RobotX 2024 Technical Design Report

National University of Singapore (Bumblebee Autonomous Systems)

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***Abstract*—For RobotX 2024, Team Bumblebee will be deploying two vehicles, the BBASV 4.0 (USV) and Jellyfish 2.0 (UAV). Learning from the issues faced during deployment and testing from RobotX 2022, current vehicle designs are centered on reliability, monitoring, and operational ergonomics. Part of this includes improving telemetry reporting which accelerated troubleshooting and fixing of issues. This facilitated faster iteration and more extensive testing of core vehicle capabilities. Ballshooter and acoustics subsystems were also developed to enable our vehicles to attempt all tasks.**

I. Design Strategy

For RobotX 2024, we have redesigned our Unmanned Surface Vehicle, the BBASV 4.0, and our Unmanned Aerial Vehicle, the Jellyfish 2.0.

In RobotX 2022, the BBASV 3.0 repeatedly faced issues that could only be hot-fixed at the competition. We redeployed it as the BBASV 3.5 to serve as a temporary test platform for new boards and peripherals. Notably, this was part of our 1-year design plan to identify pain points and guide the design of its successor. Similarly, the Jellyfish 2.0 seeks to be more flexible and maintainable than its predecessor. Besides rectifying past issues, our design strategy emphasizes on reliability, maintainability, and operability. These factors boost development and testing efficiency, allowing for more capabilities to be developed in the long run.

Fig. 1: Render of BBASV 4.0.

A. USV – BBASV 4.0

The BBASV 4.0 (Fig. 1) has a modular design, with electronics being split across the Main Hull, Power Hull, Navigation Hull[1], and Actuation Hull. Although requiring more external connectors, this design choice allows for more development to be done in parallel, and simplifies component placement inside each hull. The two largest Main and Power Hulls feature a custom watercooling loop for thermal management.

The vehicle design targets many pain points relating to maintenance and deployment. For in-water testing in Singapore, our vehicle is wet-berthed with only one side of the vehicle being accessible via a floating platform (Fig. 2). This makes access to hulls and components challenging, and so more emphasis was placed on quality-of-life features that streamline our operations, minimize human error and maximize testing time.

Fig. 2: Wet-berth at our test site in Singapore.

1) WAM-V Modifications

Multiple modifications have been made to the WAM-V platform for greater accessibility and ease of operation.

Aluminium rails on either side of the payload tray act as mounting points for securing our mast and hull rollers. Sensors and antennas are mounted on the mast, which doubles as a landing platform for the Jellyfish 2.0 (see Sec. I-C1). The roller mechanism (Fig. 3) allows easier loading of the bulkier Main

[1] Abbreviated as the *Nav Hull*

and Power Hulls, and can be locked in the extended state for access to the hulls when berthed. When stowed, this is secured in place by a set of latches and ball-lock pins.

Two batteries provide power and are mounted on each pontoon. These are secured by battery cages which double as an elevated platform (Fig. 4) for safer access to the payload tray.

Fig. 3: Rollers for loading hulls on payload tray.

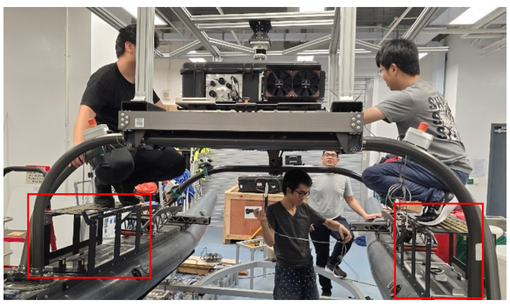

Fig. 4: Battery cages on pontoons (highlighted in red).

Actuated mounts for the hydrophones and thrusters (see Sec. III-B) have made our wet-berth deployments more convenient. While these actuated systems require extra development and integration efforts, in the long run, the faster deployment process saves us a lot of valuable in-water test time.

2) Thrusters

The BBASV 4.0 uses four thrusters, each mounted at a 45-degree angle from the centre line and thrusters all oriented towards the rear. This maximises our holonomic capability and was selected after extensive testing (see Sec. III-A) to find the most efficient configuration in terms of thrust and power consumption.

A six-thruster configuration for improved surge performance was initially explored, but was deemed too mechanically complicated to achieve.

3) Power

The POPB[2] (Fig. 33) in the Power Hull performs load balancing across both batteries and distributes power to the hulls. The Main Hull Power Board (MHPB; Fig. 27) splits this to sensors, the electrical stack in the Main Hull (Fig. 32), and the onboard PC. It also enables fine-grained power control to boards, offers over-voltage protection, and manages inrush current on power-up. More details for power distribution can be found in Fig. 26.

Power buttons controlling the batteries and the onboard PC can be found on the hulls for easy power cycling. These are found portside along with the telemetry screen on the Main Hull. This greatly minimizes the need to rotate the vehicle when berthed, which is typically only done to replace the batteries. Even so, downtime is kept to a minimum as the POPB allows for hotswapping of batteries and testing to be done concurrently.

4) Connectivity

Our hulls are connected with weather-resistant cable harnesses that transport both power and data. We utilize both a Controller Area Network (CAN) and an Ethernet network across the hulls for data transmission. For waterproof connectors, we chose the Amphenol ecomate series in favour of their durability and crimp termination, which has significantly reduced the time and effort for assembly compared to their solder-cup counterparts.

Our custom electrical boards communicate over CAN (refer to Fig. 25), building upon our vast ecosystem of CAN-enabled PCBs and firmware libraries. This serves as the backbone for transmitting data such as telemetry and thruster controls. Ethernet is used for interfacing with third-party sensors like the cameras and LiDARs, as well as a Ubiquiti access point. This access point enables wireless connection to our workstations and our Operator Control Station, the OCS3. These are connected to our onboard PC in the Main Hull via a managed network switch (Fig. 24), allowing for the use of 802.1Q VLAN tagging and Link Aggregation Control Protocol (LACP) for network segregation and physical redundancy.

For versatility, our onboard PC uses a consumer-grade CPU and motherboard. This has no in-built CAN interface, and is instead bridged to our CAN bus by our Logic Backplane board (Fig. 29) via a USB connection. Consistent Overhead Byte Stuffing (COBS) [1] and a Fletcher Checksum [2] are used to verify data integrity and enable self-recovery from corrupted transmissions. An Ethernet module on the board is also used to selectively forward telemetry from the CAN bus to the Ethernet network (see Sec. I-B).

5) Inter-vehicle Communication

To wirelessly coordinate between vehicles, we use the RFD900x modem across 3 different systems – the BBASV 4.0, Jellyfish 2.0, and OCS3 (for capturing telemetry data). An all-in-one adaptor board (Fig. 38) allows drawing power over 24 V or USB-C, and enables data from the modem's UART port to be forwarded over RS-232 or USB data lines. This shared interface simplifies integration into the multiple systems, as well as the preparation of spares.

A low-latency driver provides a ROS 2 interface to the modem for ease of integration with our software stack. This driver incorporates a lightweight protocol with reliability mechanisms such as error checking and automatic re-transmission.

[2]Plenty-of-Power Board – a tribute to the power board in the BBASV 3.0

6) *Acoustics*

The acoustics stack comprises of our custom acoustics board (Fig. 35) and a commercial off-the-shelf (COTS) data acquisition (DAQ) board for sampling hydrophone data. The hydrophones are arranged in a tetrahedral configuration and connected to the acoustics board in the Nav Hull via LEMO connectors. Inputs are amplified and passed through a tenth-order active bandpass filter (Passband: 25-40 kHz) before being sampled by the DAQ. This synchronized channel data is then processed by the Nav Board.

We use Goertzel's algorithm [3] and a signal-to-noise ratio (SNR) check to detect pinger signals. Subsequently, the Multiple Signal Classification (MUSIC) algorithm [4] is used to estimate a direction of arrival (DOA) and elevation angle. To mitigate the effects of multipath signals, estimates corresponding to unrealistically large angular changes are discarded.

Fig. 5: Interactive visualization of acoustic data.

