water, and any failure returns the vehicle to the previous stage. Every session is flown with a safety pilot on a 2.4 GHz ELRS link that is independent of the data network, with a geofence and altitude ceiling set in PX4 and flotation fitted for over-water flights. Sessions this season focused on thermal validation of the ducted cap in sustained hover, AprilTag tracking of BBASV 5.0 from flight altitude, beacon classification over the buoy replicas, and tin pickup and drop.

4) Hybrid Physical–Virtual Testing

Our vehicles are tested across three sites. BBASV 5.0 and BBAUV 5.0 share the USC pool, where they can exercise the acoustic hand-off directly, and BBASV 5.0 is also tested in open water at RSYC. Jellyfish 2.5, however, can only be flown at West Coast Park, so the UAV–ASV hand-offs cannot be tested with both vehicles present. We therefore pair the physical Jellyfish 2.5 with a simulated BBASV 5.0 in Gazebo, connected over the real Microhard link and message formats (Sec. II-C). Flying over beacon replicas, Jellyfish 2.5 sends Safe Passage waypoints to the simulated vehicle exactly as it would in competition. This lets us validate the air-to-surface hand-off safely and repeatably before the two vehicles are fielded together.

IV. Conclusion

This season Team Bumblebee commissioned three new platforms while contesting two competitions. BBAUV 5.0 was proven at RoboSub first, BBASV 5.0 inherited its field-tested stacks, and Jellyfish 2.5 evolved a known airframe. Inter-vehicle communication was kept to what the mission requires and centred on BBASV 5.0. Each choice favours reliability over reach, and each is being proven through our tiered testing programme. At Bumblebee, we believe that with careful design comes reliable performance, and we look forward to proving it on home waters.

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 also acknowledge Ahmad Musoddaq 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. 29: 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 (8)

Future Systems Technology Directorate (FSTD) — 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 (4)

DSO National Laboratories, 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 a 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 II presents a review of commercial acoustic modems not mentioned in [5]. 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 resilience 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) [11]. 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 II: 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) [12]	$3,995	22–35 kHz	FSK, PSK	80bps (FSK)– 10kbps (PSK)	1,000 m	Poor (from pool testing)	No
Subnero WNC-M25MSO4 [13]	N/A	20–32 kHz	OFDM, FSK	Up to 15kbps	5,000m	Rated for high speeds at $\pm$4 knots	Yes (proprietary UnetStack software)
Waterlinked M16 (used by various RoboSub teams) [14]	$2,650	54–62 kHz	N/A	10bps	1,000 m	Unknown	No
In-house Modem	**$\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 30. 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.

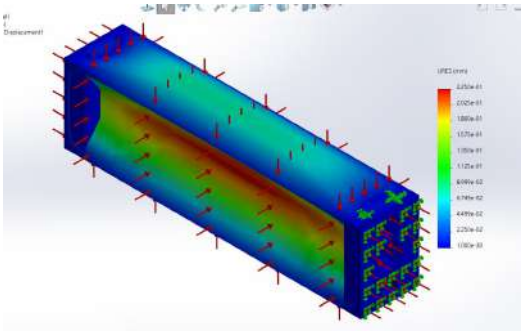


Fig. 30: Stress Analysis of MJF Battery Hull.

APPENDIX D
BBAUV 5.0 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 31, 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 32. This setup keeps peak junction temperatures well within safe limits, even under heavy sensor fusion workloads.

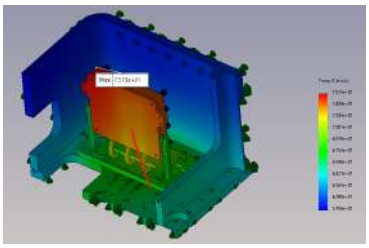


Fig. 31: Thermal simulation of the Jetson compute mount.

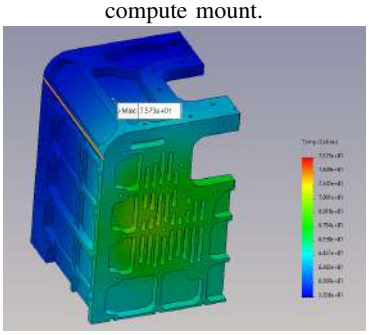


Fig. 32: Thermal simulation of the hull underside.

APPENDIX E
BBASV 5.0 COMPUTE MOUNT THERMAL STUDY

With the switch from the Jetson AGX Orin to the Jetson Thor as our main compute in BBASV 5.0, an active cooling system was needed to cool the Jetson Thor during its autonomous runs due to its significantly higher maximum heat output of 130 W as opposed to the Jetson AGX Orin's maximum output of 75W. Due to the lack of surrounding water in contact with the main hull, BBAUV 5.0's passive cooling solution cannot be replicated onto BBASV 5.0. Therefore, proper heat dissipation requires installing an active heat exchanger externally attached to the bottom of the aluminium main hull.

The active heat exchanger geometry is designed with Selective Laser Melting (SLM) fabrication in mind. The heat exchanger plate uses an inlet manifold to distribute seawater across seven parallel channels. After passing through the plate, the flows recombine in an outlet manifold and leave through the fitting at the opposite end. This arrangement maximises the cooling surfaces across the plate, providing multiple paths for heat conducted into the metal to transfer to the seawater. The external fins add surface area for heat exchange with the surrounding air.

This design eliminates the need to store onboard coolant within BBASV 5.0, helping optimise its weight. Using seawater as the coolant also allows heat from the Jetson to be discharged directly to the surrounding environment. Unlike a finite onboard coolant reservoir, which gradually warms during operation, the seawater supply is continuously renewed. This reduces the mass and volume of the cooling system. By comparing the 2 different thermal simulations in Figure 35 and Figure 36, the active heat exchanger is shown to be effective at conducting heat away from the Jetson Thor, allowing the Thor to be able to operate at peak efficiency without thermal-throttling.

