National University of Singapore (BumbleBee Autonomous Systems)

Design and Implementation of BBAUV 4.0

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Abstract - ***BumbleBee Autonomous Underwater Vehicle (BBAUV) 4.0 is the product of a team of undergraduates from the National University of Singapore (NUS). BBAUV 4.0 is a ground-up redesign of the mechanical and electrical system, improving the performance and stability of the vehicle, as well as an increased focus on software control systems. This paper discusses the design of BBAUV 4.0 and the improvements over our previous vehicles.***

1. Competition Strategy

BBAUV 4.0 represents a complete overhaul of the mechanical hull to a fully integrated design. The weight and size of the AUV has been significantly reduced, to avoid scoring penalties and increased maneuverability.

In view of the pandemic and restricted access to our workshop and testing facilities, software simulators were developed to test the vehicle.

2. Vehicle Design

Mechanical Sub-System

Figure 1: 3D model of BBAUV 4.0

Consolidated main hull

Our new AUV design weighs 24kg at neutral buoyancy, less than half that of our previous vehicle. This was achieved in part by consolidating the electronics into one main hull.

To maximise the space usage within the frame and hull, the main hull was redesigned to be rectangular. This increased the packing efficiency of the rectangular PCBs in the main hull, and eliminated the need for the majority of the sub-hulls. The new hull also allows for easier access to each electrical component in the hull for simpler troubleshooting.

The CNC machined main hull was partitioned to 2 compartments, separating the power handling components from the signal and data processing electronics. The aluminium partition wall provides structural support to the hull and aids in isolating electrical noise.

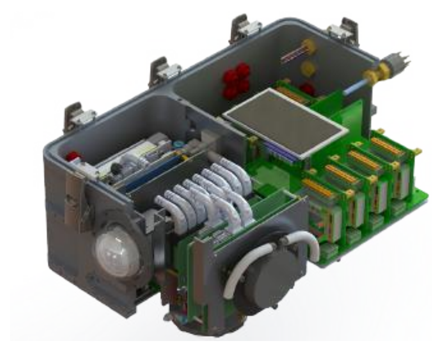

Figure 2: Internal layout of main hull

Redesigned battery sub-hull

The battery sub-hulls were redesigned to snuggly contain the batteries. The hulls were manufactured using SLM 3D printing, which allowed us to use an internal lattice and isogrid patterns for the walls and base of the sub-hull. This drastically increased the stiffness to weight ratio of the hull. The volume of the battery hulls was reduced from 3L to 1.6L, and weight from 1440g to 640g.

Figure 3: Lattice layer of battery hulls

Actuation

The new dropper and torpedo designs in BBAUV 4.0 utilize electrically operated switches and compressed springs, diverging from the previous pneumatic systems. This removed the need for an air tank and reduced the weight of the entire system. Moreover, this reduces the complexity of maintenance and reloading of the system, as there is no need to deal with the recharging of compressed air.

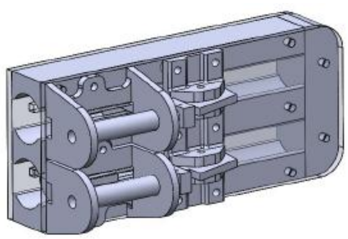

Figure 4: 3D model of torpedo launcher

To operate the launcher, 2 torpedoes will be loaded into two firing chambers to compress the internal springs. To fire, servos will activate to disengage the latches holding the torpedoes, releasing them.

Electrical Sub-System

Electrical Architecture

There are two main communication channels used in this electrical architecture, namely Controller Area Network (CAN) and Ethernet. CAN is used for communication between the embedded systems, while Ethernet is used for components that require high bandwidth.