To aid debugging and tuning, we have refined our data recording pipeline. We now use the Parquet format for its space-efficiency with large datasets, and developed an interactive front-end for easy visualization in the time and frequency domain (Fig. 5).

7) *Ballshooter*

We revisited and optimized several flywheel designs for launching the racquetballs. Inconsistent shooting of wet balls was remedied by using two textured flywheels. Each flywheel weighs 0.7 kg and spins at 3400 rpm in order to achieve muzzle velocities of up to 70 kph.

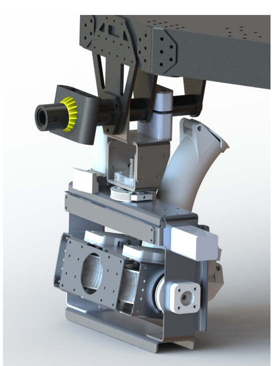

Fig. 6: Mounted Ballshooter.

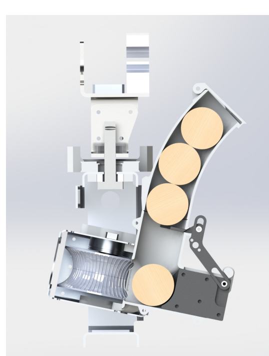

Fig. 7: Piston & Cam Mechanism.

The pan-and-tilt system allows two degrees of freedom for target tracking and stabilization. These axes use two stepper motors driven by StallGuard technology to enable sensorless homing. The loader system holds 4 balls and uses a piston to push each ball into the flywheel when firing. A gate, synchronized to the piston via a cam mechanism (Fig. 7), prevents movement of the remaining balls.

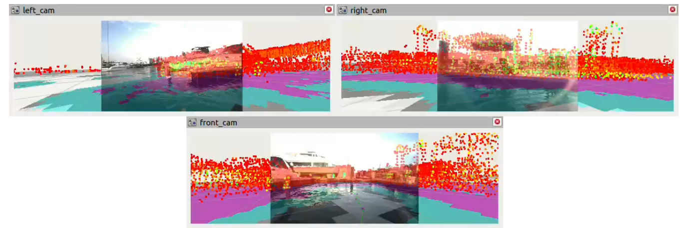

Fig. 8: Camera views (clockwise from top left: left, right, front). Coloured points overlaid on images represent fused LiDAR data.

8) *Software Stack*

The software architecture supporting BBASV 4.0 is built upon the ROS 2 (Robot Operating System) framework [5], chosen for its modularity and extensive library of tools tailored to robotics applications. This architecture enables seamless integration of various sensors, controllers, and perception systems, forming a robust and adaptable platform for autonomous navigation and decision-making. Our software system has undergone several improvements since RobotX 2022, addressing key challenges encountered in the previous competition. These updates enhance our vehicle's localization, perception, and navigation capabilities, ensuring reliable performance in complex maritime scenarios that we expect to see during RobotX 2024.

a) *Localization*

Our localization pipeline has been upgraded to address several issues, in particular, the unreliable GNSS data. Instead of relying solely on a GNSS/IMU approach, we have integrated an odometry estimate directly derived from LiDAR sensors [6]. This has proven to be reliable and significantly enhanced station-keeping capabilities. Given the presence of static landmarks within the effective range of our LiDARs throughout the course, we are confident this will hold up at the competition venue.

b) *Perception*

The perception subsystem has undergone a comprehensive redesign, moving from a wide-baseline stereo configuration to a setup employing three monocular cameras. The combined 260-degree field-of-view (Fig. 8) maximizes visual coverage and facilitates better fusion with LiDAR data.

Given the importance of reliable perception for navigation and obstacle avoidance, our camera mounts allow for quick adjustments to camera angles. In the event of LiDAR failure, the cameras can be reoriented into a stereo setup to maintain depth perception. This versatility enhances real-time adaptability and reinforces the robustness of our perception subsystem.

Both LiDAR and camera inputs are fed into several state-of-the-art models for object detection and recognition. Our updated image processing pipeline supports models like YOLOv10 [7] and GroundingDINO [8], in addition to the existing YOLOv8 [9] and classical computer vision techniques.

We employ a multi-faceted approach to sensor fusion, relying on monocular depth perception to fill the blind spots of our LiDARs. LiDAR detections are tracked and combined with object proposals from the monocular cameras via late fusion. The use of LiDAR's bird's-eye view (BEV) modality provides additional information for detection and cloud segmentation (Fig. 9), enhancing redundancy in case any estimation method underperforms. Our fusion pipeline also utilises various clustering algorithms to estimate higher-level structures within the competition arena. This signficantly enhances our gate-identification capabilities for tasks like *Dynamic Navigation*, *Entrance and Exit Gates*, and *Follow the Path*.

Fig. 9: LiDAR BEV detection (in simulation).

c) Controls and Navigation

Building on the robust controller architecture from previous vehicles, we have added support to our control system for dynamic selection of thruster layouts and seamless switching between different controllers. This flexibility allows us to rapidly prototype and test controller implementations, allowing us to find optimal solutions for the BBASV 4.0.

We have integrated the Nav2 framework [10] into our navigation pipeline, leveraging advanced features such as the Spatio-Temporal Voxel Layer [11] for efficient obstacle tracking. Our navigation system incorporates multiple global planners, including the SMAC State Lattice Planner and Visibility Voronoi [12] planners, to ensure effective collision avoidance and improved overall performance. These new capabilities enable the vehicle to navigate complex environments with greater precision.

B. Remote Control & Telemetry

The ASV Remote Control (ASVRC) enables control over various parts of the vehicle, including thrusters, actuated deployment systems, and power to individual components. On-screen telemetry is complemented by voice alerts and haptic feedback, ensuring operators are always aware of changes in key indicators. General telemetry data is also accessible by a wide range of other displays.

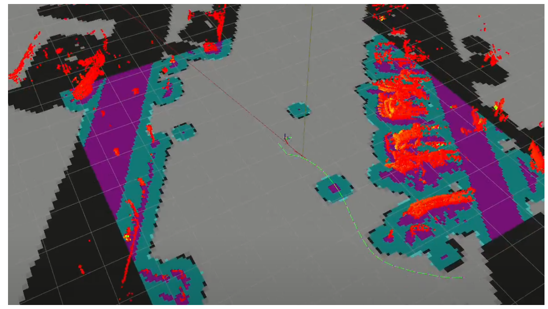

Fig. 10: LiDAR point cloud (red) and local costmap (purple) demonstrates the vehicles mapping and navigation capabilities.

From testing the BBASV 3.5, we recognized the challenges of debugging transient power- and thermal-related issues. In anticipation of this, we added thermocouples and more power management ICs to assist in isolating issues when they crop up.

We have implemented redundant telemetry reporting across multiple layers, ensuring we have vital information for troubleshooting, even in the event of an onboard PC or network failure. We have implementations to display telemetry using each layer:

- ROS 2 – Software subteam's tooling
- Network – OCS3 screen and ASVRC (Fig. 11)
- CAN – Main Hull telemetry screen (Fig. 12)

Fig. 11: ASVRC Display.

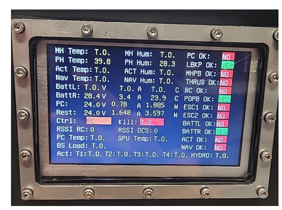

Fig. 12: Main Hull Display.

A Telegram Messenger bot also periodically broadcasts battery-related telemetry for greater visibility. This has proven useful for coordinating the movement and charging of other batteries.

C. UAV – Jellyfish 2.0

The Jellyfish 1.0 was built on a DJI Matrice 210, retrofitted with a rainproof shell for mounting external peripherals. Due to its proprietary nature, mechanical repairs and integration with the drone's software was difficult. The added weight of the shell also significantly reduced flight time to 10 minutes.

The Jellyfish 2.0 was built from scratch to address these concerns and offer more flexibility in mechanical design and software integration. The external Nylon shell, fabricated using Multi Jet Fusion (MJF) 3D printing, envelops a carbon fibre frame. This provides structural support and protects the electronics from weather elements. Energy-dense lithium-ion batteries are housed in two Nylon battery hulls that are secured to the shell with clips (Fig. 14). With a wingspan of 0.96 m,

Fig. 13: Render of Jellyfish 2.0.

