RoboSub 2021 Technical Design Report

National University of Singapore (Bumblebee Autonomous Systems)

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***Abstract*—For RoboSub 2021, Team Bumblebee's strategy involves simultaneously deploying the BBAUV 3.99 and the BBAUV 4.0 to complete the tasks efficiently, using acoustic subsystems for inter-vehicular communication. The mechanical design of the BBAUV 4.0 is optimised for space and weight, offering vastly superior manoeuvrability while eliminating the weight penalty incurred by the BBAUV 3.99. Electrical work centred on improving ease-of-access to components and decoupling individual subsystems, reducing turnaround time when debugging. Software development focused on improving the vision pipeline and implementing a behaviour tree-based mission planner to allow for quicker iterations during testing and an easier understanding of the AUV's behaviour. The team's limited access to in-water testing was supplemented using hydrodynamic simulations to tune the AUV's control systems, and custom sensor plugins were developed for our Gazebo simulator. Testing time was used to qualify our simulation results and improve our models.**

I. Competition Strategy

For RoboSub 2021, we plan to deploy both our BBAUV 3.99 (Fig.1) and BBAUV 4.0 (Fig.2) to complete all the competition tasks. We noted that although we were previously able to achieve good results with only the BBAUV 3.99, the past 3 physical RoboSub competitions were won by teams deploying two vehicles. Deploying two vehicles allows us to significantly reduce our competition run time as they can complete tasks simultaneously, while also acting as backups in case one vehicle fails to perform a task. Furthermore, we are also able to optimise each vehicle for a specific set of tasks, which we will discuss below. Lastly, while the new vehicle was still under development, our software team was able to use the stable BBAUV 3.99 platform to deploy and test our software systems.

A. Development Efforts

During the first half of the year, lab access was limited due to COVID-19 restrictions. As a result, our whole team worked remotely, with the Mechanical team relying on our accurate CAD models to continue development of our vehicles. We continued to finalise designs and send parts for manufacturing during the lockdown period, allowing us to rapidly assemble and test them once the lockdown lifted.

Even after restrictions were partially lifted, our physical pool testing opportunities were still severely limited. To make full use of our time, we split our team into two, deploying both vehicles at every test. One team focused on testing our new algorithms using the robust BBAUV 3.99, while the other team focused on finalising development of the BBAUV 4.0. To further increase the efficiency of physical testing, we developed hydrodynamic models of the AUVs, using Computational Fluid Dynamics (CFD) simulation conducted in Ansys Fluent. Control law partitioning was used to identify relevant system equations, providing a guideline for the tuning of the Proportional–Integral–Derivative (PID) controllers, reducing the number of parameters required to tune the PID controller from 24 to 8.

For our Software team, we expanded our Gazebo simulations to add a variety of task obstacles, allowing us to test the controls and sensors of the AUV without requiring physical pool tests. Furthermore, we were able to tune the parameters of our simulated vehicle to closely match our real vehicle, using data calculated by the aforementioned hydrodynamic models. This allowed us to accurately simulate the competition tasks and test various configurations of our mission planner for their effectiveness. This way, we were able to use pool time to rectify errors we couldn't predict in the simulation, such as reflections from the water surface interfering with our camera.

B. Competition Vehicles

Our first vehicle, the BBAUV 3.99, was entered in RoboSub 2018 and 2019. It was developed as both a competition vehicle as well as a research and development vehicle for commercial applications. However, its high weight incurs a large penalty under the RoboSub scoring system, and its large size prevents it from doing certain tasks effectively.

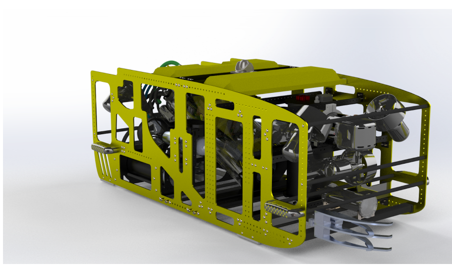

Fig. 1: 3D model of the BBAUV 3.99.

Our second and newest vehicle, the BBAUV 4.0, is designed solely for RoboNation competitions. A much smaller and lighter vehicle, it is intended to resolve the weaknesses inherent in the BBAUV 3.99 while maintaining similar capabilities.

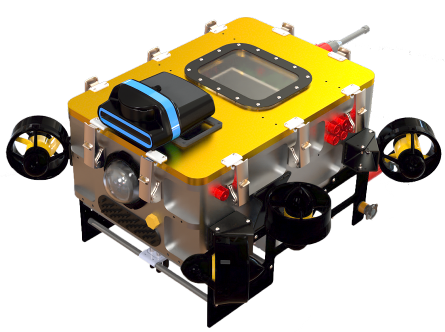

Fig. 2: 3D model of the BBAUV 4.0.