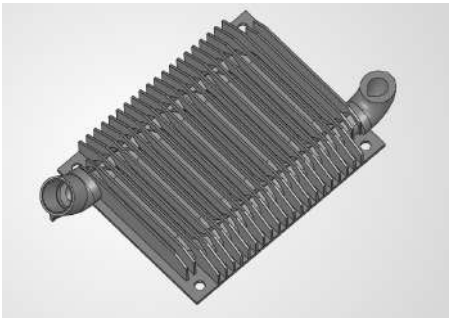


Fig. 33: Model of Heat Exchanger

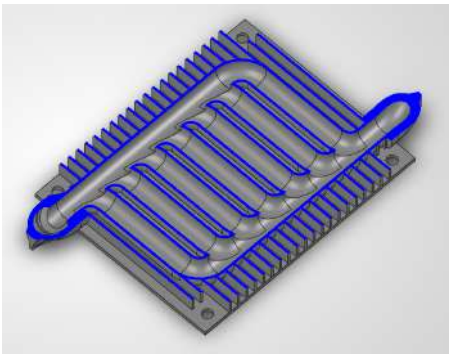


Fig. 34: Cross-Section of Model of Heat Exchanger

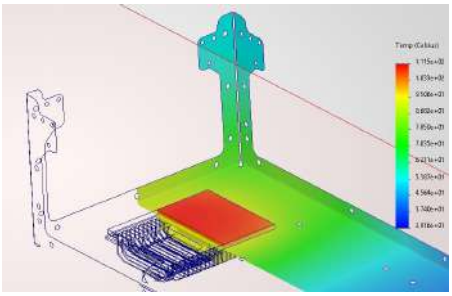


Fig. 35: Thermal Simulation of Heat Exchanger without seawater

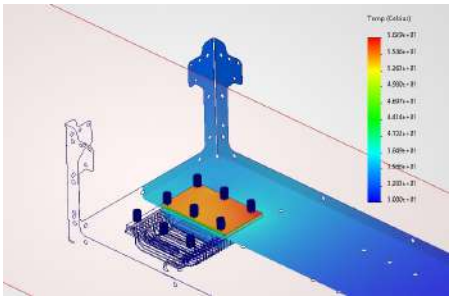


Fig. 36: Thermal Simulation of Heat Exchanger with seawater

APPENDIX F
BBAUV 5.0 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 identify 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 G.

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 vehicle-specific functionality test with a documented “criteria to clear” at every stage. Isolation is achieved using purpose-built test boards, together with standard bench equipment: 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 III: 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 IV: 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	**Vehicle 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 V, 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 G, 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 V: Incremental electrical integration test plan for the full stack, 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 the entire system from a single battery, then verify dual-battery load balancing with mismatched battery voltages	System powers up on one battery. Turning off one battery does not shut down the other or the system, and balancing holds under mismatched voltages
1.2	Telemetry screen power-on	Screen turns on and displays at least 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, and heartbeats appear and disappear correctly on insertion and removal
1.4	OCS telemetry and compute statistics	OCS receives and displays compute stack statistics (e.g. CPU temperature)
2	**Sensors**	
2.1	Observe sensor messages on the bus with CANable	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, and temperature probe readings published
3	**Lights + Actuation**	
3.1	Actuate connected lights via CANable	Lights respond to CAN commands
3.2	Actuate grabber via CANable	Grabber actuates as commanded
3.3	Fire torpedo via CANable	Torpedo launcher fires
3.4	Trigger dropper via CANable	Dropper releases
4	**Thrusters and Kill Chain**	
4.1	Command all thrusters at 0.1 duty cycle via CANable	All thrusters spin in the correct direction
4.2	Command all thrusters at 0.5 duty cycle via CANable	All thrusters sustain commanded thrust
4.3	Hard kill while thrusters are running	All thrusters stop within 1 s of kill-switch removal
4.4	Soft kill, then restore	Motors stop on soft kill, and all systems stay alive and recover after leaving the killed state
4.5	Power-cycle all channels	Every channel power-cycles cleanly and reports power-good status

Table V (continued).

#	Procedure	Expected Result
5	**Maximal Load Test (per board)**	
5.1	PSB maximal load: record V_{drop}, load-balancer, isolator and MOSFET temperatures, 12 V and 24 V ripple, and current cutoff	All metrics within limits, and current cutoff triggers at the configured threshold
5.2	PDB maximal load: same metrics as 5.1	All metrics within limits
5.3	ESCBP-L maximal load: MOSFET temperature, V_{drop}, voltage ripple	All metrics within limits
5.4	ESCBP-R maximal load: MOSFET temperature, V_{drop}, voltage ripple	All metrics within limits
6	**Functionality Test (compute + sensors)**	
6.1	Jetson power-on	Jetson boots and is reachable
6.2	Camera power-on and ping	Camera powers on and responds to ping
6.3	DVL A50 power-on	DVL powers on and streams data
6.4	3D sonar and 3-axis FOG bring-up	Sonar and FOG power on and stream data

APPENDIX G
BBAUV 5.0 ELECTRICAL INTEGRATION PROCESS AND TEST RESULTS

Following the validation methodology described in Section III-B2 and the test plans mentioned in Appendix F, 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 equipment 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 show 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. 37: 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 testing 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 38). 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 39. 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.

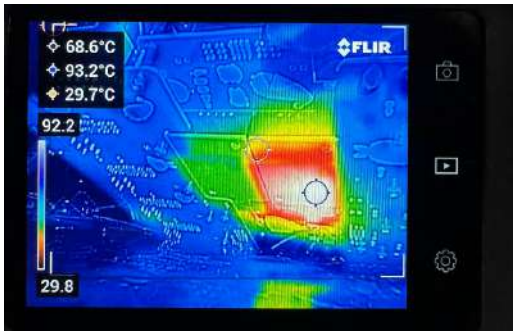


Fig. 38: Thermal image of the Power Distribution Board (PDB)

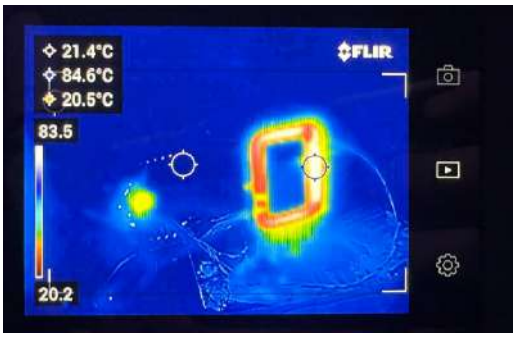


Fig. 39: Thermal image of Lights Indicator Board

Our next concern is power stability during transient currents. BBAUV 5.0 carries power-hungry components such as our in-house acoustics solution, the compute stack and the VESCs, which now run at much higher duty cycles. Isolated testing confirms that the load switches on the Power Switching Board and the ESC backplanes can handle the increased draw, but this does not guarantee the same performance once the boards are connected, because of dependencies such as the shared power chain. The incremental and full-stack integration tests are therefore essential to confirm that end-to-end power delivery is clean and stable.