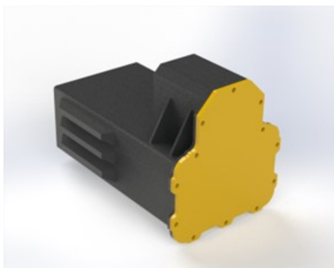

Fig. 14: Render of Jellyfish 2.0 Battery Hull.

the fully-laden Jellyfish 2.0 weighs in at 6.8 kg and offers twice the flight time of its predecessor.

Flight controls are managed with a Pixhawk 6X using the open-source PX4 firmware. An Orin NX handles computations, object detection, and mission execution built on top of ROS 2. Integration with peripherals was done using the uXRCE-DDS middleware which utilizes the uORB messaging API to expose messages from the PX4 firmware as regular ROS 2 topics.

1) Landing Platform

The dimensions of the landing area on the BBASV 4.0 have been enlarged with the redesign of its mast. A large canvas with AprilTag markers [13] is used to estimate the relative pose of the Jellyfish 2.0 (Fig. 15). Multiple marker sizes are used to aid with detections at a range of distances.

In far-range behaviour, the drone initiates a search pattern starting from the GPS coordinates transmitted from the BBASV 4.0. Marker detections and the estimated poses are then used by the the mission planner, which continually adjusts the drone's trajectory as it approaches the landing platform.

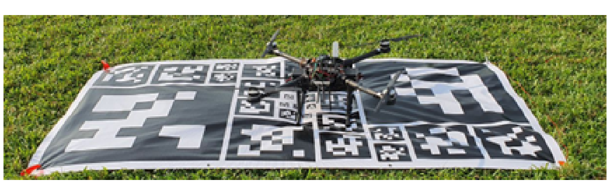

Fig. 15: Canvas with AprilTag markers.

II. Competition Strategy

Due to limited space and resources for physical testing, we conduct a lot of testing in simulations using our customized fork of Gazebo Harmonic. This serves as a testing stage for new algorithms and quick identification of issues in our perception and navigation pipelines. When we move to in-water testing, we focus on understanding real-world deviations of behaviour instead of testing the whole mission flow. We adhere to similar principles for the Jellyfish 2.0.

However, it is difficult to fully anticipate how differences in environment will affect our vehicles. Before we commit to attempting a task, we will perform preliminary testing at the competition venue. This will be used to narrow our strategy using cost-benefit analysis, as there is insufficient time to complete all tasks. In terms of points, it may also not be worth the higher development and testing cost to perfect some tasks.

To factor in dynamic conditions during autonomous runs, the BBASV 4.0 uses a task planner which formulates the subtasks as a constrained optimization problem. Tasks are quantified based on the maximum achievable points, estimated attempt duration, success rates, and sequential dependency on other tasks (like *Scan the Code*).

We prioritize allocation of manpower and testing time for core capabilities such as stationkeeping, instead of task-specific ones like the ballshooter. The development of the Jellyfish 2.0 is an exception; although it is a large drain on resources, it also significantly increases the amount of achievable points. To streamline development, a self-sufficient drone subteam was established. With careful management and periodic integration between the two vehicles, development was effectively parallel and did not hamper progress for the BBASV 4.0.

Even though most of our members are undergraduates, we confidently expand our capabilities and strive for continuous innovation, trusting in the passion and competence of our members. The Hornet Training Programme (see Sec. H-C) is the backbone of this, equipping new members with the foundational knowledge of maritime robotics and hands-on experience, allowing them to contribute considerably even from the outset.

III. Testing Strategy

Simulation tools such as SOLIDWORKS and LTspice are used to verify our designs before fabrication. Across the subteams, we test mechanical assemblies, electrical boards, and software components individually before integrating with other functional parts. For our firmware and software, we have also adopted continuous integration to automate baseline checks.

Integration is first done in the lab with a hardware twin – 3D prints are used for test fitting, and spare electrical boards for verifying firmware or hardware changes. This is especially important for the BBASV 4.0, as it remains docked throughout the testing cycle.

Before each in-water or in-field test, a list of testing goals are formulated to ensure testing remains on track. Included in this section are key test plans that have shaped our development and test cycles.

A. Thruster and Configuration Selection

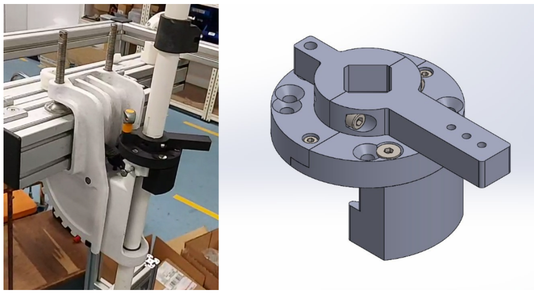

Fig. 16: Thruster setup (left) and render of mounting mechanism (right).

Other thruster models were procured to benchmark against our current Minn Kota trolling motor. A test rig was constructed, featuring a rotatable mechanism to adjust thruster mount angles (Fig. 16). A load cell was attached to the hinge hold the thruster to measure the forces exerted while varying the Electronic Speed Controller (ESC) input. From this, the thrust was calculated based on the principle of moments (Table III). Combinations of thruster mounting angles and orientations were tested to measure their average power draw (Table IV).

Based on these tests, we decided to remain with our original thruster model. A new set were acquired to replace the old thrusters, as they have been in use since 2016 and have experienced much wear and tear.

B. Actuated Thrusters

Motors lifting the thruster were selected to ensure they were capable of bearing the load of the assembly (12 kg) with a factor of safety of 1.3. These were extensively tested to bear 16 kg over 24 hours with no discernible deviation from its initial position.

Thruster rotation is aided by a 80 : 1 ratio worm gear, providing a torque multiplier of over 25 times at a conservative mechanical efficiency of 0.3 [14]. This also protects the sensitive encoder by preventing back-driving.

C. Power Subsystem

Each power channel was load-tested up to its rated current limit, where key parameters such as voltage drop, ripple percentage, temperature rise, and efficiency were monitored. This ensured that each power channel could handle its designated load while maintaining electrical performance within acceptable ranges.

These tests also proved useful in identifying issues such as accidental shutdown from MCU resets, which would otherwise have been more challenging to identify after integration. More details can be found in Appendix B.

D. UAV Test Platform

Moving away from the Jellyfish 1.0's DJI-managed control, we expected more accidents to occur with its successor's untested control stack. A minimal drone was constructed, possessing only a rough skeleton for mounting peripherals, to serve as a test platform for novel behaviours. This introduced some development overhead to tune a separate drone and verify feature parity, but greatly lowered the risk of crashing the Jellyfish 2.0, which is much more expensive and difficult to repair.

This approach enabled the drone subteam to be more comfortable in testing high-risk scenarios. For example, autonomous landing with a rapidly moving landing platform. Only after passing increasingly stringent test criteria (e.g., aligned landing → tracking landing target → automatic abort) do we test on the Jellyfish 2.0 with a similar progressive test plan.

ACKNOWLEDGEMENTS

Team Bumblebee's development and achievements would not be possible without the help from various organisations and people.

We are deeply grateful to Tan Annie and Cheah Kok Keong for their unwavering administrative support, and Dr. Goh Cher Hiang and Graham Zhu for their technical guidance. We would also like to thank Justin Seow and Tan Jun Hao Ivan for managing the Hornet Programme, as well as Hou Lin Xin, Than Duc Huy, and Troy Tim for their assistance in producing media for the team. The team would also like to thank Gabriel Tan for going above and beyond in providing assistance and technical advice on various cable assemblies, as well as Niu Xinyuan for providing invaluable advice on our controls stack. Team Bumblebee would also like to express our deepest gratitude to our sponsors listed in Appendix A.

Fig. 17: Team Bumblebee.

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APPENDIX A
SPONSORS

A. Title Sponsors

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

B. Platinum Sponsors

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

ST Engineering — For providing the Ouster OS0 LiDAR on BBASV 4.0.

