RoboSub 2023 Technical Design Report

National University of Singapore (Bumblebee Autonomous Systems)

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***Abstract*—For RoboSub 2023, Team Bumblebee's strategy involves deploying the BBAUV 4.1 to efficiently complete all tasks. Already optimized for space, weight and ease of maintenance, mechanical work centered on the reliability of our manipulators to complete all tasks with maximal success. Electrical work has been centered on maintaining current systems and researching new technologies and development processes. Software focus was on ease-of-development improvements and an overhaul of our perception pipeline. New parts were tested thoroughly in simulation and after integration with the vehicle.**

I. COMPETITION STRATEGY

For RoboSub 2023, we plan to deploy our BBAUV 4.1 vehicle (Fig. 1) to complete all competition tasks. Focusing on speed and accuracy, we aim to achieve a 100% success rate for all navigation and actuated tasks. By optimizing our vehicle for competition tasks and validating its performance through extensive testing, we believe we possess a strong, stable platform for success at this year's RoboSub.

A. Competition Vehicles

We will be competing with a single vehicle, the BBAUV 4.1. Despite the physical similarity to its predecessor, much work has been done to upgrade its features. While retaining its size and weight advantages over the competition, substantial improvements have been made to the vehicle's accuracy, reliability and maintainability. With this, we are confident of our ability to adapt to challenges during the competition preparation.

Fig. 1: 3D model of the BBAUV 4.1.

B. Course Strategy

We approach the course using a sensor fusion approach, where we combine readings from various sensors such as our sonar, object detections from machine learning (ML), and acoustic signals from the pingers, to accurately locate and identify objects relevant to the task, such as buoys in the *Start Dialing* challenge or torpedo openings in the *Goa'uld Attack* challenge.

Aligning to targets is a significant challenge, requiring a robust control system and accurate estimations for the positions of the target, vehicle, and peripherals such as grabbers and torpedo launchers.

Previously, we achieved this by combining ML object detection results with 3D computer vision techniques, such as homography estimation. This year, we have expanded on our use of computer vision to enable even faster and more accurate alignments (see Section II-C2).

To better ascertain vehicle position, our Inertial Measurement Unit (IMU) has been upgraded to enable our localization pipeline to give more accurate readings. Several tests were conducted to compare different IMUs and presented in more detail in Section III-B. For knowledge of the externally mounted peripherals such as the actuation modules, our vehicle's Unified Robotics Description Format (URDF) was extensively used to model the relationships in position and orientation between different parts of our vehicle. This allows for much better delivery of autonomy compared to previous years, especially with regard to aligning to obstacles.

To coordinate task-specific strategies, we employ a Behaviour Tree-based mission planner. Based on our experiences using it for nearly two years, improvements and refinements were made in the run-up to this year's competition.

II. DESIGN CREATIVITY

A. Mechanical Sub-System

1) Design of Main Hull

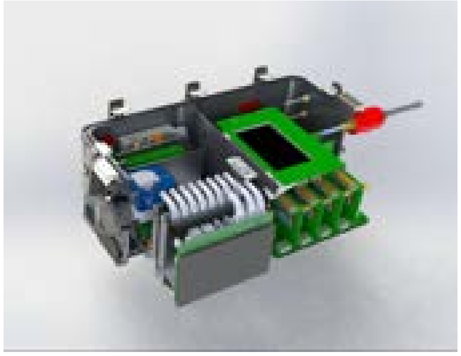

Fig. 2: Internal layout of the main hull

Inherited from its predecessor, a rectangular hull was chosen for efficient packing of internal components and electronics (Fig. 2). Finite Element Analysis was used to verify this design's ability to withstand the 3-bar pressure expected during operation. A center divider adds rigidity and also isolates electrically noisy components from sensors. The telemetry screen window in the hull cover allows us to monitor vehicle vitals during testing, and is outfitted with improved status lights to track the vehicle's progress through the competition course for easier troubleshooting.

Apart from adding buoyancy, fibreglass floats attached to the main hull's exterior also protect the vehicle from impacts in transit or during testing. Notably, floats of the top cover encase and shield the externally mounted sonar. The vehicle's buoyancy can be fine-tuned by inserting floats in the cavities of the 3D-printed shell affixed to the underside of the floats.

An octagonal frame facilitates the mounting of actuation modules, allowing for rapid prototyping and testing of our various actuators (see Section II-A3). Carrying handles on either side of the hull allow for ease of handling.

2) Design of Battery Hull

Another creative aspect of the BBAUV 4.1 is the battery hull, manufactured with novel 3D metal-printing technology; we also increased the rigidity-to-weight ratio by embedding lattices in the walls and base (Fig. 3). The main and battery hulls are directly connected with right-angled SubConn Low Profile connectors, doing away with messy cables and making battery changes quick and simple.

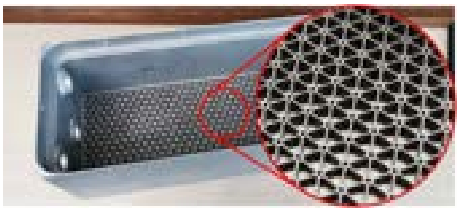

Fig. 3: Isogrid layer of the battery hulls.