While developing our new BBAUV 4.0, we reused existing designs and technologies as far as possible, to reduce the cost of developing an additional vehicle. However, improvements made to the BBAUV 4.0 were also back-ported to the BBAUV 3.99, such as our new electronically-controlled actuation system, replacing the heavier and less reliable pneumatics used on BBAUV 3.99.

C. Course Strategy

Being the faster of the two, we aim to deploy the BBAUV 4.0 for the *With Moxy* and *Choose Your Side* tasks first. For the remaining tasks, we plan to use the BBAUV 4.0 to complete the pinger tasks (*Survive The Shootout* and *Cash or Smash*), while assigning the BBAUV 3.99 to the marker following tasks (*Make the Grade* and *Collecting*). We expect both vehicles to complete their tasks at the same time (the pinger tasks are more time-consuming, but the BBAUV 4.0 is faster). If time permits, the vehicles will swap their assigned tasks and attempt to get a better score.

To facilitate this dual-vehicle strategy, we developed an inter-vehicle communication system. In order to prevent conflicts, each vehicle publishes the task that it is currently attempting; only when both vehicles signal completion of all their tasks will they swap their assignments. Furthermore, in terms of collision avoidance while navigating between tasks, each vehicle publishes its current and predicted locations; if the predicted locations are within 5m, the vehicles will move to different depths to allow them to safely pass each other. Lastly, the inter-vehicle communication system allows both our vehicles to share the positions of each task with each other, allowing for seamless swapping of tasks.

In terms of the individual tasks, we make use of a sensor fusion approach, together with a technique known as *structure from motion* in our vision pipeline. By combining our sonar images with object detection using machine-learning methods, we are able to accurately localise and identify task objects like the buoys in the *Make the Grade* task. For identifying the torpedo cutouts in the *Survive the Shootout* task, we further augment this with traditional computer vision techniques for detecting the border colour.

To complete the *Collecting* task, we first use the bottom-facing camera to follow the orange markers to the general area of the bins; we then search for them by moving in a square-shaped spiral path to balance the efficiency of detection and accuracy of motion as recorded by our Doppler Velocity Log

(DVL), using our aforementioned vision pipeline for identifying the bins themselves. To lift the cover, our plan is to leverage our position-based PID controller (discussed below) to accurately position the vehicle, utilising a fixed grabber arm to grab the cover's handle.

Bringing together these task-specific strategies is our mission planner. In previous years, we used a Finite State Machine (FSM) based mission planner due to the abundance of existing resources, and their relative ease of implementation. In our experience however, adding or removing states from an FSM-based planner is prone to human-error by virtue of needing to consider the complexities of the transitions and internal states in the state machine. This is only exacerbated under high-stress conditions, such as within the 15-minute time limit of a run. As such, we moved to a Behaviour Tree (BT) based mission planner this year, and its benefits will be elaborated under the Design Creativity section.

II. Design Creativity

A. Mechanical Sub-System

1) Design of Main Hull

In designing the main electronics hull of the BBAUV 4.0, we looked for ways to reduce wasted space on the vehicle. Noting that most commercially available boards are rectangular, we decided to make the hull rectangular to increase its packing efficiency. Compared to the already packed cylindrical hull of the BBAUV 3.99, the BBAUV 4.0 hull achieves space savings of 50% while preserving previous capabilities.

Rectangular hulls are more susceptible to warping at high pressures, so our hull is made of Computer Numerical Control machined aluminium instead of the usual acrylic pieces. Finite Element Analysis was performed to optimise the shape while ensuring that it could withstand its rated pressure of 3 bars. The hull also contains an internal aluminium wall which improves the structural rigidity of the AUV, while doubling as method of isolating the electrically noisy components (eg. the Electronic Speed Controls) from the sensors, like the Inertial Measurement Unit (IMU) and acoustic systems. We also implemented an innovative slot mounting mechanism, which enables mechanical and electrical modularity (Fig.3).

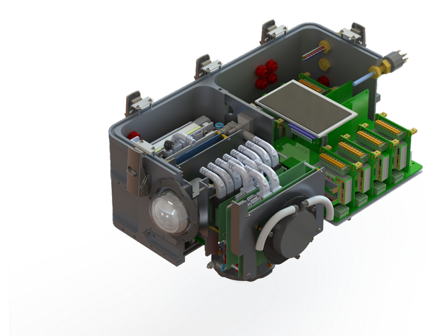

Fig. 3: Internal layout of the main hull.