With the full stack integrated, we check the supply to sensitive sensors by measuring each channel's output on an oscilloscope. For example, the Sonar power channel with no load and no thrusters running shows a peak-to-peak voltage ripple (V_{pp}) of 171 mV (Fig. 40). Loading the channel to its maximum rated current of 2.7 A with an electronic load does not increase the ripple, which instead decreases to 124 mV (Fig. 41). We stress test it further by driving the thrusters at their maximum rate of change, from 0 to 0.9 duty cycle, which produces a transient current spike of 17.5 A per thruster as measured in VESC Tool (Fig. 42). The resulting ripple, shown on the right, remains below the no-load value with a similar voltage profile (Fig. 43). This shows that power stability is maintained on all channels even under full load and transient conditions.

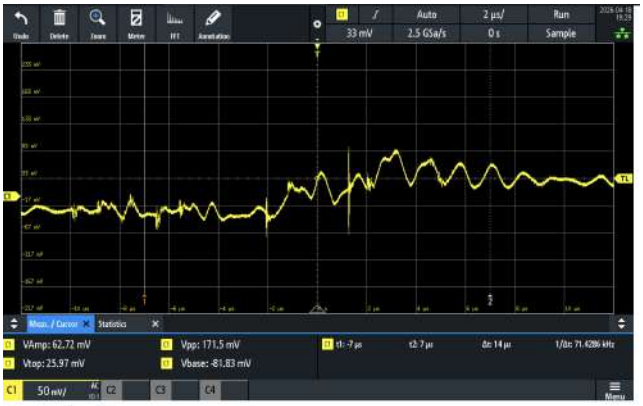


Fig. 40: Sonar power channel with no load and no thrusters (Vpp = 171 mV)



Fig. 41: Sonar power channel with full load (2.7 A, Vpp = 124 mV)

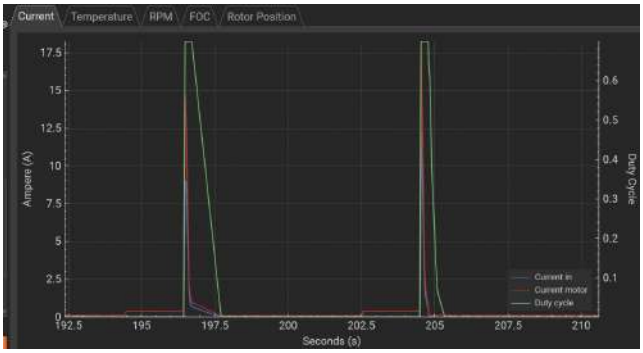


Fig. 42: Transient current spike of 17.5 A per thruster from VESC Tool Software



Fig. 43: Sonar power channel voltage ripples under full load and full thrusters

APPENDIX H
BBAUV 5.0 PRE-DEPLOYMENT TEST

TABLE VI: 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 indicate a leak. This process helps ensure the vehicle remains watertight and safe during the pool test.

APPENDIX I
BBAUV 5.0 SOFTWARE TEST PLAN

TABLE VII: Software verification and testing plan for BBAUV 5.0.

Component/ Capability	**Description**	**Methodology**	**Timeline (2026)**
Sensor-Level Drivers	Verify driver execution and coordinate frame conventions before main compute integration.	Drivers are unit tested on personal workstations, with configuration scripts for tuning parameters and frame offsets before deployment to the vehicle.	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.	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
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
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.	May – Jun
RoboSub System Validation	Validate the full system under competition conditions and verify the logic for the magnetic task.	Complete missions are run at RoboSub 2026, and the magnetic task logic is checked against the competition setup.	Jul
RobotX Task 2 Adaptation	Adapt the magnet plate for the pipeline light box and select the sonar for pipeline detection.	The magnet plate is tested on the light box replica, and the M750d and 3D-15 are compared against the pipeline replica at matched range.	Aug – Sep
Acoustic IVC and Pipe Following	Validate acoustic messaging to BBASV 5.0 and autonomous pipeline following.	Pool sessions check that decoded sequences reach BBASV 5.0 over the acoustic link while BBAUV 5.0 follows the pipeline replica.	Oct

APPENDIX J
BBASV 5.0 SOFTWARE TEST PLAN

TABLE VIII: Software verification and testing plan for BBASV 5.0.

Component/ Capability	**Description**	**Methodology**	**Timeline (2026)**
Sensor Bring-up	Verify drivers, networking and combined perception load before the hull is built.	Sensors and compute are mounted on a workshop trolley rig to confirm they share the network, measure data rates and profile the perception load.	March
Localisation	Validate GNSS-RTK fused with DLIO odometry.	The trolley rig is driven in repeated laps around campus to tune the fusion, then checked again in the pool.	April
Holonomic Control	Tune the controller and thrust allocation for four T200s and two M200s.	Gains are first trialled in Gazebo, then tuned in the pool by commanding surge, sway and yaw setpoints independently.	August
Obstacle Avoidance	Validate Nav2 planning with the STVL costmap through a buoy field.	Buoy fields are run in a Gazebo model of the Singapore River, then repeated in the pool and at RSYC with physical buoys.	August
Dock Detection and Entry	Validate bay detection, colour reading and entry without wall contact.	The OAK-D pipeline is tested on the docking-bay window replica, starting in simulation and moving to repeated approaches in the pool.	September
Water Cannon Targeting	Validate target tracking and aiming under vehicle motion.	The cannon is aimed at the target board while thruster wash disturbs the vehicle, and the targeting update rate is logged.	September
Inter-Vehicle Communication	Validate acoustic messaging with BBAUV 5.0 and Microhard messaging with Jellyfish 2.5.	Acoustic hand-offs are run with BBAUV 5.0 in the pool, and UAV hand-offs use a physical Jellyfish 2.5 with a simulated BBASV 5.0 over the real Microhard link.	October
Open-Water Validation	Validate behaviours under wind, current and waves.	Full autonomous runs at RSYC, repeating behaviours already proven in the pool.	October

APPENDIX K
FIELD TESTS AND STRATEGY ADJUSTMENTS

A. Sites and Logistics

Field testing is conducted at three sites. BBAUV 5.0 and BBASV 5.0 are tested in the Olympic-size pools of the National University of Singapore University Sports Centre (USC); BBASV 5.0 additionally in open water at our wet berth at the Republic of Singapore Yacht Club (RSYC), where wind, current and GNSS multipath from surrounding structures are present; and Jellyfish 2.5 at West Coast Park, where flight is permitted over open ground and water. Each session brings replicas of the competition elements built by our mechanical team (Figs. 44 and 45), power apparatus, the network reel and Operator Control Station (OCS), a network switch, tables and chairs, and hand tools. The RSYC berth removes the transport step for BBASV 5.0 between sessions, which is what made one open-water sessions feasible alongside the pool schedule as of writing this report.