DSO National Laboratories — For cash support.

Republic of Singapore Yacht Club — For providing a testing location and wet berth for the BBASV 4.0.

Altium — For providing software licenses.

C. Gold Sponsors

Bossard, Fugro, Kentronics, MacArtney, SBG Systems, SLM Solutions and Würth Electronik.

D. Silver Sponsors

Festo, MEDs Interconnect, Samtec, Solidworks, Southco, Avetics and Bossard.

E. Bronze Sponsors

Blue Trail Engineering, Kraus & Naimer, Lionsforge, Pololu, TGN Technology and Waterlinked.

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

- **POPB**: Power Hull Power Board
- **MHPB**: Main Hull Power Board
- **DAQ**: Data Acquisition Board (Acoustics)
- **ASVRC**: Remote Controller of our USV (Radiomaster TX16S Mark II)
- **OCS**: Operator Control Station (OCS3 / OCS1 backup)
- **Telem**: Short-form for telemetry data (key vehicle stats and data)
- **Jellyfish**: Bumblebee's Unmanned Aerial Vehicle
- **MCU**: Microcontroller Unit on various electrical boards
- **PSU**: Power Supply Unit for the custom PC

Appendix B
Main Hull Power Board Validation

Each power channel can be controlled individually and monitored by the MHPB, which allows for power sequencing to be implemented. This reduces inrush current and consequently lowers the electrical stress on key components. Sequencing also allows for power statuses of critical components, such as the fans and the water pump, to be verified before other components are turned on. Additionally, an on-board warning buzzer is installed to warn users in the event of a fault.

Power components that were chosen for the MHPB include 24 V load switches, synchronous buck converters for 12 V / 5 V, and a COTS 54 V boost converter. These all featured slow rise times to limit in-rush current during power-up. Some of these components feature hiccup-mode protection, while others turn off completely in fault conditions. To support fault recovery, the MCU re-enables the channels after a set period.

To verify each feature, comprehensive tests were carried out on the MHPB with a load tester. Key metrics such as voltage drop, ripple percentage, and switching frequency were measured with an oscilloscope across test points on the board:

- Temperature: Hottest temperature and component in the region was also noted down (shown in brackets)
- Voltage Ripple: Defined as Vpp / Target; an acceptable range is within 5%
- Efficiency: Defined as $(V_{\text{out}} \times I_{\text{out}})/(V_{\text{in}} \times I_{\text{in}})$; an acceptable range is $> 85\%$, with $> 90\%$ being exceptional

The results of the load tests conducted on the 12 V power channels can be found in Tables I and II.

Based on the tests and component specifications, it was concluded that the 12 V power channels could handle a step load from 0-4 A to a sustained 4 A load, and were capable of hot-plugging without any adverse effects on the performance or integrity of the channels.

Load Curr (A)	**0**	**2**	**3**	**4**
PSU Current (A)	0.03	1.05	1.58	2.12
Voltage (V)	11.98	11.9	11.85	11.8
Vpp (mV)	-	0.4	0.4	0.4
Switching Freq. (kHz)	-	-	508.9	507.6
Temp. (°C)	-	52 (buck)	70 (buck)	98 (buck)
% Ripple	-	0.4	0.4	0.4
% Efficiency	-	94.45	93.75	92.77

TABLE I: Load Test Results for Fan + Pump 12 V Channel.

Load Curr (A)	**0**	**2**	**4**
PSU Current (A)	0.03	1.1	2.1
Voltage (V)	12.01	11.9	11.8
Vpp (mV)	-	16	16
Switching Freq. (kHz)	-	496	496
Temp. (°C)	42 (buck)	57 (buck)	105 (buck)
% Ripple	-	0.32	0.32
% Efficiency	-	90.3	93.81

TABLE II: Load Test Results for Logic Backplane 12 V Channel.

Appendix C
Thruster Testing Results

ESC Input	**Thrust (N)**		
	Minn Kota	**Newport**	**Copenhagen VL**
200 (20%)	24.00	129.75	15.58
400 (40%)	81.75	141	75.08
600 (60%)	161.25	177.75	185.58
800 (80%)	240.00	196.5	276.25
1000 (100%)	314.25	258	272.00

TABLE III: Measured thrust across thruster models as a function of ESC input.

Thruster configurations in Table IV are specified in the format *Fore Thrusters / Aft Thrusters*, with the number indicating thruster mount angle from the center line, and $(+)$ / $(-)$ referring to thrusters oriented towards the fore / aft respectively. See Fig. 18-21) for an illustration of these configurations.

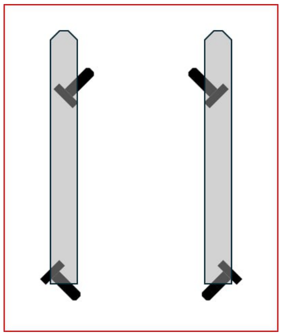

Fig. 18: 45- / 45+ configuration.

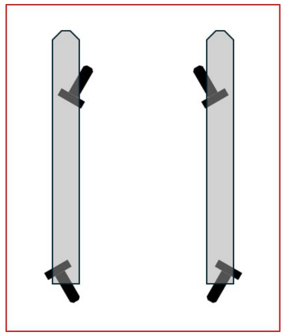

Fig. 19: 30- / 30+ configuration.

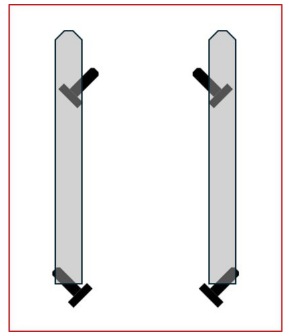

Fig. 20: 45- / 45- configuration.

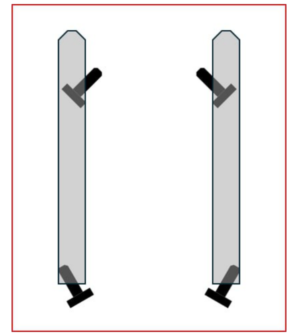

Fig. 21: 45- / 30- configuration.

Configuration	**Power Consumption (W)**						
	Stationkeep	**Surge (+)**	**Surge (-)**	**Yaw (R)**	**Yaw (L)**	**Sway (R)**	**Sway (L)**
45- / 45+	140.41	1611.6	1630.8	2717.4	1653.8	2704.4	2665.3
30- / 30+	369.80	1081.2	1057.8	2270.6	2111.4	2755.1	2585.7
45- / 45-	209.79	975.41	2251.5	2465.9	1949.5	2828.5	2606.8
45- / 30-	166.17	1010.4	2413.3	2404.6	2630.9	2663.8	2340.0

TABLE IV: Power consumption for various configurations. The current configuration is 45- / 45-.

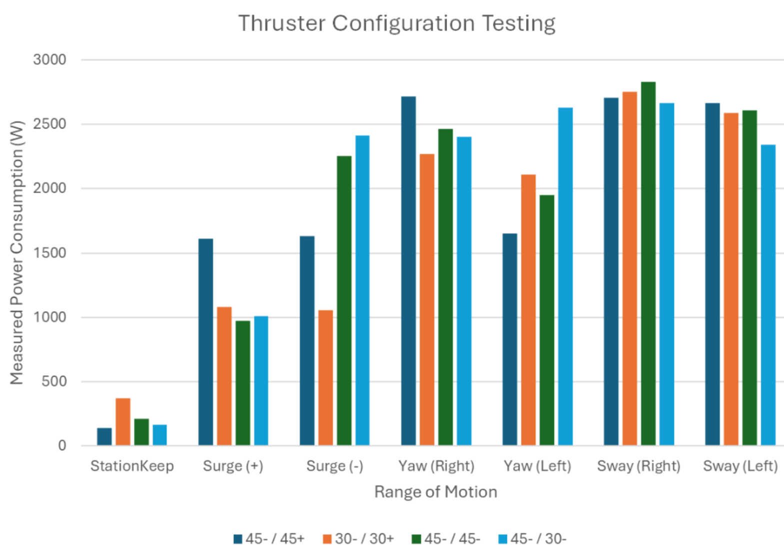

Fig. 22: Comparison of power consumption across thruster configurations.

