RoboSub 2022 Technical Design Report

National University of Singapore (Bumblebee Autonomous Systems)

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***Abstract*—For RoboSub 2022, Team Bumblebee's strategy involves deploying the BBAUV 4.0 to efficiently complete all tasks. The mechanical design of the BBAUV 4.0 optimises for space and weight, yielding vastly superior manoeuvrability while eliminating the weight penalty of the BBAUV 3.99. Electrical work centred on testing and integrating new sensors, as well as improving overall system reliability. Software development focused on an updated behaviour-tree mission planner, improvements to the controls system, and driver development for our new sensors. Physical testing was conducted at a steady pace, and was supplemented using hydrodynamic simulations to tune the AUV's control systems.**

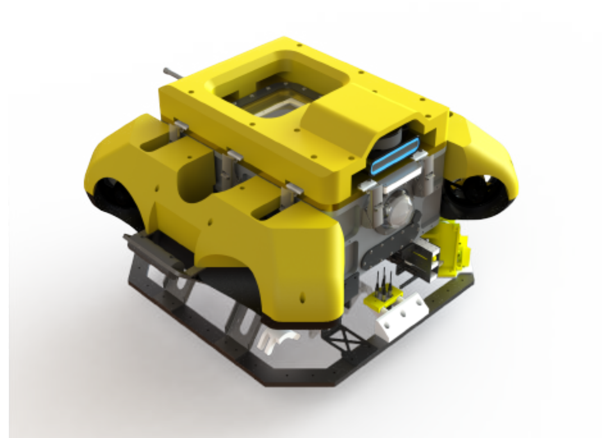

Fig. 1: 3D model of the BBAUV 4.0.

I. COMPETITION STRATEGY

For RoboSub 2022, we plan to deploy our BBAUV 4.0 (Fig.1) to complete all competition tasks. Taking advantage of the lack of physical RoboSub competitions these past 2 years, we have iterated tirelessly on our newest vehicle, and have achieved feature parity with our older BBAUV 3.99.

A. Competition Vehicles

During RoboSub 2021, our team strategy dictated that both the BBAUV 3.99 and BBAUV 4.0 be deployed. However, after extensive testing, the team has opted to deploy only BBAUV 4.0 this year in light of its superior overall performance.

A much smaller and lighter vehicle, BBAUV 4.0 was purpose-built for tackling RoboNation competitions unlike the BBAUV 3.99, which falls behind in both speed and weight. In addition, limitations for further improvement due to legacy issues inherent to BBAUV 3.99 led us to shift our focus to BBAUV 4.0 as our primary competition-ready vehicle. After intensive upgrading and tuning, we are confident that the BBAUV 4.0 can complete all competition tasks faster than BBAUV 3.99 ever could.

B. Course Strategy

For our task strategy, we employ a sensor fusion approach; our vision pipeline combines sonar images with machine learning (ML) object detection to accurately localise and identify task objects, like the buoys in *Make the Grade* or the torpedo openings in *Survive the Shootout*. Thus our strategies for these, plus *With Moxy* and *Choose Your Side*, are similar: approach the targets using localisation from our vision pipeline before performing task-specific actions. For final alignment and adjustments, we exclusively use ML object detection, as our sonar cannot reliably detect objects at close proximity.

The *Collecting* and *Cash or Smash* tasks are also handled exclusively by ML object detection, since we are unable to use the sonar for bottom-facing tasks. We track the centroids of the detected objects, precisely adjusting the AUV's alignment using our highly accurate Doppler Velocity Log, together with a revamped controls system. Since both tasks require grabbing actuation, we also designed a versatile grabber capable of performing both tasks, yet small enough to fit within our size constraints (see *Design Creativity*).

Bringing together these task-specific strategies is our mission planner. Previously, we used a Finite State Machine (FSM)-based mission planner due to the abundance of existing resources and its relative ease of implementation. However, we found that modifying states in an FSM-based planner is error-prone due to the complex transitions and internal states of the FSM. This is further exacerbated by high-stress conditions like the 15-minute window of a run. As mentioned in last year's paper, we have since moved to a Behaviour Tree (BT)-based planner. After a year of extensive usage, we have identified its flaws and developed a second, improved version which will be discussed below.