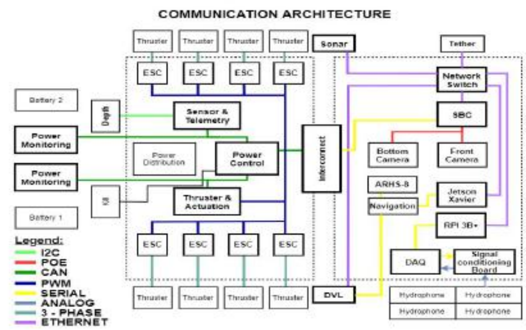

Figure 5: Communication architecture block diagram

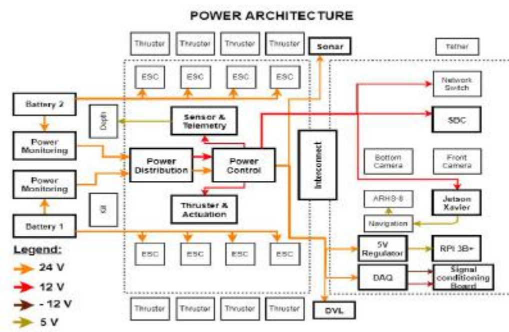

Figure 6: Power architecture block diagram

The power architecture utilises a load balancing system to draw power from two batteries. This provides a hot swap feature, that allows the changing of batteries without having to shut down the vehicle. Additionally, the galvanic isolation between internal electronics and inductive loads protects the sensitive components from any electrical noise.

The Power Monitoring Board controls and monitors the main power lines of the vehicle. By reading the state of charge of the battery using a battery fuel gauge IC, the board is able to approximate the remaining runtime of the AUV.

Modular Design

With the new design, the electronics are no longer mounted on the end cap, but instead sit in the hull. This allows the electrical system to employ multiple backplanes, segregating the low level and high level circuitry into sections. These sections of the system can be easily removed without taking apart the vehicle. The components can be easily accessed after opening the top lid and replacement can be done effortlessly in a plug-and-play fashion.

Another advantage of the decoupled design is allowing each system to function independently. Failures in any system can be unambiguously traced, making debugging easier. The separated backplane also allows for equipment sensitive to electrical noise, such as the IMU and acoustics, to be physically isolated, providing further protection from the other parts of the system.

STM32 Microcontrollers

For BBAUV 4.0, STM32 microcontrollers were used in place of the previous ATmega microcontrollers. This provides functionalities such as in-system debugging and the ability to process more information at higher communication bandwidth.

The STM32 microcontrollers include an integrated CAN controller interface, which eliminates the need of an external CAN circuitry. This greatly simplified the design and space required (⅓ the original space).

The new CAN system improves the data bandwidth by 75% (200 frames/s to 350 frames/s). The increased capacity paves the way for inter-AUV communication through a single CANBUS channel.

Inter-System Communication

A CANBUS link and Ethernet controller were employed to establish communication within the vehicle. The CANBUS link allows the SBC to interface with the CANBUS network, and the Ethernet controller is used to provide an access point to the CANBUS using ethernet.

As the ethernet controller is not reliant on the SBC, full control of the vehicle is maintained even in the event of an SBC failure.

The ability to directly access lower level systems provides the capability to perform hard-reset of the electronics remotely via the toggling solid state switches, without having to open the hull.

Acoustic sub-system

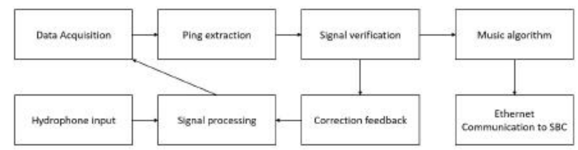

Figure 7: Acoustics flow diagram

The Acoustic subsystem features a signal processing board which includes a programmable gain amplifier. It is automated to ensure a uniform amplitude of the incoming ping which allows for a consistent result regardless of the proximity from the pinger and prevents clipping of signal at the same time. The data acquisition board (DAQ) compares the ratio between current amplitude of the ping and the optimal amplitude, and scales the gain factor of the amplifier accordingly.

In order to accurately extract the relevant incoming acoustic pings, a dynamic thresholding method based on short-time fourier transform is used. In addition, an SnR check weighted towards known sources of noise is done on the extracted ping, to ensure that the extracted signal is not a false positive.