Appendix D
Architecture Block Diagrams

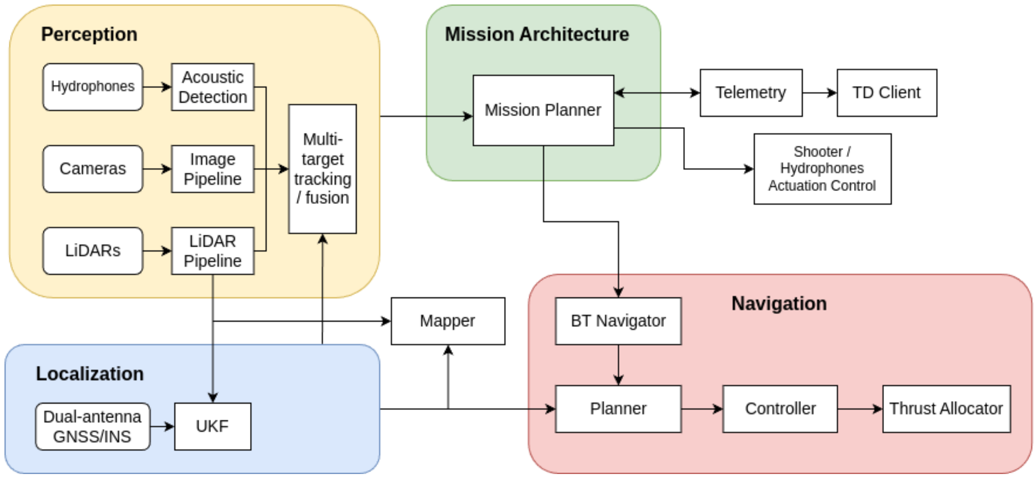

Fig. 23: High-level overview of BBASV 4.0's software architecture.

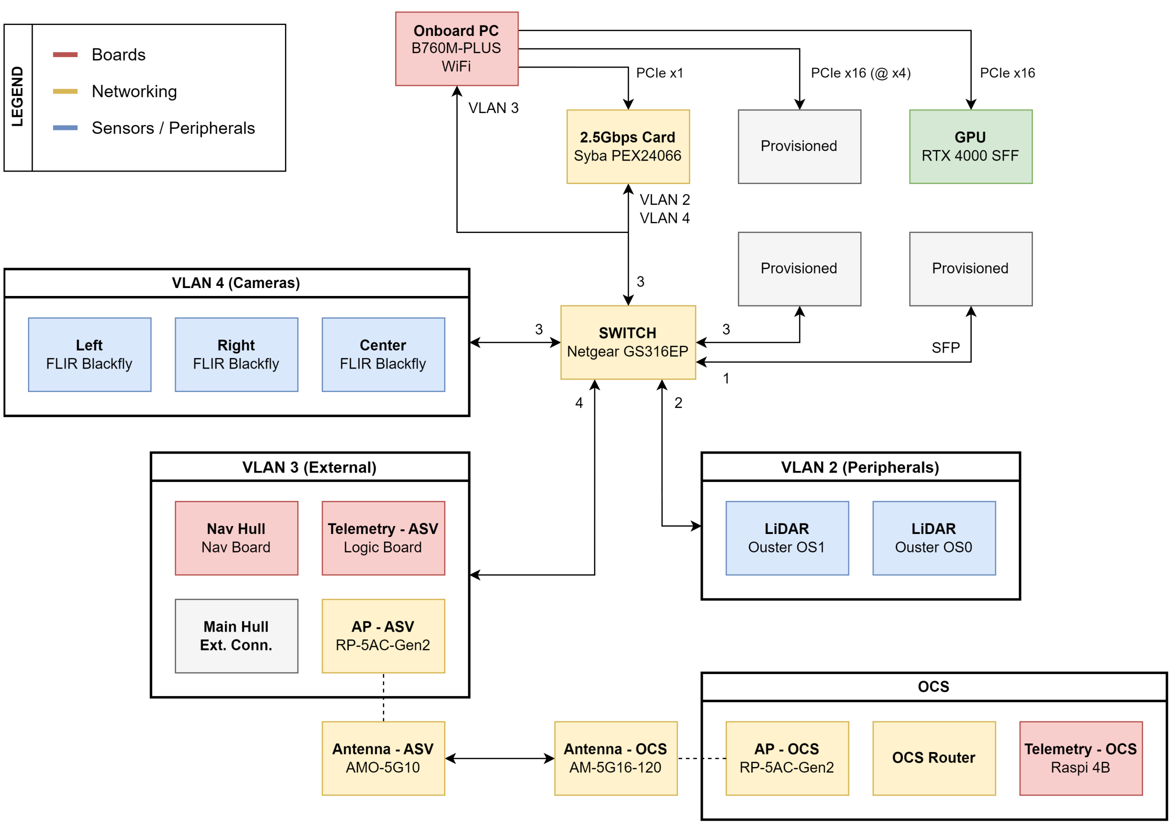

Fig. 24: Intra-ASV network architecture.

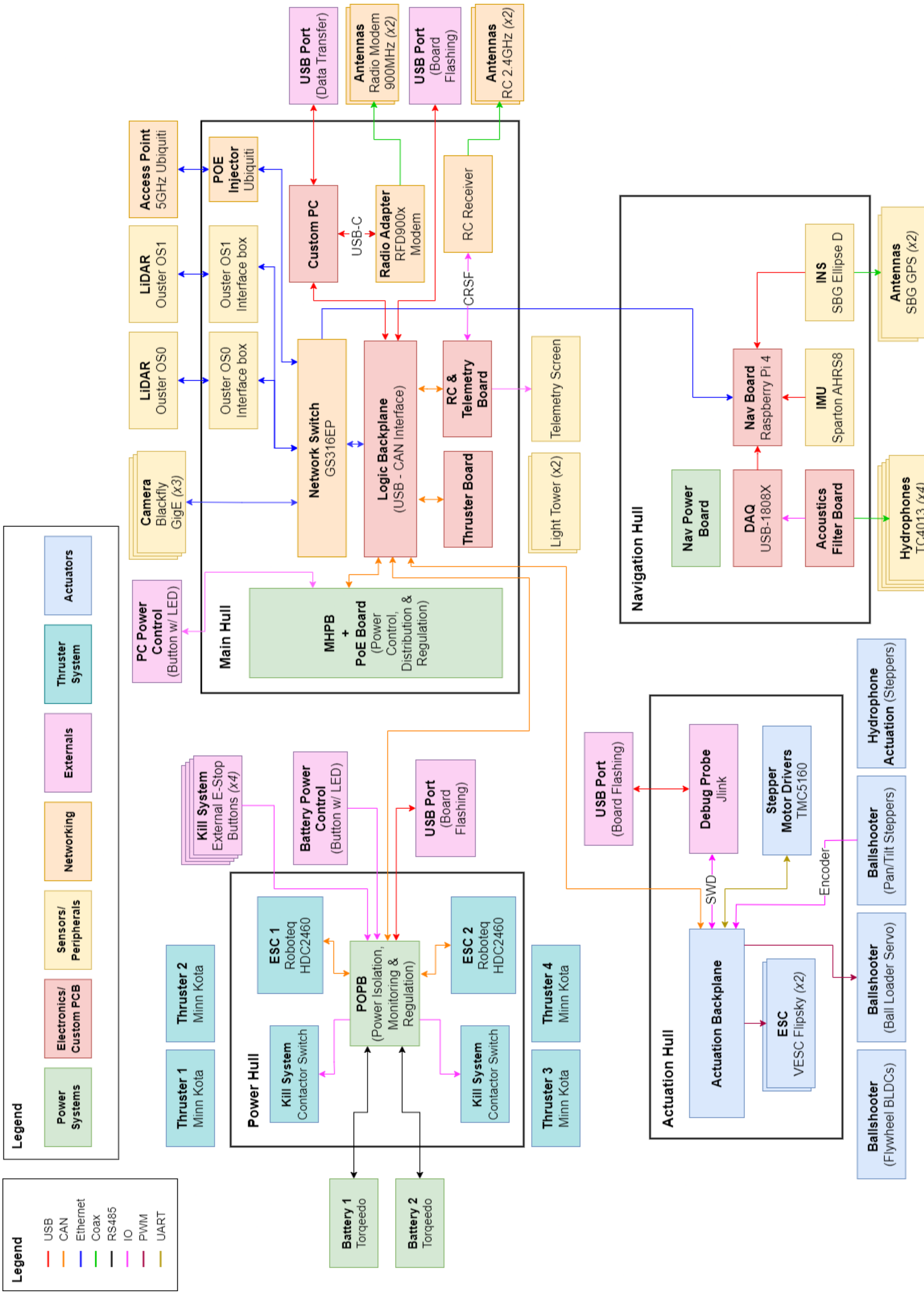

Fig. 25: Electrical communication (intra-ASV) architecture.