Our vehicle also has a transparent window to observe internal components and a display screen which highlights the vehicle's internal pressure, battery level and other important indicators.

2) Cooling System

The BBAUV 4.0's cooling system takes advantage of our aluminium hull by using thermal adhesive tape to dissipate heat from our Single-Board Computer (SBC) and Graphics Processing Unit (GPU) directly onto the hull walls (Fig.4) and, by extension, the surrounding water. This simple and passive heat dissipation method obviates the need for additional components and complexity for component cooling.

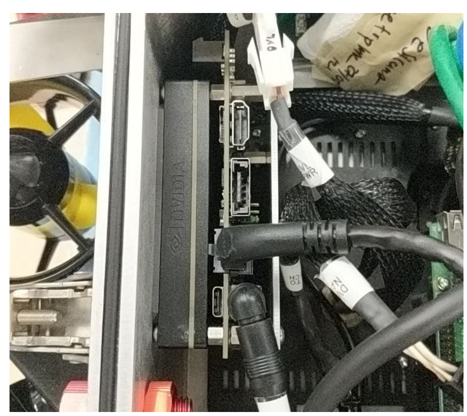

Fig. 4: SBC mounted with thermal adhesive tape.

3) Design of Battery Hull

Another creative aspect of our new AUV is the battery hull, manufactured using novel 3D metal printing technology. We embedded internal lattices and isogrid patterns for the walls and base of the battery hull, increasing the rigidity-to-weight ratio. By using 3D-printing, we were also able to manufacture tight corners, which are difficult to create using traditional methods. This allows the battery to fit exactly into the hull, once again minimising internal space wastage. Together, these factors significantly reduce the vehicle's weight and volume.

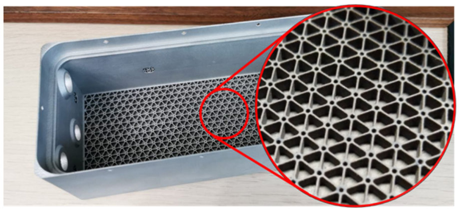

Fig. 5: Isogrid layer of the battery hulls.

The rectangular design of both the main and battery hulls also allows them to be directly connected by right-angled SubConn Low Profile connectors, further cutting weight by reducing the length of cabling required.

4) Design of Actuation Systems

The BBAUV 3.99 previously used a pneumatic system for the ball dropper and torpedo launcher. However, this system requires a buffer to re-pressurise the tank between actuations, and also necessitates a separate hull to contain the pneumatic valves, occupying both weight and space.

Our vision to reduce the weight, footprint and maintenance time of the new BBAUV 4.0 led us to develop an electronically controlled actuation system (Fig.6), removing the need for air canisters and an additional hull.

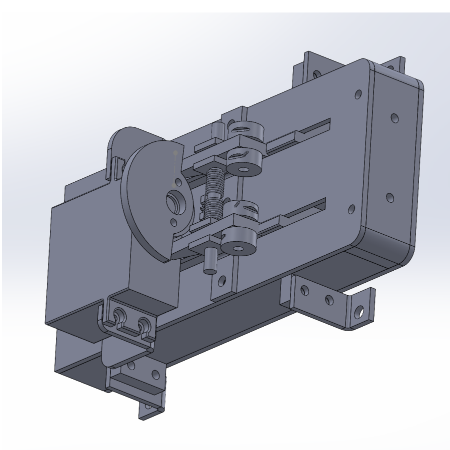

Fig. 6: BBAUV 4.0 Torpedo Launcher.

The new dropper uses a single servo motor to control the position of the blocking arms, while the new torpedo launcher uses a compressed spring and latch system that is actuated via a servo motor. The grabber system utilises the commercial off-the-shelf Blue Robotics Newton Gripper, due to its robustness and simplicity for tasks that require manipulating PVC pipe obstacles.

5) AUV Indicator Lights

To provide real-time, at-a-glance feedback of the vehicle's state during autonomous testing and competition runs, the BBAUV 3.99 uses internal LED strips, which are visible through its transparent hull. To maintain this functionality with the BBAUV 4.0's opaque aluminium hull, we developed an in-house RGB lighting system that is entirely enclosed within a Blue Robotics M10 Penetrator, requiring no external cabling. Its low profile design reduces drag, while still being externally visible.

We determined that the off-the-shelf Blue Robotics lights were unsuitable since they could only display a single colour, making it difficult to differentiate between states, or requiring more than one light to do so.