3) Design of Actuation Systems

Facing the novel challenge of picking up a large, flat chevron, two grippers utilizing different techniques were designed and tested in parallel to maximize our chances of success.

Our stepper motor-driven gripper (Fig. 4(a)) uses torsion springs in its compliant claw design. Capped with a layer of rubber for extra grip, this design grasps all course obstacles reliably, enabling us to tackle *Location* and *Engaging Chevrons*.

Anticipating chevrons close to the *DHD* walls to be challenging for the claw, inspiration was taken from industrial vacuum suction arms to create our own hydraulic vacuum gripper (Fig. 4(b)). A peristaltic pump uses surrounding water as the hydraulic fluid

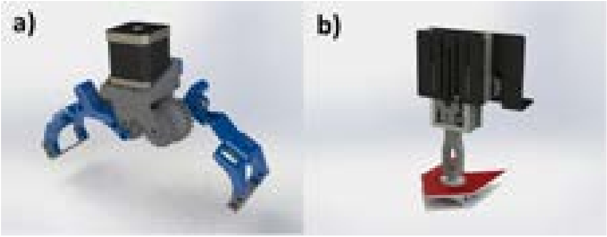

Fig. 4: (a) Stepper motor-driven claw gripper. (b) Pump-powered suction gripper.

to create a local vacuum inside the suction cup, holding the chevron tightly to the arm. This arm is extended directly on top of a chevron using a telescopic pulley mechanism which will not be obstructed by the *DHD* walls. Due to the flat and smooth surface of the chevrons, a flat suction cup was used instead of a bellows suction cup.

Both our ball dropper and torpedo launcher use the Bluetrail underwater servo for their excellent reliability and depth rating. Our 3D-printed torpedos have also been refined to be more hydrodynamic (see Section III-C), allowing *Goa'uld Attack* to be completed consistently.

B. Electrical Sub-System

1) Communications Architecture

The BBAUV 4.1 adopts a heterogenous architecture, with custom PCBs each serving a specialized purpose. Various communication protocols are used by these boards, sensors and our single-board computers (SBC) as detailed in Fig. 21. Inspired by automotive applications, we utilize the Controller Area Network (CAN) bus for its robust, half-duplex differential communication between embedded systems. Where high bandwidth data transfer is required, SBCs and peripherals providing a networked interface are connected to an Ethernet switch. The CAN network is split into two unconnected buses that rely on the Thruster and Actuation Board (TAB) to forward messages between them.

This year, we have upgraded our Operator Control Station (OCS) that provides connectivity between the BBAUV 4.1 and the software subteam during tethered operation. Quality-of-life improvements include an integrated 4G modem and enhanced WiFi connectivity. An in-built telemetry reporting screen allows members on standby to monitor critical statistics (e.g., battery voltage and board statuses), allowing for easier triaging and faster troubleshooting. This minimizes vehicle downtime when testing and dedicates more time towards trial runs for the actual tasks.

Apart from relying on upper layers of our software stack, we have also introduced telemetry reporting at the network layer. By modifying the SBC-CAN board which bridges the CAN and Ethernet domains, we are now able to also broadcast telemetry data over UDP, providing redundancy and flexibility in our monitoring.

2) Power Control and Monitoring

Our custom-designed Power Monitoring Board (PMB) reports battery statistics such as voltage, charge and current consumption. Additionally, it is capable of determining the battery's state of health and charging cycle, allowing for better estimation of operational time in light of degrading battery life. The routing of power between different components is shown in Fig. 22.

When the voltage drops appreciably, PMB fail-safes ensure that the onboard under-voltage protection system will trigger a warning and disable electronics to prevent damage to the batteries. Coupled with a centralized power control board, systems can be selectively prioritized to conserve power during low-power scenarios. More importantly, this affords the ability to independently power cycle components. Hot-swappable batteries also reduce the need for disruptive restarts of the vehicle, keeping our operational uptime as high as possible.

3) Backplane System

Our backplane system mounts the vehicle's electronic components to the main hull, allowing for more versatility as opposed to mounting on the end-cap. The backplanes (Fig. 15 and 18) provide power and communication lines that simplify the development of custom daughter boards (Fig. 16, 17, 19 and 20) as connectors are internally standardized, which also allow for boards to be easily redesigned in the future.

In preparation for RoboSub 2023, more power and communication lines were added to the backplanes to reduce the amount of wired connections in the hull. This reduces crosstalk and electrical noise, and aids maintenance and debugging efforts. More debugging ports were also added to aid monitoring. The new backplanes also have a thicker copper layer that improves heat dissipation and increases the current limit that can be drawn by daughter boards. This allows greater speeds to be achieved without risk of the thruster Electronic Speed Controls (ESC) overloading the power lines.

In our experience with plug-and-play daughter boards, as the connectors near their rated mating counts, the gradual oxidation and degradation of the contacts result in slower transmission speeds and occasional disconnections. As a preventive action, contact cleaners and lubricants are extensively used in our maintenance routines to extend the lifespan of existing boards and drive down cost and wastage.