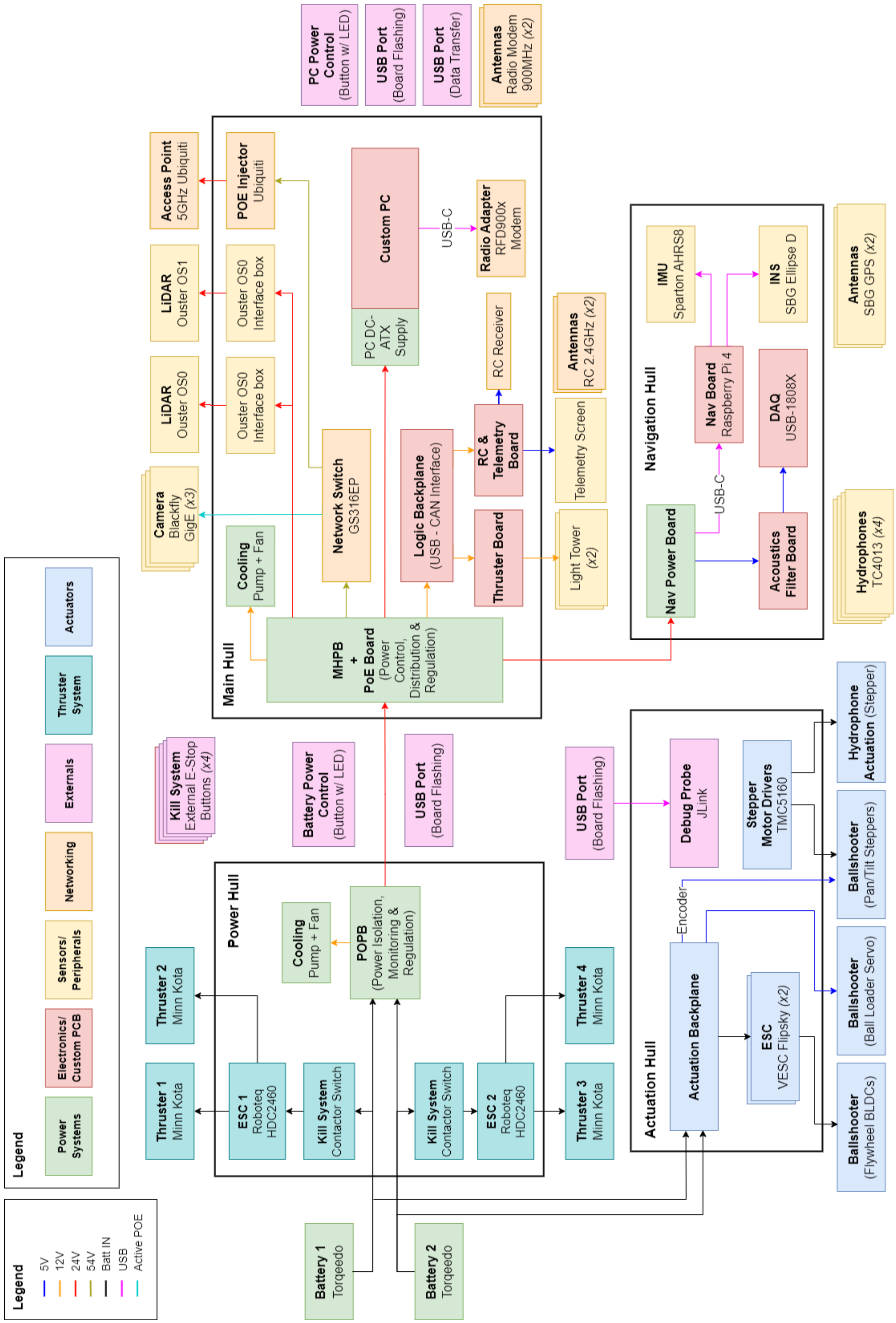

Fig. 26: Electrical power (intra-ASV) architecture.

APPENDIX E
COMPONENT SPECIFICATIONS (BBASV 4.0)

Component	Vendor	Model / Type	Specifications	Custom / Purchased	Cost	Year of Purchase
Main Hull, Power Hull,	Pelican	Pelican 1605 Air	Holes were cut to fit connector panels	Purchased	$250 ea	2023
Actuation Hull	Pelican	V300 Vault	Holes were cut to fit connector panels	Purchased	$120	2024
Navigation Hull	Fibox	Ekoe 130 G Enclosure	Holes were cut to fit connectors	Purchased	$95	2023
Batteries	Torqeedo	Power 24-3500 (x2)	3700Wh	Purchased	$7000 ea	2023
Thruster(s)	Minn Kota	Minn Kota RT80 Saltwater Transom-Mount Motor (x4)	Trolling Motors	Purchased	$1650 ea	2023
Motor Controller(s)	Roboteq	HDC2460 (x2)	Dual Channel DC Motor Controller	Purchased	$900 ea	2022
Hull Connectors	Amphenol Corporation	Assorted RJF TV, RTS & 97B Series Connectors	-	Purchased	$3000 total	2023
Batteries & Thrusters Cable Harness	MEDs Interconnect	Amphenol 97B Series Connectors	-	Custom	$15000	2024
Power & Communications Cable Harness	MEDs Interconnect	Assorted Amphenol Connectors	-	Custom	Sponsored	2024
Power Isolators	Vicor Corporation	24V DC-DC Converter	-	Purchased	$650 ea	2023
Motherboard	ASUS	TUF GAMING B760M GAMING PLUS WIFI	32GB DDR5 RAM	Purchased	$400	2024
CPU	Intel	i7-12700		Purchased	$300	2022
GPU	Nvidia	RTX 4000 SFF		Purchased	$2500	2024
Network Switch	Netgear	GS316EP	16 Port PoE Switch	Purchased	$500	2022
LiDAR	Ouster & ST Engineering	OS0, OS1	128-plane, 64-plane	Purchased	Sponsored	2022
Camera(s)	Teledyne FLIR	Blackfly S POE Gigabit Camera (x3)	BFS-PGE-31S4C-C	Purchased	$600 ea	2019
Power Control, Regulation, Telemetry, Signal Filtering, Motor Control	In-house	Custom-made Printed Circuit Boards (PCBs)	-	Custom	$15000 total	2023-2024
High-Level Control	Raspberry Pi	RPi 4 Model B+	8GB LPDDR4-3200 SDRAM	Purchased	$110	2023
INS	SBG Systems	Ellipse-D	Dual Antenna RTK INS	Purchased	Sponsored	2022
IMU	Sparton	AHRS-8P	-	Purchased	Sponsored	2019
Hydrophones	Teledyne Reson	TC4013	Acoustic Transducers	Purchased	Legacy	2017
Data Acquisition Module (DAQ)	Digilent	MCC USB-1808X	-	Purchased	$1350	2023