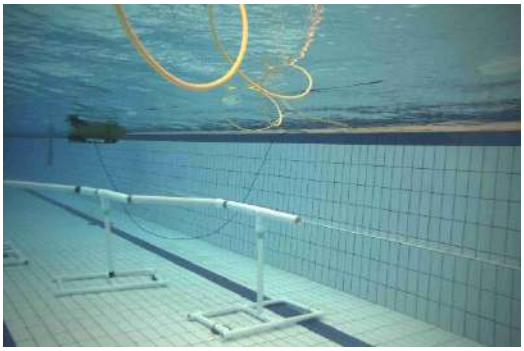


Fig. 44: Pipeline replica with switchable RED/GREEN segments.

B. Session Procedure

At RSYC, the vehicle is launched from the berth under manual control and held on station before autonomy is engaged, so that the first autonomous action is always a controlled one within tow-line reach. At West Coast Park, every flight is preceded by a geofence and return-to-launch check against the site boundary, and a second team member maintains visual line of sight throughout.

C. Findings and Strategy Adjustments

Beyond validation of individual software components (Appendix I), field tests reveal blind spots that only appear in full deployments. The findings to date that changed our approach are as follows.

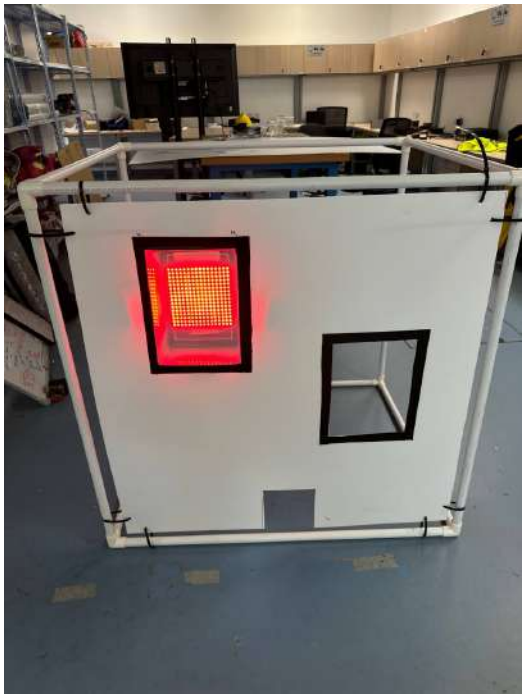


Fig. 45: Dock window replica for Task 3.

Task 2: 3D sonar versus forward-looking sonar. We tested the Water Linked 3D-15 and the Blueprint Oculus M750d against the pipeline replica at the same range. Beyond a few metres, the 3D-15 picked up too few points on the hollow pipeline to give a heading, while the M750d still showed a partial but usable outline out to 5 m. We therefore selected the M750d to give BBAUV 5.0 a heading towards the pipeline from range, with the camera taking over tracking once the vehicle is close.

Task 3: perception and cannon under disturbance. The physical dock window allowed colour-sequence decoding and window pose estimation to be tested under real lighting rather than in simulation, and exposed the interaction between cannon targeting and vehicle motion. With the vehicle station-keeping on water, the pan–tilt servo loop was verified to hold the target; this was the test that justified the OAK-D edge-perception pipeline over the 2024 LiDAR–camera approach.

APPENDIX L
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.

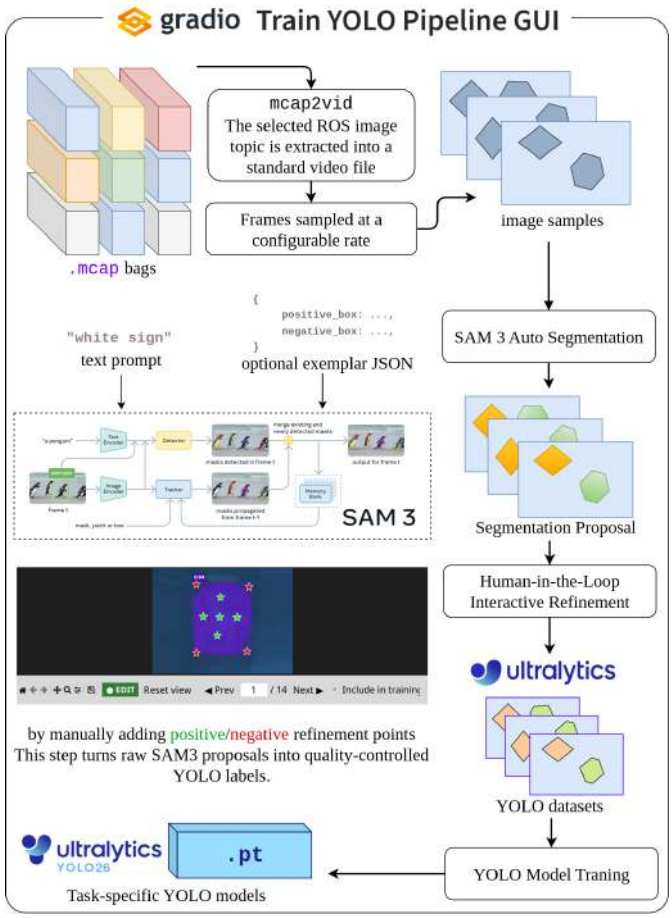


Fig. 46: Block Diagram of the SAM3-Aided MLOps Labelling Pipeline.

APPENDIX M
ARCHITECTURE BLOCK DIAGRAMS

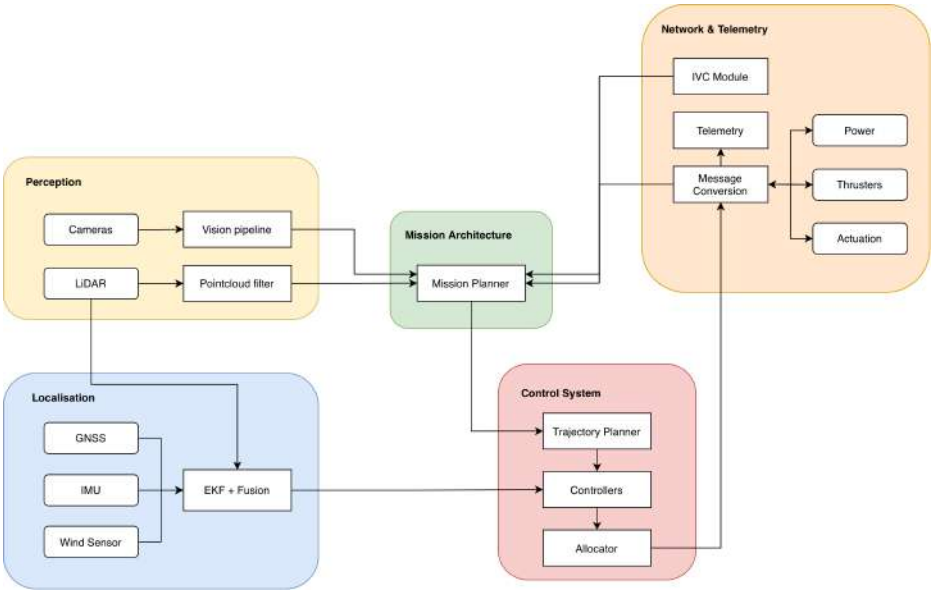


Fig. 47: High-level Overview of BBASV 5.0's Software Architecture.