4) Firmware Improvement + DevOps

Control messages from the software stack are forwarded through multiple boards before arriving to the ESCs. Reducing the latency of our communications and making the firmware generally more performant thus had a great impact on the vehicle's responsiveness. This was primarily achieved by moving from polling loops towards interrupt-driven, Real-Time Operating System (RTOS)-like code structure. Upstream software are also positively affected; less oscillatory behaviour was observed in our Proportional-Integral-Derivative (PID) controller due to the faster feedback loop between controller and ESCs.

This is complemented by our migration to the PlatformIO IDE, which supports multiple architectures and platforms in a single codebase, simplifying code organization and sharing of common code. This has facilitated standardization and reduction of our technical debt, and alongside our increased usage of static analyzers and linters, has greatly reduced our chances of introducing bugs. Adoption of proper workflows for version control and using a self-hosted Continuous Integration build pipeline has also made collaboration easier and safer.

5) Status Light Module

Previously, only one RGB LED was used as a status indicator to provide feedback to operators outside the pool, but was found to have limited visibility under daylight and required a redesign. After testing and evaluation (see Section III-A), a 9 LED configuration for the module was selected and integrated with our Sensor and Telemetry Board (STB). The copper-cored PCBs are directly connected to the exposure pad of the LEDs to facilitate heat dissipation and keep temperatures sufficiently cool. For brightness control of the LEDs, the LT3950 constant current driver was selected for its flexibility and safety features such as overcurrent, overvoltage and open LED.

6) Actuation

With our two gripper designs, our actuation system now consists of 2 Bluetrail underwater servos and 2 stepper motors. The latter utilizes the TMC2209 drivers for smooth and precise control of the grippers. Using Trinamic's StallGuard™, actuators can be calibrated to a reverse-EMF threshold in order to automatically stop the stepper movement without additional sensors or external input. Using CoolStep™, the maximum current threshold is dynamically set based on the load of individual motors, minimizing the overall power consumption and heat generation. The newly added suction gripper also uses SpreadCycle™ in its telescopic pulley mechanism for dynamic motor control.

7) Acoustic Signal Processing

Due to its stability, our acoustic subsystem has undergone minimal changes. An automated programmable gain amplifier on the Data Acquisition Board (DAQ) normalizes incoming pings to reduce signal clipping, providing consistent measurements at all distances from the pinger. Pings are extracted using short-time Fourier transforms with dynamic thresholding, and pings with a low signal-to-noise ratio are discarded, allowing the acoustic subsystem to perform even in noisy environments.

C. Software Sub-System

1) Mission Planner

Adopted last year, our mission planner utilizes Behaviour Trees (BT) and has proven to be highly effective in defining complex behaviours for our vehicle. We have enhanced our mission planner with a Graphical User Interface (GUI) to facilitate easy designing and modification of mission plans. Furthermore, harnessing the abstracted nature of

BTs, we have refactored our mission plans to enable different tasks to reuse the same high-level logic, thereby simplifying the mission planning process.

2) *Machine Learning Pipeline*

We have upgraded our perception pipeline to leverage the benefits of both deep-learning and traditional computer vision (CV) approaches in order to improve our chances of localizing the different obstacles in the TRANSDEC environment.

The upgraded pipeline incorporates deep-learning models such as SuperPoint [1] and SuperGlue [2] to directly estimate obstacle poses by accurately matching image features from our camera against template images provided in training. These are used alongside object detection and segmentation models such as YOLOv8 [3], and supplemented by traditional CV algorithms like Scale-Invariant Feature Transform (SIFT) or Perspective-n-Point (PnP).

An advantage of this hybrid pipeline is the ability to dynamically adjust our approach based on environmental conditions and/or the task at hand, allowing us to optimize the perception system's performance for various scenarios. In general, these improvements have enabled us to achieve more precise and robust perception capabilities.

3) *Control System*

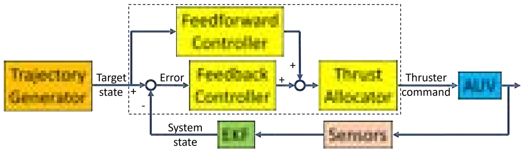

Fig. 5: Control system block diagram.

Our tried-and-tested control system is largely unchanged. The trajectory generator uses linear segments with polynomic blend to generate smooth continuous paths. These trajectories have limits imposed on the velocity, acceleration and jerk of the vehicle to avoid controller saturation, improving performance for distant setpoint goals.

We utilize a control law partitioning scheme – a full state feedback controller enables positional and velocity tracking, and a feedforward controller to compensate for non-linear terms in the vehicle's motion dynamics.

Our thrust allocator uses quadratic programming to optimise each thruster's command based on the required forces, and maintains control along each axis of motion even during thruster saturation.

III. Test Strategy

A. *Custom Light Module*

Key areas that were considered during the current iteration were the LED's brightness, heat generated, and meeting the power budget. The circuit for the constant current driver was simulated using LTSpice to verify the behaviour of the driver and LEDs (Fig. 6). Using the simulation, the values of capacitors and inductors in the buck-boost circuit were also optimized for minimal ripple current.