B. Electrical Sub-System

1) Design of Electrical Architecture

There are two main communication channels used in our electrical architecture: Controller Area Network (CAN) and Ethernet. Ethernet is used for systems requiring high bandwidth, while CAN is used for communication between the embedded systems.

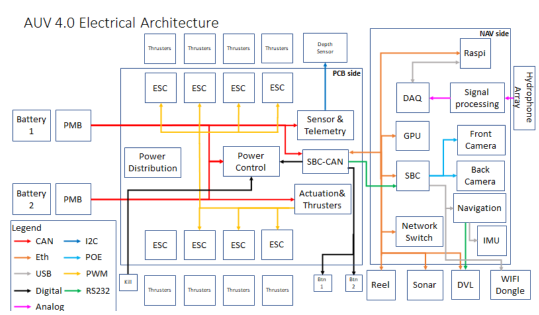

Fig. 7: Communication architecture block diagram.

Our custom-designed Power Monitoring Board reads the battery charge through a fuel gauge IC, allowing us to display an estimate of the remaining

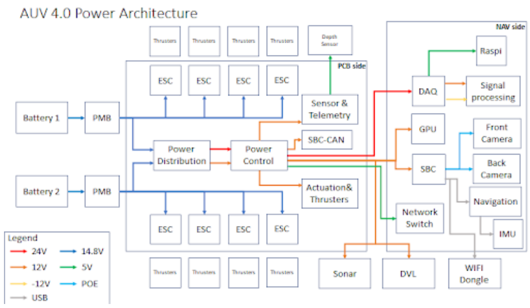

Fig. 8: Power architecture block diagram.

operational run-time of the vehicle. Additionally, this monitoring system allows our control board to prioritise power to systems and selectively disable them in low-power scenarios. Finally, we also integrated an under-voltage protection system that shuts the electronics down to prevent damaging the batteries if their voltage drops too low.

By incorporating a load-balancer between the 2 batteries, we were able to make them hot-swappable, so that the vehicle can remain running during battery changes — minimising operational downtime. Furthermore, sensitive components are protected from any electrical noise with galvanic isolation between internal electronics and inductive loads.

2) *Backplane System*

The backplane design adopted ensures that the electronics are no longer mounted on the end cap, but sit in the hull instead. This allows the electrical system to employ multiple backplanes, segregating the low and high level circuitry into sections. These backplanes can be easily accessed by opening the top lid in a plug-and-play fashion, allowing us to easily remove and replace boards for maintenance without being obstructed by other internal components.

Another benefit of decoupling the backplanes is to allow each system to function independently. This allows failures in the system to be unambiguously traced, making debugging easier. It also isolates electrically sensitive equipment, such as our IMU and acoustics boards, from the electrical noise generated by the other electronics, thus increasing the accuracy of sensor measurements.

3) *Communication network*

To improve inter-system communication, we implemented a CAN link, which enables the SBC to directly connect to systems over the CAN. Additionally, an Ethernet controller is also used to provide direct access to the systems on the CAN without going through the SBC. This redundant connection allows us to access both the CAN and the Ethernet networks even during SBC failure, which lets us retain control over the AUV in such an event. On top of that, we are able to perform remote hard-resets on our electronics by toggling solid state switches, without the need to open the hull.

4) *Acoustic signal processing*

In the BBAUV 4.0, the acoustic subsystem uses an automated programmable gain amplifier that allows us to obtain a uniform amplitude of the incoming ping, enabling more reliable measurements. This results in both a reduction in signal clipping, and consistent outputs regardless of distance from the pinger. Scaling of the amplifier's gain factor is done by comparing the ratio between the optimal and the current amplitude of the ping, which is done on the Data Acquisition (DAQ) board. To increase reliability and reduce false positives, we check the signal-to-noise ratio on the extracted ping, weighted towards known sources of noise. Furthermore, ping extraction is performed using short-time Fourier transformation with a dynamic thresholding method, allowing the ping to be accurately extracted with little latency even in noisy environments.

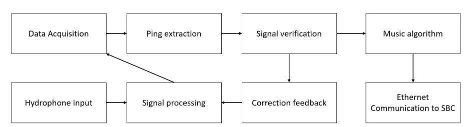

Fig. 9: Acoustics flow diagram.

The TC4013 hydrophones used for localisation can double as transmitters and receivers for acoustic communications. Hence, to integrate communication functionalities into the existing acoustic localisation hardware, additional transmit and receive channels were integrated into the signal conditioning and DAQ board, while firmware was also developed for the DAQ to provide signal encoding and decoding capabilities.