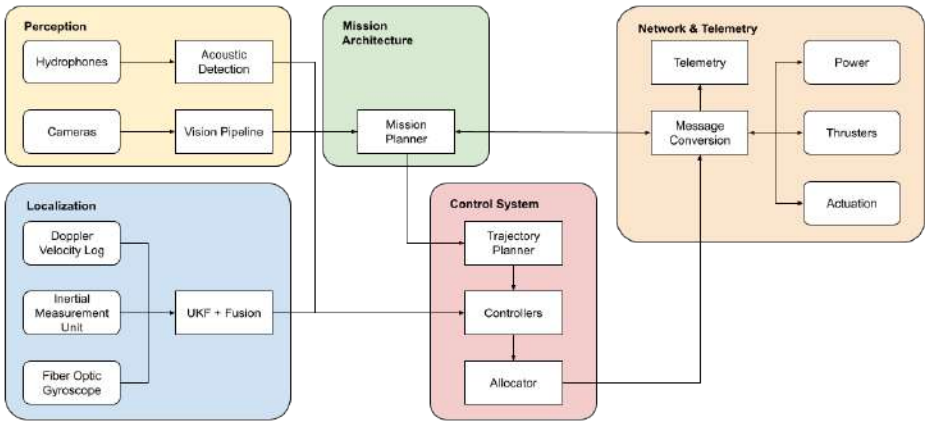


Fig. 48: High-level Overview of BBAUV 5.0's Software Architecture.

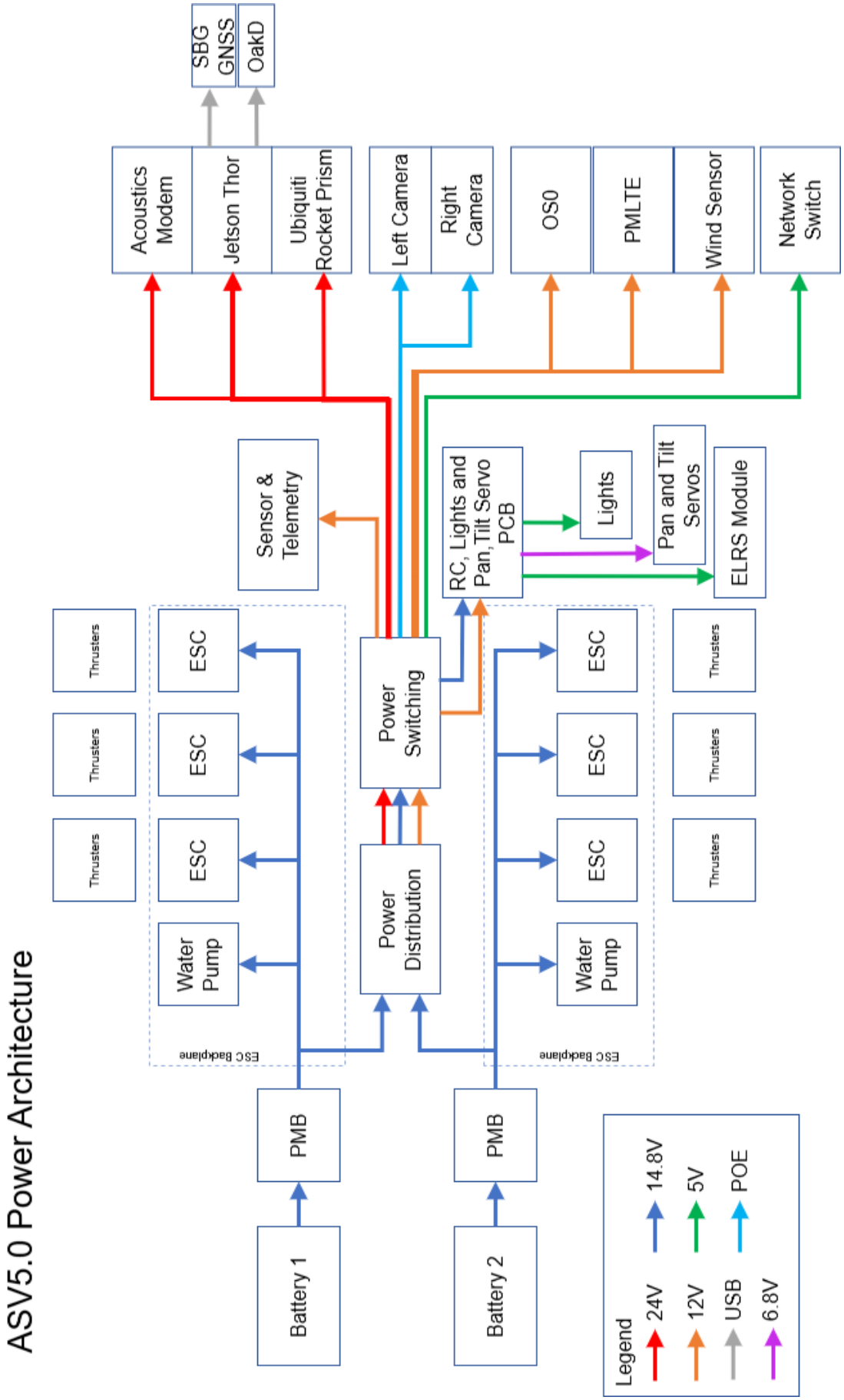


Fig. 49: BBASV 5.0 Power Architecture.