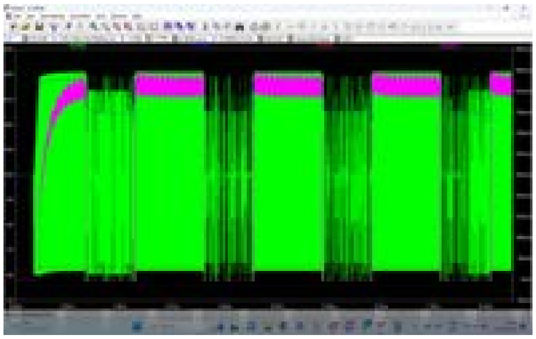

Fig. 6: LTSpice simulation of current (pink) and voltage (green) through driver over time.

The panel of the light module is designed to accomodate up to 12 LEDs. Visibility testing was conducted in daylight from a 30-m distance in batches of 4, 8 and 12 LEDs. The tests were not conducted within the main hull as the module was in the prototype phase, but were deemed sufficient for a first estimation. Although tests revealed that 8 LEDs were sufficient, the schematic was ultimately designed using 9 LEDs in a 3-3-3 configuration (Fig. 7). This made the circuit layout simpler and allowed for more efficient buck converters to be used.

Thermal tests were carried out using a thermocouple to measure the temperature of the LEDs at 1-minute intervals. At an ambient temperature of 26° C, temperatures remained below 60° C even after continuous operation at maximum power for 20 min. Although the LEDs have a rated maximum operating temperature of 155° C, the primary concern was

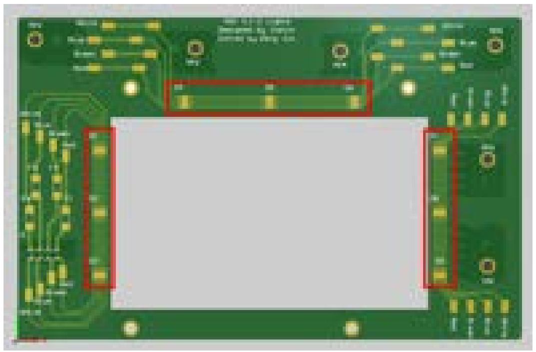

Fig. 7: 3D Model for light module, LEDs in red.

this new heat source affecting the operation of other thermally-sensitive sensors.

On the electrical side, power consumption was measured using a bench power supply and oscilloscope by probing the current and voltage across the LEDs to calculate transient power draw. The ripple current was verified to lie within the margins of our power budget, which is especially important as the LEDs draw power directly from a 12-V DC converter that only supports up to 120 W. Using a load tester to simulate the LEDs, the current driver was also benchmarked against various resistance values to ensure its stability under various conditions. These resistances were derived from the datasheet of the LED.

B. IMU Comparison

In previous years, we found that the IMU was highly susceptible to external magnetic interference. In order to investigate and understand the issue in detail, a test mount was printed to allow for testing of several IMUs at the same time under the same conditions.

One test involves conducting a 180-degree yaw on the test mount and measuring the resultant vehicle yaw over time (Fig. 8). It was observed that the old IMU has a delayed response which is especially obvious after a large difference in yaw. This was ascertained to be an issue with the sensor characteristics and was resolved by switching to another IMU. With this newer IMU, we note a reduction in position error by up to 50% over a 2-minute period.

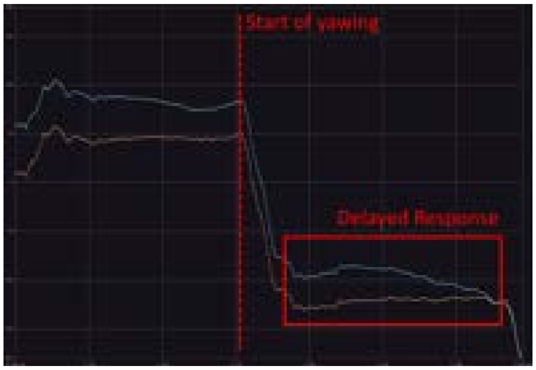

Fig. 8: Measured yaw values of old (blue) and new IMU (orange) over time.

C. Torpedo Improvements

The torpedoes used last year have been redesigned to be positively buoyant with reduced drag. Assisted by Computational Fluid Dynamics (CFD) analysis in SolidWorks, our current torpedoes are redesigned for minimal drag and trajectory disturbance. CFD results are given in Appendix A.

The torpedo launcher was also redesigned, as torpedoes were loose and would fall out during certain manoeuvres. This resulted in inconsistent loading and large variances in travel distance over several attempts. Several designs were tested by firing at a styrofoam board underwater. The results of torpedo spread are given in Appendix B. A cross profile is also used to accommodate the new torpedoes with round cross-section to provent rotation when loaded.

It was also suspected that the moving metal components were causing magnetic interference, contributing to IMU drift, and have thus been replaced with plastic parts.