The integration of acoustic inter-vehicular communications into the existing acoustic localisation hardware helps in minimising any cross-interference through precise timing of the communication signals. As a Field-Programmable Gate Array (FPGA) is utilised for processing, communication and data acquisition can be performed in parallel, and the addition of communication functionality does not affect localisation.

We use Quadrature Phase Shift Keying (QPSK) as our modulation technique, as the low transmission sensitivity of the TC4013 results in a low signal-to-noise ratio not suitable for amplitude shift-keying (ASK), and the low bandwidth of frequency shift-keying (FSK) make it undesirable. Error detection is done via an 8-bit Cyclic Redundancy Check (CRC8), and the stop-and-wait automatic repeat-request (ARQ) is utilised to ensure reliable data transfer.

5) *WiFi Integration*

To increase our testing efficiency, we connected a WiFi dongle to the AUV's SBC via USB. This allows us to remote into the vehicle simply by surfacing the vehicle, without having to roll out a tether from our Operator Control System, saving a great deal of time. This allows us to quickly connect to the vehicle to send commands, reconfigure our mission planner and other parameters, or send shutdown/restart commands. As an added benefit, the wireless connection acts as an additional fail-safe connection to the AUV.

C. *Software Sub-System*

1) *Mission Planner*

As previously mentioned, we transitioned to a BT-based mission planner this year due to its flexibility and ease of maintenance. Based on the *BehaviorTree.CPP* package, the BT-based mission planner offers many advantages over the traditional FSM planner. Unlike the layout of an FSM, the BT's tree structure makes it easy to immediately interpret at a glance the robot's behaviour in various situations. This linear structure and the well-defined transitions between node states in a BT also make it easier to configure robot behaviours simply by dragging nodes around, without having to worry about transitions between a large number of states. This allows BT mission planners to react to more situations, while it would take exponentially more states and transitions with an FSM mission planner to achieve similar behaviours.

Not only can nodes be extensively re-used, trees can also be re-used as parts of other larger trees; this high level of composability and abstraction allows us to define increasingly complex robot behaviours with ease. Furthermore, our BT mission planner allows for tree structures and parameters, which are encoded in XML files, to be changed at runtime without requiring code recompilation, saving precious time in competition settings.

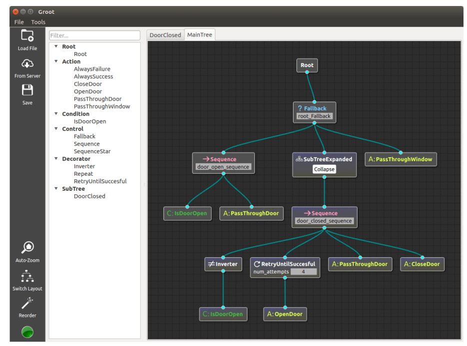

Fig. 10: Sample BT-based mission plan.

We use a graphical BT tool, *Groot* (Fig.10), to easily modify the existing BT using a visual editor. This tool also allows us to observe the BT in real-time as it executes, which is invaluable in saving time and energy when trying to debug the program flow of the mission planner.

2) *Vision Pipeline*

Our system adopts a multi-sensory approach for tracking and localising objects of interest, by fusing the data obtained from the camera and sonar with the AUV's odometry. Various filters and thresholding techniques are used on the sonar image to extract objects of interest. The sonar is used to determine the range R and azimuth θ to the identified objects, while the elevation φ is determined by projecting the φ search space and matching detections from the sonar to that of the camera.

A particle filter is then initialised to track the 3D position and velocity of identified objects. The particle model is updated based on vehicular dynamics, obtained from the DVL and IMU. The robustness of our algorithm is improved by weighting each particle based on several heuristics, such as optical velocity of the sonar pixel and the object dimensions. The particles are then resampled, with those having a higher weight being more likely to be selected.

3) *Control System*

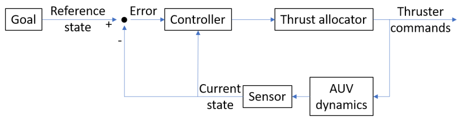

Fig. 11: Unified control architecture.

A unified control architecture was developed to increase the modularity of the existing navigation stack. Its modular design allows us to share the control system for both the BBAUV 3.99 and BBAUV 4.0, mitigating the drawbacks of a dual-vehicle deployment. To accommodate the different thruster layouts on each vehicle, instead of sending thrust commands directly, the control system uses thrust matrices that describe the mapping from each axis of movement to thruster commands, unique for each vehicle.