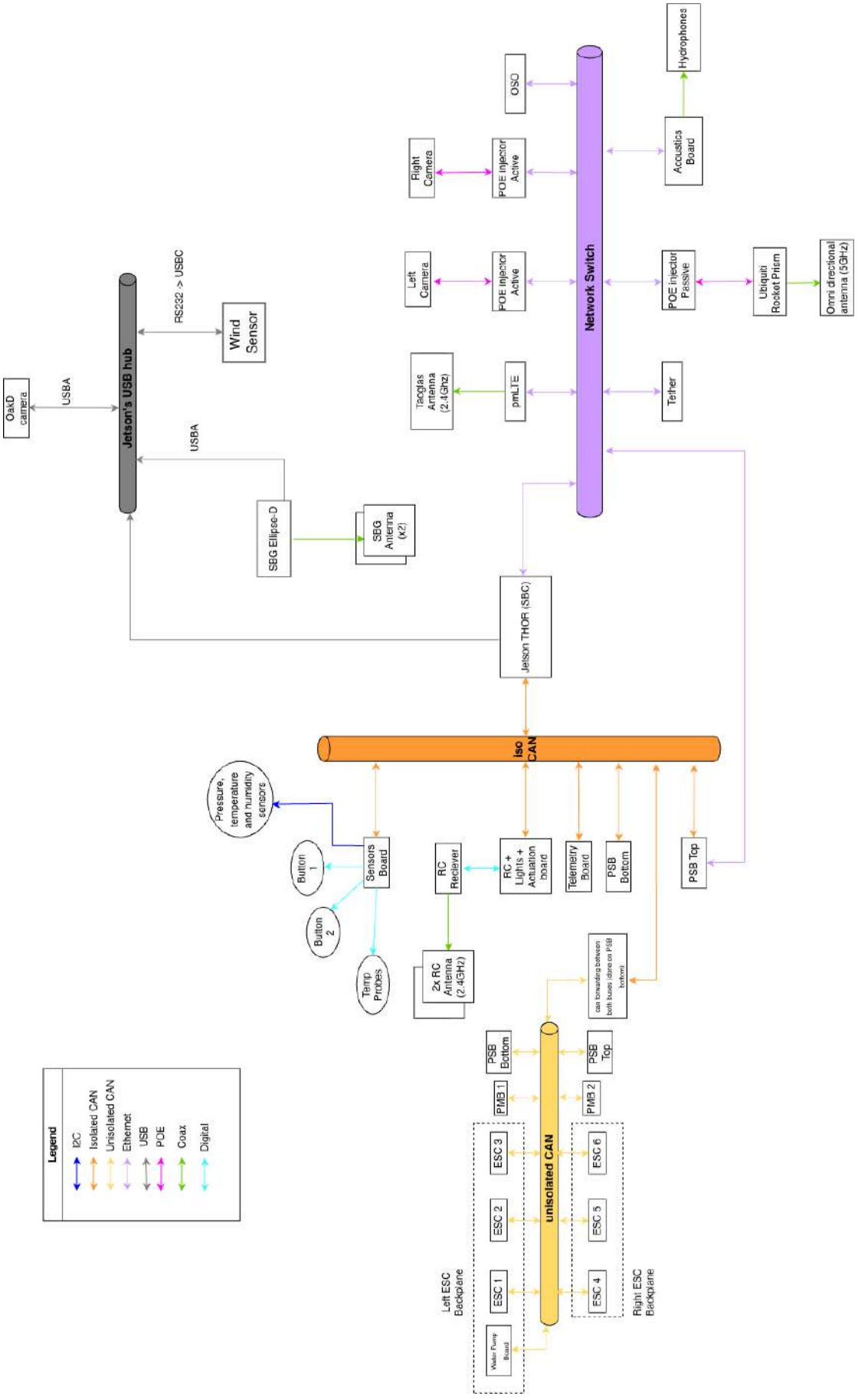


Fig. 50: BBASV 5.0 Communication Architecture.