ACKNOWLEDGEMENTS

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APPENDIX A
TORPEDO CFD ANALYSIS

The CFD simulation results of the old model (Fig. 9) and two proposed designs (Fig. 10 and 11) are presented here. Note that the colour scale for fluid velocities are normalized for ease of comparison.

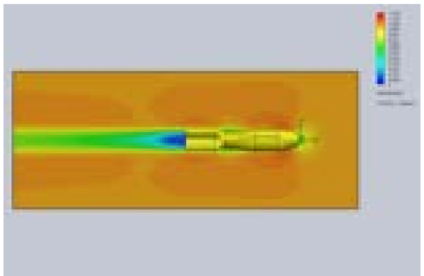

Fig. 9: CFD results of old torpedo.

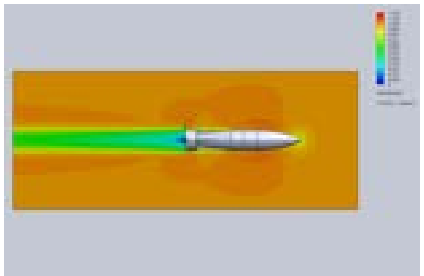

Fig. 10: CFD results of current torpedo.

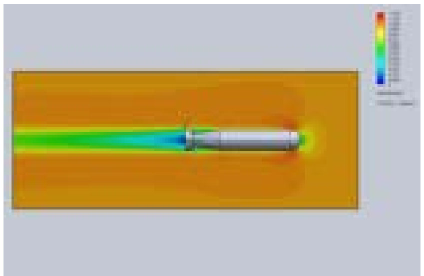

Fig. 11: CFD results of alternative model.

APPENDIX B
TORPEDO LAUNCHER SPREAD

The first new launcher design utilizes a spring-loaded slot blocking mechanism (Fig. 12). Blockers situated at the front move into place, and successfully prevented torpedoes from falling out in tests.

Fig. 12: Spring-loaded slot blocking launcher.

An alternative design uses holding pins to grip the torpedoes (Fig. 13), inspired by the alignment pins found in NERF guns. This design requires minor edits to the torpedo model to accommodate the pin.

Fig. 13: Holding pin launcher.

Both designs have a comparable spread as shown in Fig. 14. During tests in the pool however, it was noted the spring-loaded slot blocking launcher causes the torpedoes to veer, and so the holding pin launcher was used instead.

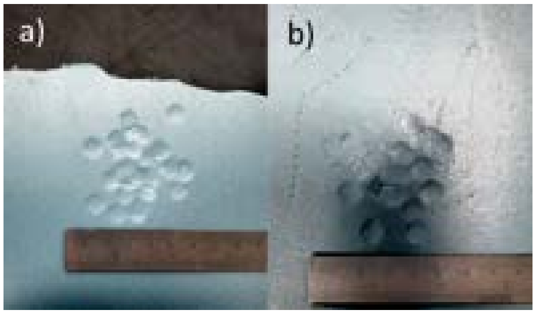

Fig. 14: Spread of torpedoes on styrofoam board. (a) Holding pin launcher. (b) Spring-loaded slot blocking launcher.

APPENDIX C
BACKPLANE SYSTEM

Our backplane system makes extensive use of the Samtec PowerStrip™ connectors. Where connections to other third-party components are required, adapter daughter boards (Fig. 17) are used instead of designing with proprietary connectors for flexibility and preventing vendor lock-in.

Such a design also simplifies power control from a centralized power control board (Fig. 18).

APPENDIX D
ARCHITECTURE BLOCK DIAGRAMS

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

- **DAQ**: Data Acquisition Board (Acoustics)
- **DVL**: Doppler Velocity Log
- **FOG**: Fiber-Optic Gyroscope
- **PMB**: Power Monitoring Board
- **SBC-CAN**: Custom board bridging our CAN network and our main SBC
- **STB**: Sensor and Telemetry Board
- **TAB**: Thruster and Actuation Board

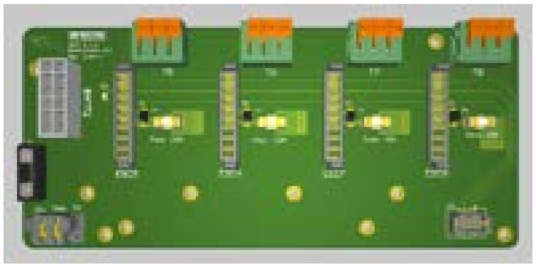

Fig. 15: 3D model of ESC backplane.

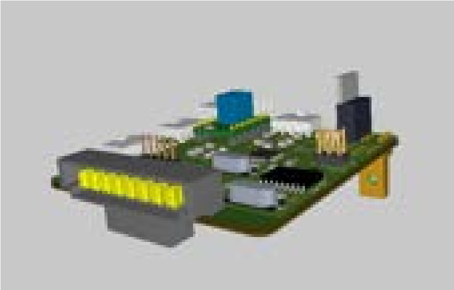

Fig. 16: 3D model of Actuation daughter board.