II. Design Creativity

A. Mechanical Sub-System

1) Design of Main Hull

We chose a rectangular hull for BBAUV 4.0 to get efficient packing for internal components and electronics. Finite Element Analysis was used to ensure our design could withstand the 3 bars of pressure expected during operation. A centre divider wall within the hull gives rigidity while isolating electrically noisy components from the sensors.

A fibreglass float fits on the outside of the hull, making it much more resilient to external impacts while maintaining superior manoeuvrability. A 3D-printed shell was designed to fit below the fibreglass floats (Fig.1), including cavities for buoyancy tuning via float insertions. More floats on the top cover protect the sonar while adding buoyancy. These exterior coverings are designed not to interfere with opening the hull, enabling faster access during testing. This protective layer gave us the confidence to bump into the buoy for *Make the Grade*.

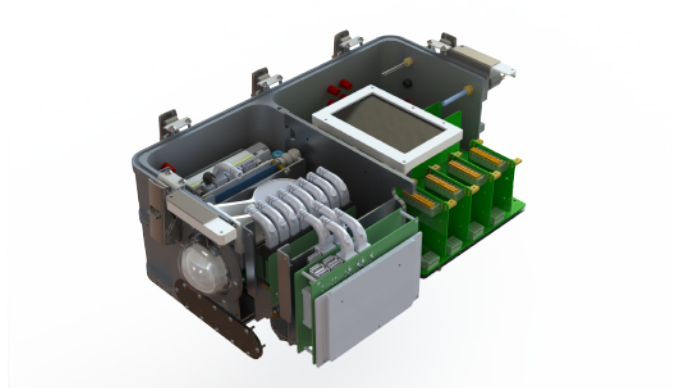

Fig. 2: Internal layout of the main hull.

The new octagonal mounting frame of BBAUV 4.0 allows for more actuation modules to be mounted while still being protected. Carrying handles were also added for ease of operation and handling.

2) Design of Battery Hull

Another creative aspect of our new AUV 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). Unlike traditional methods, 3D printing allows for tight corners, giving our battery a snug fit. Together, these factors significantly reduce the vehicle's weight and volume.

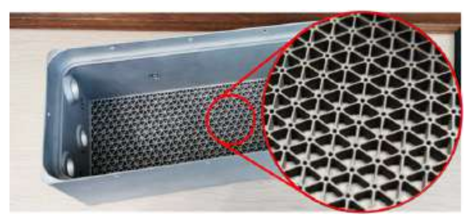

Fig. 3: Isogrid layer of the battery hulls.

The main and battery hulls are directly connected with right-angled SubConn Low Profile connectors, reducing the length of cabling required.

3) Design of Actuation Systems

The bulky newton gripper of years past was replaced with a smaller claw, utilising bevel gears and a stepper motor (Fig.4); the claws tuck neatly under the hull to reduce their footprint. We can grab both vertical and horizontal objects with the same claw, completing *Collecting* and *Cash and Smash* by picking up the lid and bottles respectively.

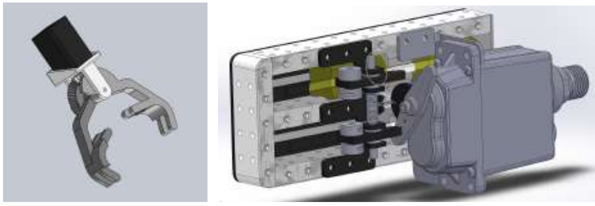

Fig. 4: BBAUV 4.0 Grabber and Torpedo Launcher.

Our ball dropper and torpedo launcher use the Bluetrail underwater servo (Fig.4); while larger than our old custom servos, it markedly enhances the reliability and depth rating of both actuators.

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 embedded systems.