This modular architecture provides greater code separation between the high- and low-level control of the AUVs, supporting rapid testing and implementation of different low-level control strategies and thruster configurations for each vehicle. It also allows higher-level control strategies, such as the one described below, to be easily reused across our vehicles.

4) *Velocity-based Path Follower*

We developed a path following algorithm based on velocity setpoints, instead of a traditional position-based algorithm. This new algorithm estimates the Menger curvature of the forward path of the vehicle, with a certain look-ahead distance. Based on the curvature of the path and its cross-track error with the vehicle's current position, we calculate velocity setpoints which are sent to the PID control loop, which will calculate the correct thruster outputs to achieve the desired velocity.

In RoboSub 2019, we deployed a purely position-based following algorithm, due to its fine control ability, crucial for the various manipulation tasks. However, that algorithm performed poorly when required to traverse around obstacles, for example during the narrow gate challenge. In situations such as these, we can use the new velocity-based path follower, while retaining the existing position-based follower for tasks requiring precise positioning of the vehicle.

5) *Non-linear PID*

To improve the existing position-based follower, we implemented a non-linear PID controller, which increases the vehicle's responsiveness and minimises the wind-up of the integral term. Using additional feedback from the AUV's current state, we decouple the compensation for higher-order vehicle dynamics, which cannot be easily done using simple linear control schemes. To calculate the optimal gain values for the PID controller, we ran CFD simulations to obtain the vehicle's hydrodynamic properties, which are discussed below.

III. Experimental Results

A. *Pressure Rating*

To ensure reliability of the AUV's hulls, the BBAUV 4.0 was pressure tested at 3 bars of pressure in a pressure testing tank. This confirmed that the vehicle meets its original design specifications, and verifies the reliability of its waterproofing.

B. *Hydrodynamic Model*

A hydrodynamic model of the BBAUV 4.0 was generated (Fig.12) and CFD simulations were conducted to reduce the number of parameters needed to tune the PID controller.

We used control law partitioning to identify relevant system equations, providing a guideline for tuning the controllers. This approach greatly improved the efficiency of PID tuning: we were able to cut down the number of parameters to 1 value per rotational axis, and the time taken to only an hour.

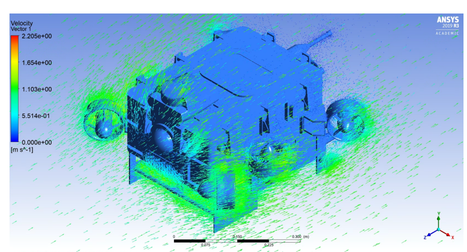

Fig. 12: Flow analysis in Ansys Fluent.

Unfortunately, the hydrodynamic model we developed exhibited discrepancies from the AUV's real world performance during open loop testing, while limited physical testing prevented further tuning of the model. We aim to further develop and refine the model once physical restrictions relax.

C. Cooling system

During bench testing for the operations of the BBAUV 4.0, the IMU magnetometer readings were inaccurate, and we traced the source of the problem to the magnetic field generated by the DC motor in our water cooling pump (Fig.13).

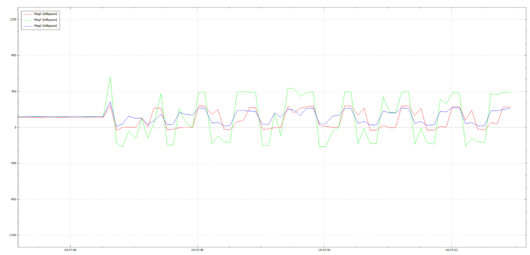

Fig. 13: Magnetic noise generated.

After many attempts to resolve the problem, including encasing the motor in a steel box (while it did reduce the magnetic noise, it was not sufficient), we decided to abandon the liquid cooling system entirely; due to the compact nature of our hull, it was deemed unlikely that we could achieve an acceptable level of isolation between the IMU and the motor that would not affect the magnetometer's accuracy.

As a replacement, we developed a new design for the cooling system as previously mentioned. To evaluate the new cooling solution for the AUV, a 1-hour stress test was conducted on our Jetson Xavier and SBC, and maximum temperature data was collected. We found that the temperatures of our SBC and GPU hit a maximum of 68°C, which is well below the maximum recommended temperature of 80°C.

D. Gazebo-ROS Simulator

In view of the COVID-19 pandemic, physical testing of the AUV system was suspended; to support continuous development of our software stack, we developed a simulator for the new AUV (Fig.14).