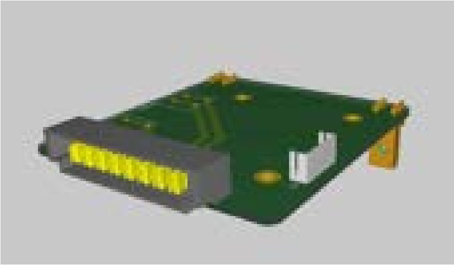

Fig. 17: 3D model of ESC adapter daughter board.

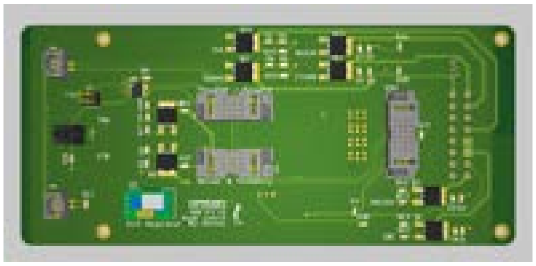

Fig. 18: 3D model of power control backplane.

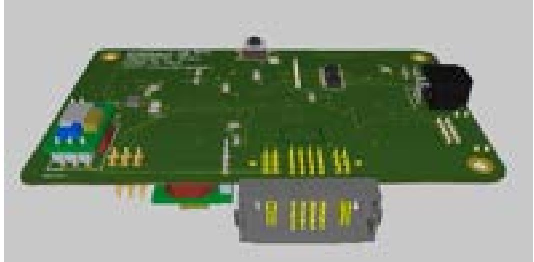

Fig. 19: 3D model of Sensor and Telemetry daughter board.

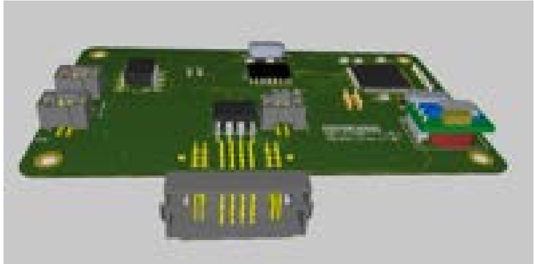

Fig. 20: 3D model of Thruster and Actuation daughter board.

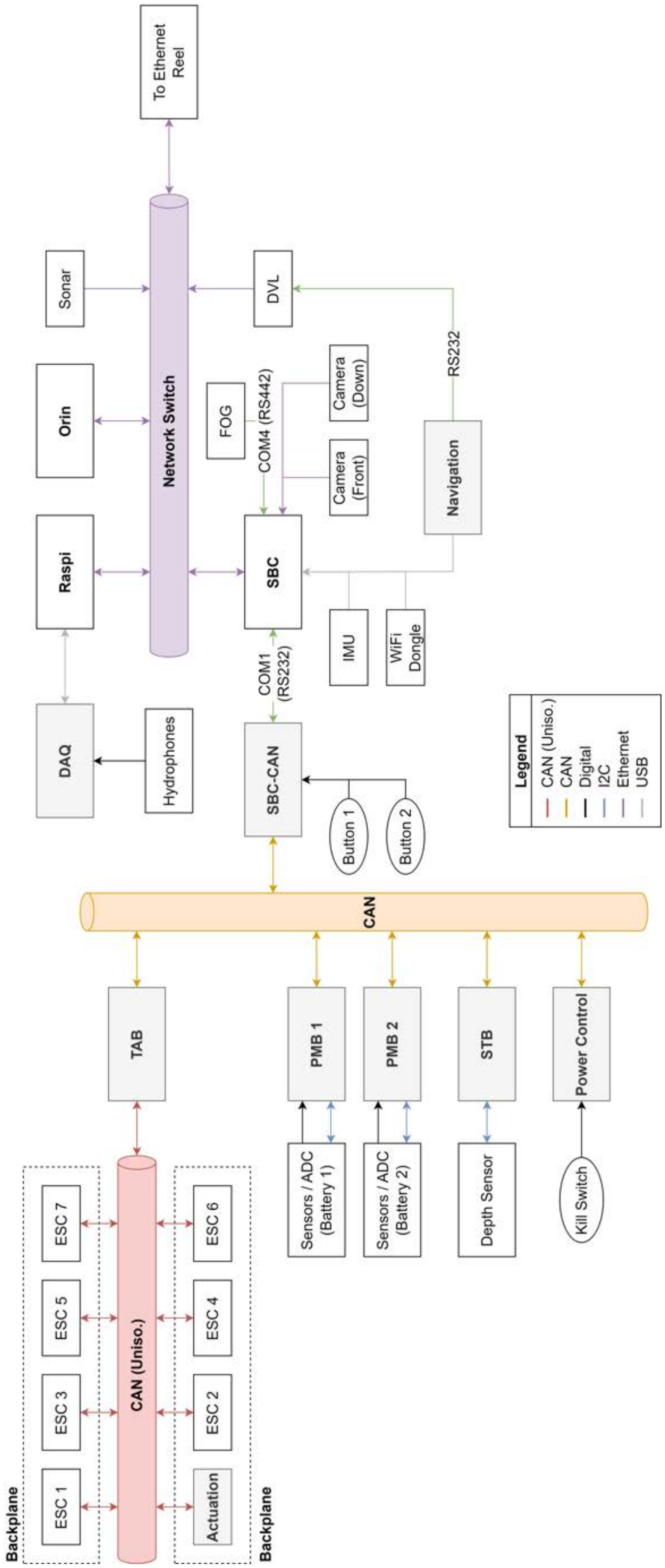

Fig. 21: Inter-board communication architecture block diagram.