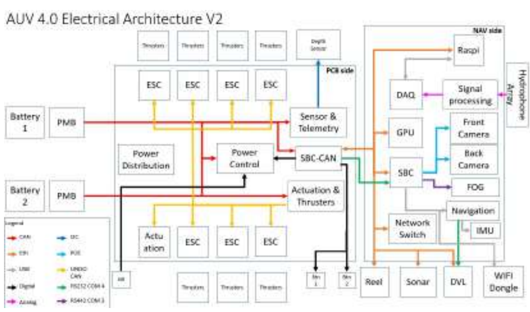

Fig. 5: Communication architecture block diagram.

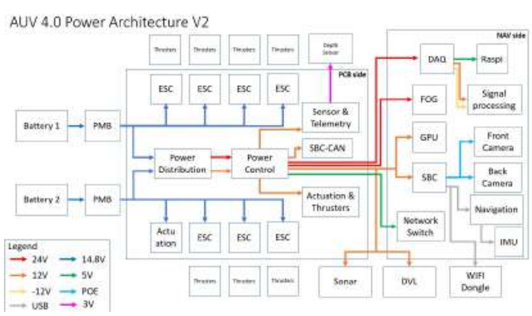

Fig. 6: Power architecture block diagram.

Our custom-designed Power Monitoring Board reads the battery charge via a fuel gauge IC, letting us show the estimated operational time on the vehicle's display. Additionally, this monitoring enables our control board to selectively prioritise and disable systems during low-power scenarios. Finally, an under-voltage protection system is also integrated; electronics are disabled to prevent damaging the batteries if their voltage drops critically.

Our batteries are hot-swappable by means of a load-balancer between them; the vehicle can stay running during swaps, minimising operational downtime. Sensitive components are also protected from electrical noise via galvanic isolation between internal electronics and inductive loads.

2) Backplane System

Our backplane system lets the electronics sit in the hull, instead of being mounted on the end-cap. This gives the electrical system flexibility to use multiple backplanes, separating the high- and low-level circuitry. These backplanes are easily accessed by opening the top lid, and individual boards can be replaced in a plug-and-play fashion. This lets us perform maintenance without being obstructed by other components.

Another benefit of separate backplanes is that each system can function independently; this allows any failures to be quickly traced, easing debugging. It also isolates electrically sensitive equipment, such as our IMU and acoustics boards, from the electrical noise generated by the other electronics, thus increasing sensor measurement accuracy.

3) Acoustic Signal Processing

The BBAUV 4.0's acoustic subsystem uses an automated programmable gain amplifier that gives us a uniform amplitude of the incoming ping, enabling more reliable measurements. This results in both a reduction in signal clipping, and consistent output 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 low latency even in noisy environments.

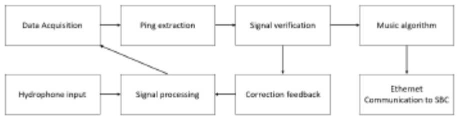

Fig. 7: Acoustics flow diagram.

4) Fibre-optic Gyroscope

A new fibre-optic gyroscope (FOG) was installed to complement our IMU, which has trouble when around ferrous objects, such as pool walls. The new sensor has a low rate of drift, and is much more impervious to external electromagnetic interference than our IMU. Using our existing sensor-fusion pipeline, we are able to combine the absolute heading given by the IMU together with the relative angular velocity reported by the FOG.

C. Software Sub-System

1) Mission Planner

As previously mentioned, we switched to a BT-based mission planner last year for its flexibility and maintenance ease. Based on the *BehaviorTree.CPP* package, it has many advantages over a traditional FSM planner, like being able to quickly interpret the AUV's behaviour. The linear structure and well-defined node transitions also make it easier to configure robot behaviours simply by repositioning nodes, without accounting for innumerable state transitions. This lets our planner accommodate more situations, whereas an FSM would require exponentially more states and transitions to compete.

BT planners also give us a high level of composability and abstraction: both nodes and subtrees can be reused, allowing us to define increasingly complex robot behaviours easily. Furthermore, our planner allows for tree structure and parameter configuration at runtime without recompilation, saving precious time in a competition setting.