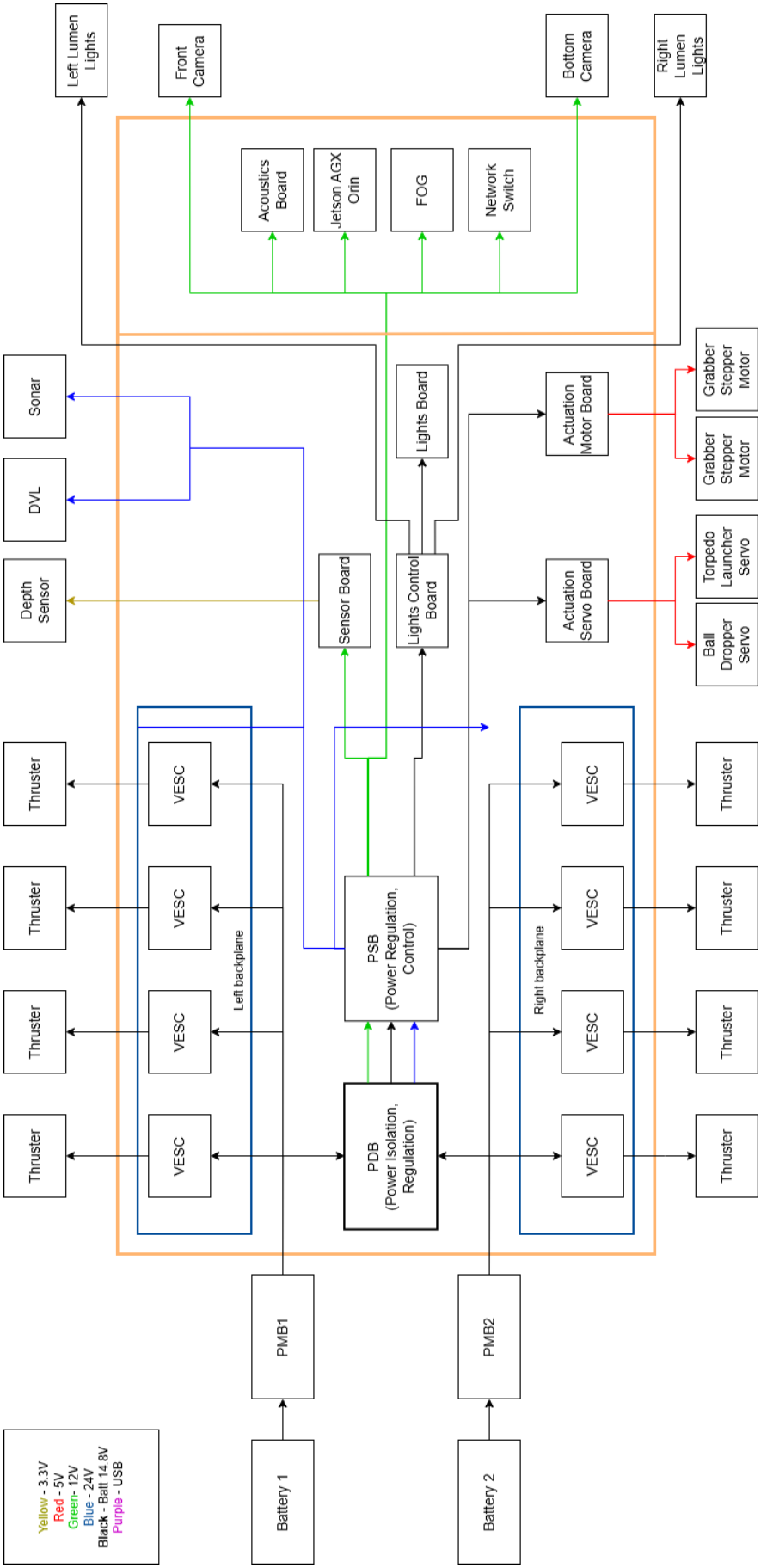


Fig. 51: BBAUV 5.0 Power Architecture.

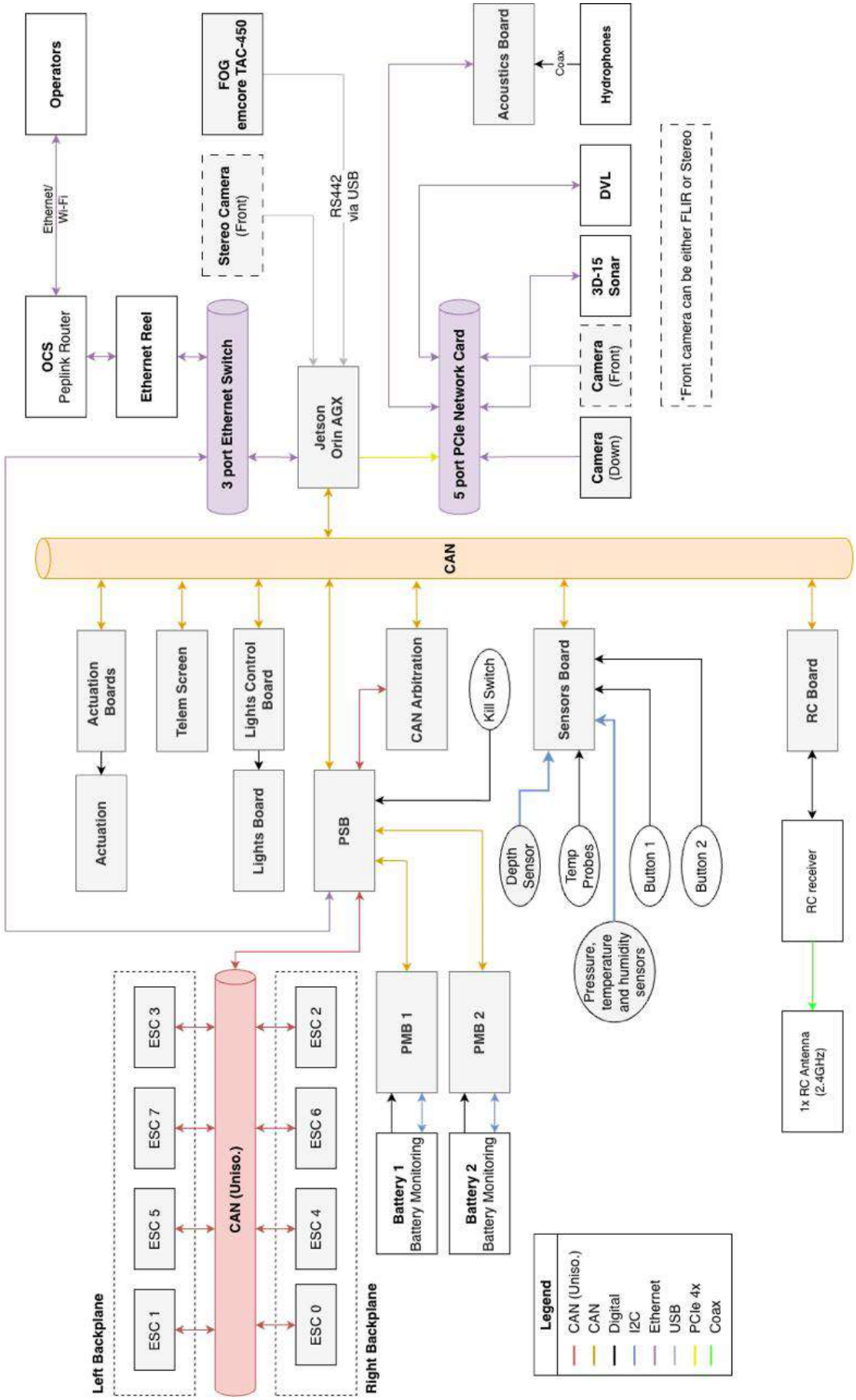


Fig. 52: BBAUV 5.0 Communication Architecture.

APPENDIX N
COMPONENT SPECIFICATIONS (BBASV 5.0)

Component	Vendor	Model / Type	Specifications	Custom / Purchased	Cost	Year of Purchase
Main Hull Base	Brown Metal Engineering	Custom Aluminium Sheet Metal Bending	Aluminium 5052	Custom	$250	2026
Main Hull Side Panels	Shen Zhen Firstek Co.ltd	Custom Carbon Fibre Milling	3K Matt Carbon Fibre	Custom	$150	2026
Pontoon Hull End Caps	Brown Metal Engineering	Custom Aluminium Sheet Metal Bending	Aluminium 5052	Custom	$130	2026
Pontoon O-ring Adapter	In-house	Fused Deposition Modelling	ABS	Custom	—	2026
Pontoon Battery Hulls	In-house	Fused Deposition Modelling	ABS	Custom	—	2026
Mast Assembly	In-house	Fused Deposition Modelling	ABS	Custom	—	2026
Thrusters	Blue Robotics	T200 (x4)	X configuration, 45° to vehicle axes, on carbon-fibre tube frame	Purchased	$260 ea	2026
	Blue Robotics	M200 (x2)	Stern, from base BlueBoat	Purchased	Sponsored	2026
Waterproof Connectors	MacArtney Group	Assorted Micro & Low-Profile SubConn Series	—	Purchased	Sponsored	2019
Hull Connectors	Amphenol Corporation	Assorted RJF TV, RTS & 97B Series Connectors	—	Purchased	$3,000	2023
Penetrators	Blue Robotics	Assorted Wetlink Penetrators	—	Purchased	$300	2025
Thruster Control	In-house	BEESC	6-layer PCB, current-sense tuned to thruster profile, USB-C debug	Custom	$100 ea	2026
Heat Exchanger	RapidDirect	Custom SLM print	AlSi10Mg; internal seawater channels; mounted under Jetson Thor	Custom	$230	2026
Water Pump	Mikroe	AW500S (x2)	One for heat-exchanger seawater loop, one for cannon supply	Purchased	$12 ea	2026