The AUV simulator was developed on top of the *UUV Simulator*, a package that contains Gazebo plugins and ROS nodes for simulating physics and sensors of AUVs. Through both hydrodynamic simulations and real world testing, we were able to finely tune our vehicle's parameters, based on the

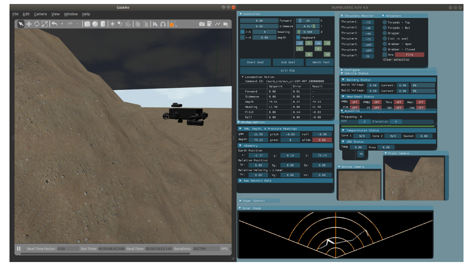

Fig. 14: Gazebo-ROS AUV simulation.

Fossen model for nonlinear modelling of underwater vehicles [1].

A custom sonar plugin was also developed for the simulator to simulate the Oculus sonar on the BBAUV 4.0. The sonar image is generated from the aerial perspective of a point cloud obtained from a depth camera plugin offered by Gazebo.

This end-to-end simulator allows new features to be quickly tested in a virtual environment for logic and architecture issues, helping to speed up processes by tightening the feedback loop between writing and testing code, decreasing turnover times for more agile software development.

As mentioned above in the competition strategy, we have also added task obstacles to the simulator this year, which allows us to quickly and effectively prototype our task-specific logic for our mission planner.

E. MATLAB Simulator

A simplified simulator was designed in *MATLAB Simulink* using the multibody add-in (Fig.15); it is designed with the sole purpose of simulating the vehicle model and control systems of our AUV with high fidelity.

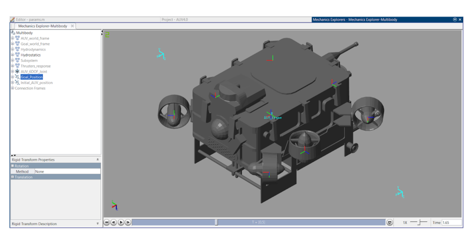

Fig. 15: MATLAB simulation.

The use of blocks in *Simulink* (Fig.16) facilitates rapid experimentation and tuning of different control schemes.

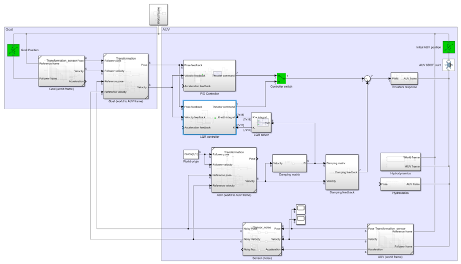

Fig. 16: Simulink blocks for the simulator.

This also allows members from the Mechanical sub-team, who are not as well-versed with the software architecture, to work on developing and tuning control systems directly. This simulation stack allows us to iterate more quickly when tuning the control system, and in conjunction with the hydrodynamic simulation discussed above, lets us quickly and effectively tune our controls system.

ACKNOWLEDGEMENTS

Team Bumblebee's development and achievements would not be possible without the help from various organisations and people. The team would like to express their deepest gratitude to the sponsors (Refer to Appendix C), including the Title Sponsors — National University of Singapore (NUS), and Platinum Sponsors — DSO National Laboratories, and Future Systems and Technology Directorate (FSTD). In addition, the team would also like to thank Sport Singapore and the Republic of Singapore Yacht Club for their continuous support.

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APPENDIX A
COMPONENT SPECIFICATIONS