After a year of testing by our software team, we discovered several flaws with our initial implementation, which we hope to rectify with our new version. The first version was based on the ROS 2 navigation stack, and suffered from being overly generic. Adding new nodes involved many error-prone steps, while the extensive use of configuration files proved cumbersome since many options were not relevant for us. Our new planner greatly simplifies this by loading nodes on a per-package basis, instead of repeatedly defining them in configuration files. In addition, nodes interfacing with ROS topics, services, etc. were rewritten to better fit the ROS 1 paradigm.

2) Machine Learning Pipeline

We completely revamped our machine learning pipeline this year, making it faster and more modular. Instead of a mixture of Python 2 and Cython, we now use Python 3 for easier maintainability without sacrificing speed. The new modular design also allows additional models to be added in the future, eg. models with rotated bounding boxes, which would be useful for *Cash or Smash* in detecting the lid orientation. We also refactored our existing YOLOv5-based architecture to allow the use of TensorRT, letting us leverage device-specific optimisations, maximising our Nvidia Jetson Xavier's potential and gaining a 2x FPS increase.

3) Control System

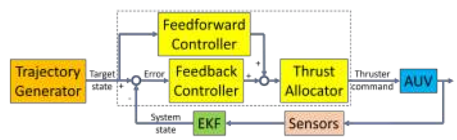

Fig. 8: Control architecture.

We implemented a trajectory generator to create smooth continuous paths for the AUV to follow. The trajectories are calculated using linear segments with polynomic blend, with limits on the maximum velocity, acceleration, and jerk of the vehicle. This improved performance for distant setpoint goals by avoiding controller saturation.

The control system makes use of control law partitioning, including a full state feedback controller which enables positional and velocity tracking, and a feed-forward 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. Experimental Results

A. Thruster ESC

During initial testing, the vehicle's heading was found to oscillate heavily during forward motion.

The issue was found to be caused by the latency of the ESCs used to control the T200 thrusters.

Three models of ESCs were tested: Tekin RX8 Gen2, Blue Robotics Basic ESC, and Flipsky Mini FSESC4. The Tekin ESC initially designed for the BBAUV 4.0 had the largest latency at 300 ms, the Blue Robotics ESC yielded 130 ms, while the Flipsky had a latency of only 5.3 ms. Since our controls system runs at 20 Hz, the delay of the Tekin and Blue Robotics ESCs were very significant at 3-5 timesteps, greatly degrading the AUV's performance.

The modules for each ESC model were tested with an Arduino MEGA and a CAN Shield. With an oscilloscope, the latency was measured from the trigger signal edge till the time when the ESC output changed.

For the Blue Robotics ESC, a delay of approximately 130 ms was observed. This large delay between the input signal (CH1 in yellow) and the thruster output changing (CH2 in blue) causes oscillations when tuning the controls system.

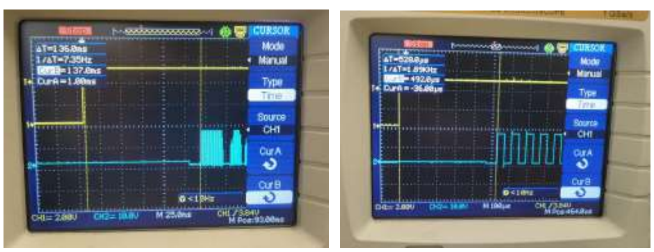

Fig. 9: Oscilloscope data for Blue Robotics ESC (left) and Flipsky Mini FSESC4 (right); note 25 ms vs 100 µs time division.

Through our testing, we settled on the Flipsky Mini FSESC4 with its relatively quick response of 500 µs. After switching over to the Flipsky Mini FSESC4, the performance of the BBAUV 4.0 greatly improved, reducing the heading oscillation during forward motion.