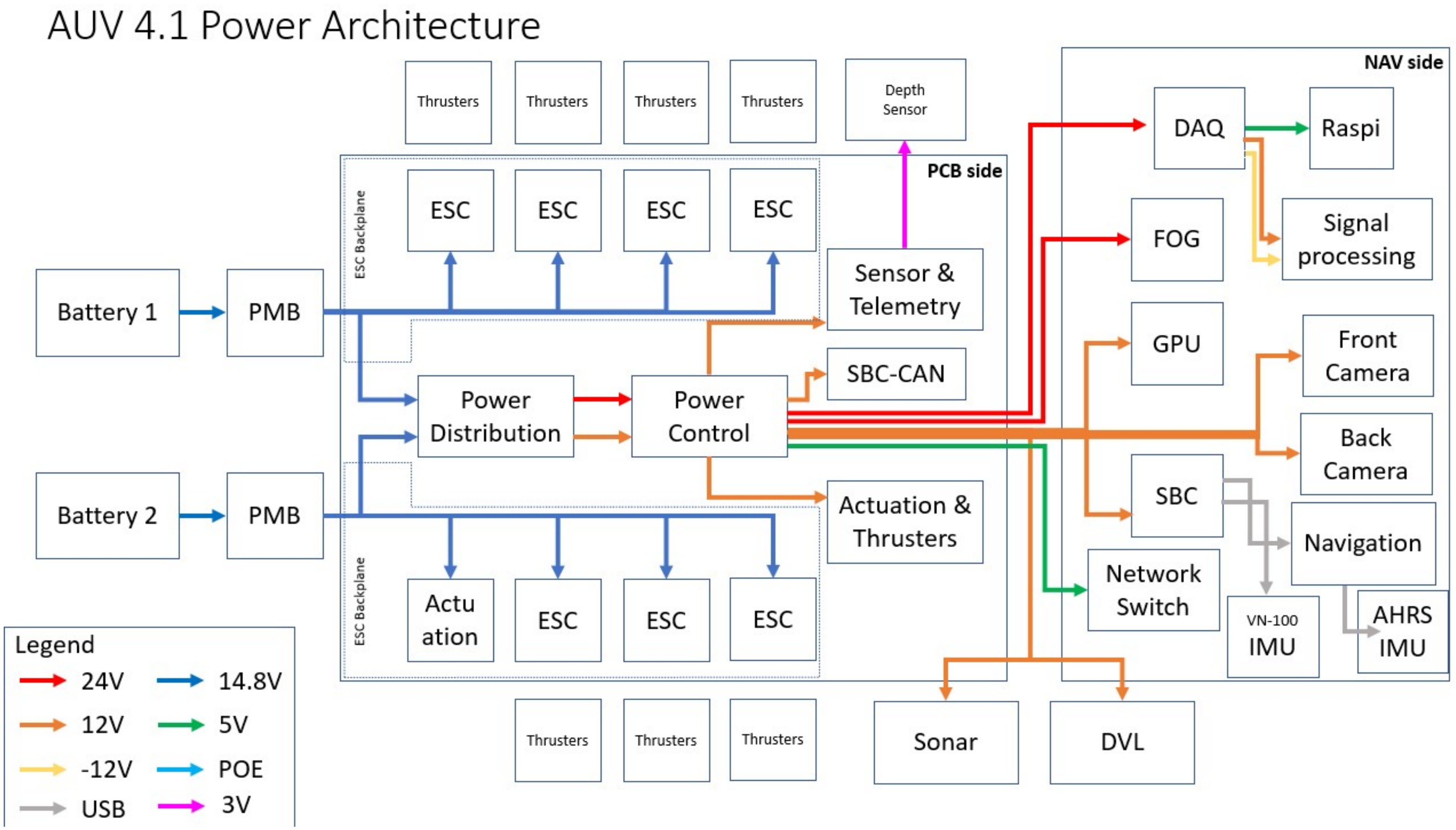

Fig. 22: Power architecture block diagram.