Component	Vendor	Model/Type	Specifications	Cost
Main Hull	Samco Enterprise, Feimus Engineering	Custom Aluminium Milling	Custom	\$2,700
Frame	Cititech Industrial	Custom Aluminium Laser-cut	Custom	Sponsored
Battery Hull	SLM Solutions	Custom Aluminium Selective Laser Melting	Custom	Sponsored
Waterproof Connectors	SubConn Inc., MacArtney	Assorted Micro and Low-profile Series	Peak Depth: 300 bar	Sponsored
Thrusters	Blue Robotics	T200	—	\$176 ea
Motor Control	Blue Robotics	Basic ESC	—	\$27 ea
High-level Control	Raspberry Pi	RPi 3 Model B+	1.4GHz 64-bit quad-core processor	\$39
Actuators/ Manipulators	In-house	Custom design	ABS	Sponsored
Battery	Tattu	Custom-made 4-cell battery	16000 mAh	\$120 ea
Battery Monitoring System	In-house	Custom-made circuit board	Custom	Sponsored
Power Isolator	Murata	UWQ-12/17-Q48PB-C	204W Isolated 24V-12V	\$52
		UVQ-24/4.5-D24P-C	108W Isolated 24V-12V	\$67
Single Board Computer	AAEON	GENE-KBU6	Intel Core i7-7600U	Sponsored
		BIO-ST03-P2U1	Intel i210	
GPU	Nvidia	Jetson Xavier	AGX Module	\$999
Internal Comm Network	In-house	CAN/Ethernet	1000kbps/1000Mbps	Sponsored
External Comm Interface	In-house	Ethernet	1000Mbps	Sponsored
IMU	Sparton	AHRS-8P	$\pm$1.2 Gauss	Sponsored
Doppler Velocity Log	Teledyne Marine	Pathfinder DVL	600kHz Phased Array	\$16,000
Camera(s)	BlackFly S PoE Gigabit Camera	BFS-PGE-31S4C-C	2448×2048 at 22 FPS	\$594
Hydrophones	Teledyne Reson	TC4013	Acoustic transducers	Legacy
Sonar	Oculus	M750d	Dual-Frequency Multibeam Sonar (750KHz/1.2MHz)	\$21,300
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	—	—	35	—
Hardware/ Software expertise ratio	—	—	3:1	—
Testing time: simulation	—	—	200 hours	—
Testing time: in-water	—	—	40 hours	—

APPENDIX B
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, who have supported us throughout the years. In order to bolster our relationship with the community, Team Bumblebee strongly believes in sharing our knowledge and experiences with the community.

A. Lab Tour and Sharing Sessions

As part of Team Bumblebee's public relations campaign, the team extended invitations to various international teams for visits to our lab, so as to exchange knowledge and build lasting friendships.

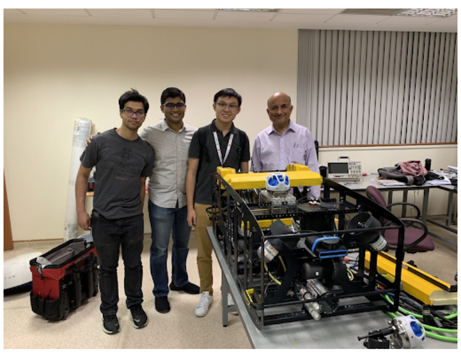

Fig. 17: Lab visit by a professor from Florida.

Despite the COVID-19 pandemic, we have received multiple emails from teams interested in starting their own robotics team. We have engaged them enthusiastically, and hope to meet them in the future at competitions.

B. Industrial Partnership and Appreciation

Industrial partners are essential for the sustainability of Team Bumblebee. Without their support, our team would not have been able to achieve or sustain excellence. Therefore, industrial visits are organised with industrial partners to gain experience and first-hand exposure to real-world challenges.

SLM Solutions is one of our latest sponsors, who have assisted us in manufacturing the battery hulls for our new BBAUV 4.0 using metal 3D-printing as discussed above.

Fig. 18: Industrial visit to SLM Solutions.

Fig. 19: Collaboration with a local secondary school.

C. Collaboration with Local Schools

Team Bumblebee is collaborating with a local secondary school to conduct robotics lessons to inspire the students of age 13–16. The program aims to teach the students the basics of AUVs, and provide guidance for them to design and build their very own AUV.

D. Recruitment of New Members

Fig. 20: Online recruitment session.

In order to engage new students starting their university journey, an online recruitment drive was held as part of the NUS's Engineering Life fair, *E-genium*. This has provided Team Bumblebee with the opportunity to reach out to a wide audience of freshmen who might be interested in the program, and entice them to join the team.

E. Hornet Training Program

Fig. 21: Team Hornet working on their Hornet 6.0 vehicle.

Since its inception 6 years ago, the Hornet Training Program has evolved into a staple element of training for the freshmen in our team. Through this program, we provide new members a platform to build an AUV to compete in the Singapore AUV Challenge. Our main objective is to challenge the freshmen to explore and implement bold designs instead of replicating what others and their predecessors have done.

APPENDIX C
SPONSORS

A. Title Sponsors

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

B. Platinum Sponsors

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

DSO National Laboratories — For cash support and technical guidance.

C. Gold Sponsors

Festo, Cititech Industrial Engineering, Kentronics Engineering, MacArtney Underwater Technology, Würth Electronik, AAEON Technology, SLM Solutions and Fugro.

D. Silver Sponsors

Bossard, SolidWorks, MathWorks, Southco, Samtec and Sparton.

E. Bronze Sponsors

Edmund Optics and Richport Technology.

F. Supporting Organisations

Republic of Singapore Yacht Club and Sports Singapore.