B. Kill Switch Interference

We realised that there was some interference with the kill switch in certain pool environments, due to the metallic body of the AUV 4.0 chassis being grounded. Initially, we were attaching a PMOS switch to the kill switch; in some cases, the conductivity of the pool water was high enough to connect the kill switch contacts to chassis ground, thus activating the switch by pulling it to ground. To increase reliability, the kill switch circuitry was changed to use an NMOS gate that needs to be pulled up to 5V to activate.

C. FOG Calibration

Calibration data was not available to us for the FOG sensor, so we had to perform our own in-lab calibration; we gathered readings from the sensor over a range of rotations and temperatures, then plotted them in MATLAB. We then performed a surface fit on the data to get a polynomial equation that allows our software to convert the voltage output from the sensor into angular velocity.

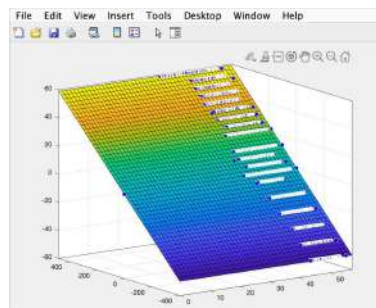

Fig. 10: MATLAB plot of FOG sensor reading data

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.

REFERENCES

[1] T. I. Fossen, Handbook of marine craft hydrodynamics and motion control. Hoboken N.J.: Wiley, 2021.

APPENDIX A
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	16000 mAh	Purchased	$120 ea	2019
Battery Monitoring System	In-house	Custom-made circuit board	—	Custom	Sponsored	2022
Power Isolator	Murata	UWQ-12/17-Q48PB-C	204W Isolated 24V-12V	Purchased	$52	2019
		UVQ-24/4.5-D24P-C	108W Isolated 24V-12V	Purchased	$67	
Single Board Computer	AAEON	GENE-KBU6	Intel Core i7-7600U	Purchased	Sponsored	2019
		BIO-ST03-P2U1	Intel i210			
GPU	Nvidia	Jetson Xavier	AGX Module	Purchased	$999	2019
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	±1.2 Gauss	Purchased	Sponsored	2019
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	—	—	35	—	—	—
Hardware/ Software expertise ratio	—	—	3:1	—	—	—
Testing time: simulation	—	—	100 hours	—	—	—
Testing time: in-water	—	—	200 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, to exchange knowledge and build lasting friendships.

Fig. 11: Lab visit by a professor from Florida.

Despite the COVID-19 pandemic, we have received multiple emails from groups 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 regularly 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. 12: Industrial visit to SLM Solutions.

Fig. 13: 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 between from ages 13–16. The program aims to teach the students the basics of AUVs, while providing guidance for them to design and build their very own AUV.

D. Recruitment of New Members

Fig. 14: Online recruitment session.

In order to engage new students starting their university journey, an online recruitment drive was held as part of the NUS Engineering Life fair, *E-genium*. This allowed Team Bumblebee the opportunity to reach out to a wide audience of potentially interested freshmen, giving us the chance to entice them to join the team.

E. Hornet Training Program

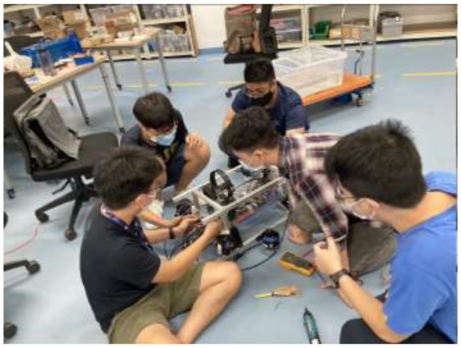

Fig. 15: Team Hornet working on their Hornet 7.0 AUV.

Fig. 16: Team Hornet testing their Hornet 7.0 AUV.

Since its inception 7 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 (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.

C. Gold Sponsors

Fugro, Festo, Cititech Industrial Engineering, Kentronics Engineering, Würth Electronik, AAEON Technology, SLM Solutions, SBG Systems, and Avetics.

D. Silver Sponsors

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

E. Bronze Sponsors

Edmund Optics.

F. Supporting Organisations

Republic of Singapore Yacht Club and Sports Singapore.