APPENDIX E
COMPONENT SPECIFICATIONS

Component	Vendor	Model / Type	Specifications	Custom / Purchased	Cost	Year of Purchase
Main Hull	Samco Enterprise, Feimus Engineering	Custom Aluminium Milling	—	Custom	$2,700	2019
Frame	Cititech Industrial	Custom Aluminium Laser-cut	—	Custom	Sponsored	2021
Battery Hull	SLM Solutions	Custom Aluminium Selective Laser Melting	—	Custom	Sponsored	2020
Floats	Admiralty International	Diab HCP30	—	Custom	$4,650	2022
Nylon Shell	3D Print Singapore	HP MJF	—	Custom	$1,000	2022
Waterproof Connectors	SubConn Inc., MacArtney	Assorted Micro and Low-profile Series	Peak Depth: 300 bar	Purchased	Sponsored	2019
Waterproof Servos	Blue Trail Engineering	SER110X	Peak Depth: 10 bar	Purchased	$380 ea	2021
Thrusters	Blue Robotics	T200	—	Purchased	$176 ea	2021
Motor Control	Flipsky	Mini FSESC4.20 50A	—	Purchased	$145 ea	2021
High-level Control	Raspberry Pi	RPi 3 Model B+	1.4GHz 64-bit quad-core processor	Purchased	$39	2019
Actuators/ Manipulators	In-house	ABS/HP MJF	—	Custom	Sponsored	2022
Battery	Tattu	Custom-made 4-cell battery	15000 mAh	Purchased	$200 ea	2023
Battery Monitoring System	In-house	Custom-made circuit board	—	Custom	Sponsored	2022
Power Isolator	Murata	UWQ-12/10-Q12PB-C	120W Wide-range Isolated DC-DC to 12V	Purchased	$52	2021
		UWE-24/3-Q12PB-C	72W Wide-range Isolated DC-DC to 24V	Purchased	$67	
Single Board Computer	Avalue	ECM-TGU	Intel Core i7-1185GRE	Purchased	$1,000	2023
GPU	Nvidia	Jetson Orin	AGX	Purchased	$2,500	2022
Internal Comm. Network	In-house	CAN / Ethernet	1000kbps / 1000Mbps	Custom	Sponsored	—

External Comm. Interface	In-house	Ethernet	1000Mbps	Custom	Sponsored	—
FOG	Fizoptika	VG103S-2LND	—	Purchased	$3,060	2021
IMU	Sparton	AHRS-8P	—	Purchased	Sponsored	2019
	VectorNav	VN-100	—	Purchased	$1,500	2023
Doppler Velocity Log	Teledyne Marine	Pathfinder DVL	600kHz Phased Array	Purchased	$16,000	2019
Camera(s)	BlackFly S PoE Gigabit Camera	BFS-PGE-31S4C-C	2448 × 2048 at 22 FPS	Purchased	$594	2019
Hydrophones	Teledyne Reson	TC4013	Acoustic transducers	Purchased	Legacy	2017
Sonar	Oculus	M750d	Dual-Frequency Multibeam Sonar (750KHz / 1.2MHz)	Purchased	$21,300	2019
Algorithm: vision	—	—	Thresholding, Particle filter, Machine learning	—	—	—
Algorithm: acoustics localisation	—	—	Multiple Signal Classification (MUSIC), Short-Time Fourier Transform (STFT) based Ping Extraction	—	—	—
Algorithm: acoustics communication	—	—	Short-Time Fourier Transform (STFT), Quadrature Phase Shift Keying (QPSK)	—	—	—
Algorithm: localisation & mapping	—	—	Error State Kalman Filter	—	—	—
Algorithm: autonomy	—	—	BehaviorTree.CPP	—	—	—
Open source software	—	—	OpenCV, ROS, PyTorch	—	—	—
Team size	—	—	38	—	—	—

Hardware/ Software expertise ratio	—	—	3:1	—	—	—
Testing time: simulation	—	—	100 hours	—	—	—
Testing time: in-water	—	—	200 hours	—	—	—

APPENDIX F
OUTREACH ACTIVITIES

Ever since our humble beginnings in 2012, Team Bumblebee has continued to grow, and we have become one of the most accomplished student teams in the maritime robotics scene. Despite this, we remain grateful to the 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. Through these visits, we hope to exchange knowledge and build lasting friendships.

Fig. 23: Lab visit by a local pre-university institution.

Fig. 24: Lab visit by an international team.

B. Industrial Partnership and Appreciation

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

Fig. 25: A recent sponsor appreciation event.

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 have graciously loaned us sensors and other equipment to assist in our testing and development.

Fig. 26: 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.

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.

Through this program, students are encouraged to explore and experiment with novel designs, fostering a spirit of innovation and creativity. We have recently concluded the eighth iteration of the Hornet Training Program (Hornet 8.0), and have welcomed the new members into Team Bumblebee for the development of BBAUV 4.1.

Fig. 27: Some Hornet 8.0 members conducting a pool test.

D. *Collaboration with Local Schools*

Team Bumblebee have conducted sharing sessions at a local high school to inspire students to pursue engineering as a career. The team shared about their experiences at RoboNation's competitions (RoboSub, RobotX) and the development and testing of vehicles leading up to it.

Fig. 28: Collaboration with a local high school.

APPENDIX G
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.

DSO National Laboratories — For cash support and technical guidance.

ST Engineering — For loaning of equipment.

Altium — For providing software licenses.

Republic of Singapore Yacht Club — For providing a testing location.

Wartsila — For providing equipment.

C. *Gold Sponsors*

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

D. *Silver Sponsors*

Bossard, Festo, Samtec, Solidworks, Southco and Sparton.

E. *Bronze Sponsors*

Blue Trail Engineering, Edmund Optics, Lionsforge, Pololu and TGN Technology.