Water Cannon	In-house	Pump + pan/tilt assembly	AW500S pump (above); K-Power DM150W servos	Custom	—	2026
Pan/Tilt Servos	K-Power	DM150W (x2)	Cannon pan and tilt	Purchased	$13 ea	2026
Battery	Raitan	Molicel INR-21700-P42A	6P / 48 Ah	Purchased	$330 ea	2026
Battery Monitoring System	JLCPCB	In-house Custom-made Circuit Board	—	Custom	$200 ea	2026
Microcontrollers	STMicroelectronics	STM32F103C8T6	—	Purchased	$2 ea	2025
	—	STM32F407VET6	—	Purchased	$2 ea	2025
Compute Unit	RS Components	Nvidia Jetson Thor	120 W envelope	Purchased	$4,960	2026
LiDAR	Ouster & ST Engineering	OS0-128	128-Plane	Purchased	Sponsored	2019
INS	SBG Systems	Ellipse-D	Dual Antenna RTK INS	Purchased	Sponsored	2022
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
AprilTag Markers	Metal Prints Singapore	4x tags at pontoon corners	UAV relative localisation	Custom	$240	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
Power Switching, Lights Control, Internal Sensors, Telemetry Display, Actuation Interface, Comms. Conversion Boards	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	—	—
Shore Data Link	Ubiquiti	Rocket Prism 5AC (pair)	5 GHz Basestation	Purchased	$300 ea	2018
UAV / Mesh Data Link	Microhard	pMLTE-4GL-2450	2.4 GHz, IP-native mesh	Purchased	$480 ea	2026
Remote Control Link (kill)	Radiomaster	TX16S Mark II	2.4 GHz ELRS	Purchased	$250	2023
Radio Receiver	BetaFPV	SuperD ELRS	2.4 GHz ELRS	Purchased	$30	2023
Algorithm: Acoustics Localisation	—	—	Multiple Signal Classification (MUSIC), Short-Time Fourier Transform (STFT) based Ping Extraction	—	—	—
Algorithm: Vision	—	—	OpenCV, YOLO26, Point Cloud Library (PCL), Perspective-n-Point (PnP)	—	—	—
Algorithm: Localization & Mapping	—	—	Unscented Kalman Filter (UKF), Spatio-Temporal Voxel Layer	—	—	—
Software: Autonomy	—	—	Py Trees	—	—	—
Software: Framework	—	—	ROS2 Jazzy, Nav2, PyTorch	—	—	—
Team size	—	—	36	—	—	—
Hardware/ Software Expertise Ratio	—	—	2:1	—	—	—
Testing time: Simulation	—	—	100 hours	—	—	—
Testing time: In-water	—	—	100 hours	—	—	—

APPENDIX O
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	SER202X	—	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
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, YOLO26, XFeat	—	—	—
Algorithm: Localisation	—	—	Unscented Kalman Filter (UKF)	—	—	—
Software: Autonomy	—	—	Py Trees	—	—	—
Software: Framework	—	—	ROS2 Humble, PyTorch	—	—	—
Team size	—	—	36	—	—	—
Hardware/ Software Expertise Ratio	—	—	2:1	—	—	—
Testing time: Simulation	—	—	50 hours	—	—	—
Testing time: In-water	—	—	120 hours	—	—	—

APPENDIX P
COMPONENT SPECIFICATIONS (JELLYFISH 2.5)

Component	Vendor	Model / Type	Specifications	Custom / Purchased	Cost	Year of Purchase
Single Board Computer	Waveshare	Nvidia Orin NX 16GB	1 TB SSD, 16 GB 128-bit LPDDR5 DRAM	Purchased	$1,014	2024
Flight Controller	Holybro	Pixhawk 6X	STM32H753	Sponsored	$300	2024
GPS	Holybro	F9P	—	Purchased	$280	2026
Power Distribution	Mateksys	XCLASS PDB FCHUB-12S	—	Purchased	$30	2024
Data Link / Telemetry	Microhard	pMLTE-4GL-2450	2.4 GHz, shared mesh with BBASV5.0 and shore; carries MAVLink telemetry and ROS 2 traffic	Purchased	$480 ea	2026
Pilot Control Link	Radiomaster	TX16S Mark II	2.4 GHz ELRS	Purchased	$250	2026
Radio Receiver	BetaFPV	SuperD ELRS	2.4 GHz ELRS	Purchased	$30	2026
Camera (downward)	Arducam	IMX219	160° FOV	Purchased	$30	2024
Motor	T-Motor	505X integrated propulsion system	505S 380KV, Alpha 60A 6S ESC	Purchased	$250 per motor-ESC combo	2024
Battery	Raitan	Molicel INR-21700-P42A	6S2P / 8 Ah	Purchased		2026
Payload Actuation	In-house	Magnetic tin gripper	Upper magnet plate, lower pusher plate, 2 servos, TPU compliant mounts; fully 3D-printed	Custom		2026
Payload Servos			Drive pusher plate for release	Purchased		2026
Drone Shell	In-house	—	Multi-Jet Fusion 3D printed PA12 Nylon	Custom	$300	2024
Enclosure Cap	In-house	Ducted redesign	Inlet/outlet air ducts, CFD-verified airflow	Custom	—	2026
Carbon Fibre Frame	In-house	—	—	Custom	$100	2024
Flotation	In-house	—	—	Custom	—	2026

Algorithm: Perception	—	—	YOLO26, AprilTag	—	—	—
Software: Flight Controller Firmware	—	—	PX4	—	—	—
Software: Framework	—	—	ROS 2, uXRCE-DDS bridge to PX4	—	—	—

APPENDIX Q
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. 53: Lab visit by Professor Oussama Khatib.

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



Fig. 55: Our 2025 Sponsor Appreciation Event.

C. Hornet Training Programme

The Hornet Training Program is our hands-on engineering initiative for 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.

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 Singa-



Fig. 56: Visit to RSN.



Fig. 57: Hornet XI in action during Pool Test in 2026.

pore, including Republic Polytechnic, to share insights and discuss emerging robotic trends.



Fig. 58: 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. 59: 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. 60: Joint public showcase with OceanOneK at Singapore Oceanarium.