Internal Comm. Network	In-house	CAN / Ethernet	1000kbps / 1000 Mbps	Custom	-	-
External Comm. Network	Ubiquiti	AirMAX Rocket Prism AC	5 GHz basestation, 500 Mbps	Purchased	$300 ea	2018
Remote Controller	Radiomaster	TX16S Mark II	2.4GHz ELRS	Purchased	$250	2023
Radio Receiver	BetaFPV	SuperD ELRS Receiver	2.4GHz ELRS	Purchased	$30	2023
Radio Modem (UAV comms)	RF Design	RFD900x	900MHz ISM Band Radio	Purchased	$200 ea	2022
Actuation Stepper Motors	Stepperonline	Assorted Nema Series Stepper Motors	-	Purchased	$30-50 ea	2024
Ball Shooter BLDC Motors	T-motor	Navigator Type Motors	MN501-S	Purchased	$100 ea	2023
Algorithm: Acoustics Localization	-	-	Multiple Signal Classification (MUSIC), Short-Time Fourier Transform (STFT) based Ping Extraction	-	-	-
Algorithm: Localization & Mapping	-	-	Unscented Kalman Fiter (UKF), Spatio-temporal Voxel Layer	-	-	-
Algorithm: Perception	-	-	OpenCV, PCL, YOLOv8, YOLOv10, YOLOv11, GroundingDINO, Segment Anything	-	-	-
Algorithm: Autonomy	-	-	Behavior-Tree.CPP	-	-	-
Software: Framework	-	-	ROS2, Nav2	-	-	-
Software: Acoustics Visualization	-	-	dash.js, plotly-resampler	-	-	-
Team Size	-	-	50	-	-	-
Hardware/Software Expertise ratio	-	-	3:1	-	-	-
Testing Time: simulation	-	-	300 hours	-	-	-
Testing time: in-water	-	-	390 hours	-	-	-

APPENDIX F
COMPONENT SPECIFICATIONS (JELLYFISH 2.0)

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	$1014	2024
Flight Controller	Holybro	Pixhawk 6X	STM32H753	Sponsored	$300	2024

GPS	Holybro	M9N	-	Purchased	$100	2024
Power Distribution	Mateksys	XCLASS PDB FCHUB-12S	-	Purchased	$30	2024
Telemetry	Dronebridge	ESP32 Dronebridge module V3	-	Purchased	$20	2024
Radio Modem (UAV Comms)	RF Design	RFD900x	900MHz ISM Band Radio	Purchased	$200 ea	2022
Receiver	Frsky	X8R	1.5 km Range	Purchased	$30	2024
Transmitter / Remote Control	Radiomaster	TX16S	4-in-1 transmitter	Purchased	$250	2024
Camera	Edmund Optics	FLIR Blackfly USB 3	BFS-U3-31S4C-C	Purchased	$900	2024
Camera	Arducam	IMX219	160° FOV	Purchased	$900	2024
Cameras	Edmund Optics	Flir Blackfly USB 3		Purchased	$900	2024
	Arducam	IMX219		Purchased	$30	2024
Motor	Avetics/T Motor	505X integrated propulsion system	505S 380KV, Alpha 60A 6S ESC	Sponsored	$250 per motor-esc combo	2024
External Comm. Network	D-Link	DWR-910M 4G	-	Purchased	$60	2024
Drone Shell	In-house	-	Multi-Jet Fusion 3D printed with PA12 Nylon	Custom	$300	2024
Carbon Fibre Frame	In-house	-		Custom	$100	2024
Software: Flight Controller Firmware	-	-	PX4	-	-	-

Appendix G
3D Models of Electrical Boards

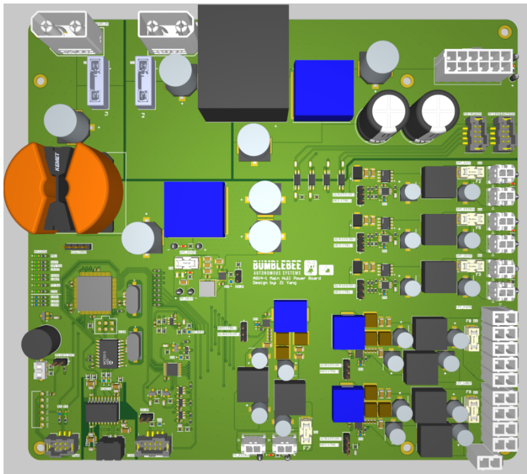

Fig. 27: 3D model of Main Hull Power Board.

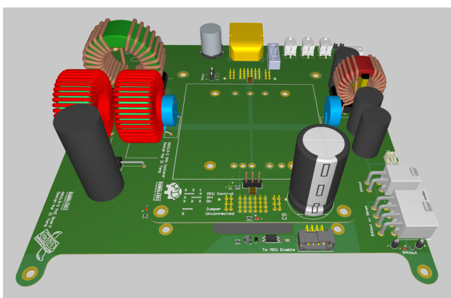

Fig. 28: 3D model of PoE 54V Stack.

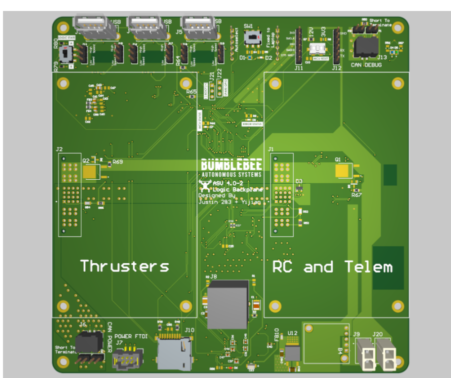

Fig. 29: 3D model of Logic Backplane.

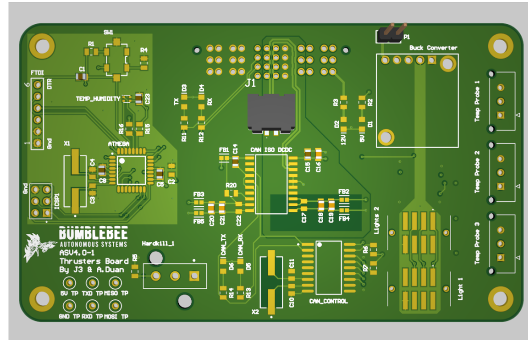

Fig. 30: 3D model of Thrusters Daughter Board.

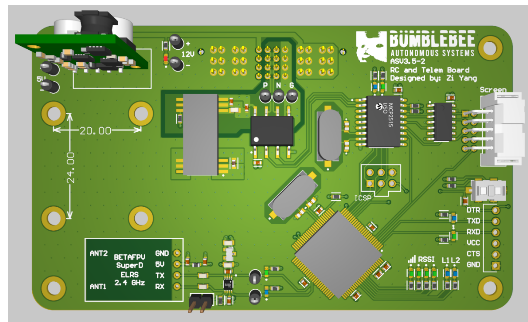

Fig. 31: 3D model of RC and Telemetry Daughter Board.

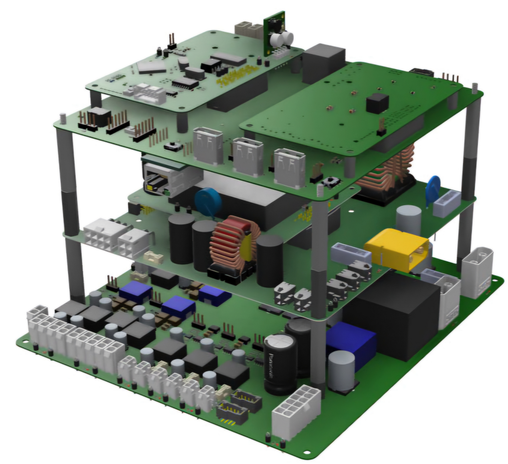

Fig. 32: 3D model of the entire Main Hull Electrical Stack.

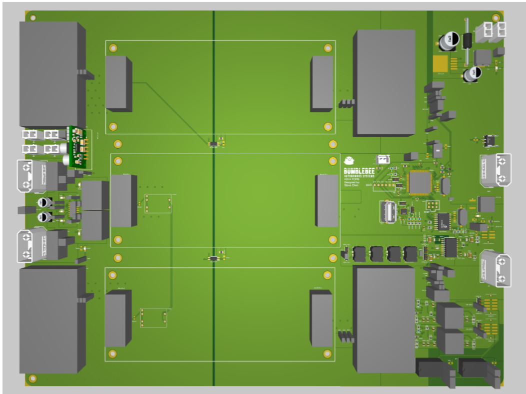

Fig. 33: 3D model of Power Hull Power Board.

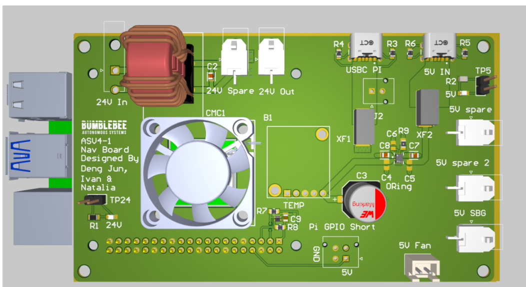

Fig. 34: 3D model of Navigation Power Board.

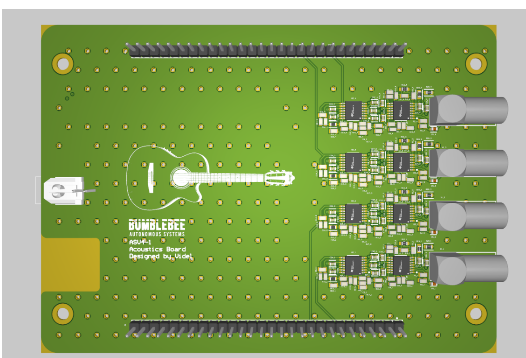

Fig. 35: 3D model of Acoustics Amplifier and Filter Board.

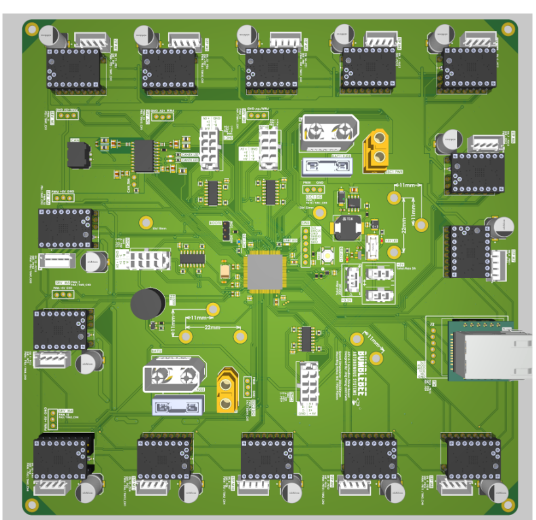

Fig. 36: 3D model of Actuation Backplane.

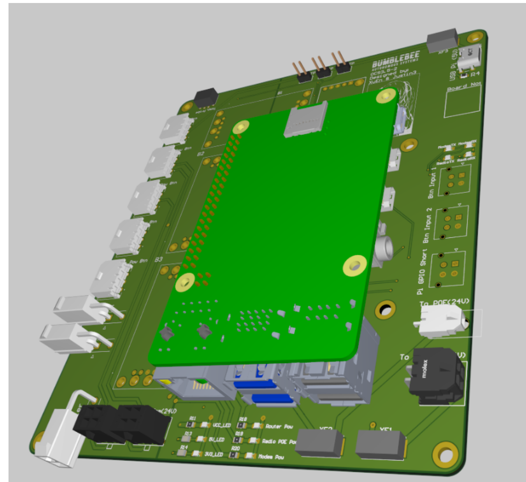

Fig. 37: 3D model of Operator Control Station 3 Board.

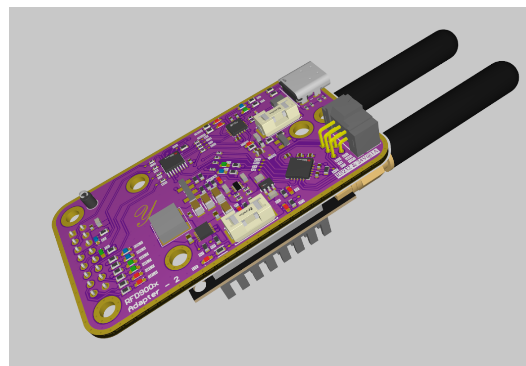

Fig. 38: 3D model of Adaptor Board for Radio Modem.

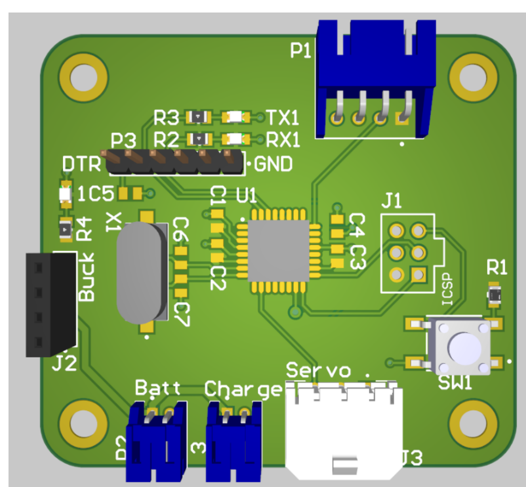

Fig. 39: 3D model of Jellyfish Floatation board.

APPENDIX H
OUTREACH ACTIVITIES

Since our beginnings in 2012, Team Bumblebee has continued to grow steadily, becoming one of the more recognizable student teams in the maritime robotics scene. We continue to be grateful to this community and our sponsors for their support throughout the years. We believe in the importance of fostering new relationships, and strive to share our knowledge and experiences as a form of giving back to the community.

A. Lab Visits

As part of Team Bumblebee's public relations campaign, we regularly conduct lab visits for fellow robotics teams and enthusiasts in the field of marine robotics from around the world. This year, we hosted several international teams who flew over to Singapore to participate in the Singapore AUV Challenge. Through these visits, we hope to exchange knowledge and build lasting friendships.

Fig. 40: Lab visit by Hydrobots Havoc and Oceanic Seekers from India.

Fig. 41: Lab visit by OrcaAUV team from Republic of China.

B. Industrial Partnership and Appreciation

Team Bumblebee is grateful to our industrial partners and sponsors, without whom our team would not be able to achieve continued excellence.

In order to gain experience and understanding of real-world challenges, our team also regularly organizes visits with industrial partners. ST Engineering is one of our major sponsors who has graciously hosted us onboard their USVs, providing a great learning opportunity for the team.

Fig. 42: Our 2023 sponsor appreciation event.

Fig. 43: Industrial visit to ST Engineering.

C. Hornet Training Programme

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

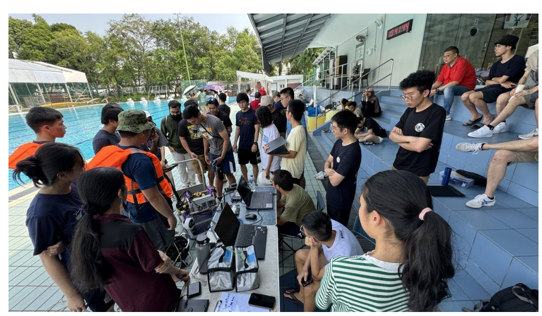

Fig. 44: Hornet 9.0 in action during SAUVC 2024.

The Hornet Training Program serves as an introduction to engineering and robotics. In this program, students are entrusted with the task of designing, building, and testing an Autonomous Underwater Vehicle (AUV) for the Singapore

AUV Challenge (SAUVC). Through this program, students are encouraged to explore and experiment with novel designs, fostering a spirit of innovation and creativity. We recently concluded the ninth iteration of the Hornet Training Program (Hornet 9.0), with the team achieving a commendable 13th place finish among over 40 teams at SAUVC 2024. Since then, we have welcomed the new members into Team Bumblebee for the development of BBASV 4.0 and for Robosub 2025, the BBAUV 5.0.

D. *Collaboration with Local Schools*

Team Bumblebee also conducted sharing sessions with local high school students to inspire them to pursue engineering in their undergraduate studies, and pique their interest in maritime robotics. The team shared about their experiences at RoboNation's competitions (RoboSub, RobotX) and the development and testing of our vehicles.

Fig. 45: Collaboration with a local high school.

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