Software Sub-System

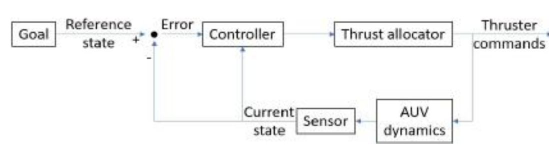

Figure 8: High-level design of AUV controls

Unified Control Architecture

A unified control architecture was developed to increase the modularity of the existing navigation stack. The new navigation stack allows for high-level control strategies, such as that for path planning and path following, to be re-used easily across multiple vehicles. Instead of sending desired thrust commands directly to thrusters for each vehicle, matrices describing desired thruster mappings are generated for each AUV, which uniquely convert controller commands into target thrust of each thruster, depending on the low-level control strategies used.

The modularised architecture allows for a cleaner separation of code for high-level and low-level control of the AUVs. This supports rapid testing and implementation of different low-level control strategies and thruster configurations for each vehicle.

New Path Following with Velocity Setpoints

For BBAUV 4.0, path following capabilities were added to allow for greater control of the AUV, as compared to the previous position-based controller. In order to accomplish accurate path following, precise control in both the position and velocity space was required.

The new path following algorithm estimates the menger curvature of the path ahead of the vehicle within a certain look ahead distance. Velocity setpoints are then calculated based on the sharpness of the curvature and the cross-track error between the path ahead and the vehicle's current position. The PID control loop then calculates the thrust required for the vehicle to attain the current velocity setpoint.

In Robosub 2019, a purely positional-based controller was adopted for its ability to provide the fine controls necessary to attempt the various manipulation tasks. However, this implementation required a significant amount of time to traverse around obstacles, such as when attempting the narrow gate challenge. The new path tracking algorithm provides both position and velocity space control, allowing for faster movements, without compromising the precise controls needed for the various manipulation tasks.

Non-linear PID

A non-linear PID was implemented for positional control of the vehicle. The non-linear PID improves the response of the vehicle, and minimises the issue of wind-up of the integral term. The model dynamics obtained from the CFD simulations allow for simpler tuning of PID values as the optimal gain values can be calculated empirically from target frequency and damping coefficient.

Additional feedback of the current state of the AUV decouples the compensation for higher-order vehicle dynamics, which cannot be easily dealt with using simple linear control schemes. The quadratic gain values are calculated from the vehicle hydrodynamic properties obtained from the CFD simulations.

Computer Vision

Our system adopts a multi-sensory approach for tracking and localising objects of interest, by fusing the data obtained from the camera and FLS 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 φsearch 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 DVL and IMU. The robustness of our algorithm is improved by assigning a weightage to each particle based on several heuristics, such as optical velocity of the sonar pixel and the object dimensions [1]. The particles are then resampled, with those having a higher weightage being more likely to be selected.

3. Experimental Results

Fluid Dynamics Simulation

Computational fluid dynamics (CFD) simulation of the vehicle was performed in ANSYS Fluent to obtain the hydrodynamic properties of the vehicle, such as damping coefficient and added mass matrix.

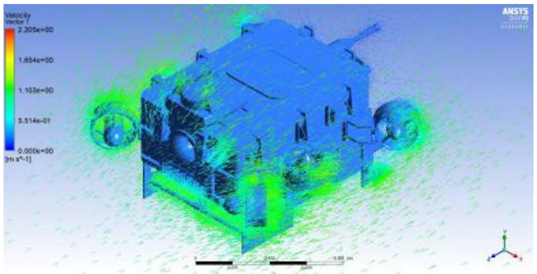

Figure 9: Flow analysis in ANSYS Fluent

The simulations allowed for more accurate model-based simulations for design of the control systems without performing pool tests.

Software Gazebo-ROS Simulator

In view of the Covid-19 pandemic, physical testing of the AUV system was suspended. To support continuous development, a simulator was developed for the AUV.

Figure 10: Gazebo-ROS AUV simulation

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 underwater autonomous vehicles. The Fossen model [2] for nonlinear modelling of underwater vehicles was used, with both linear and quadratic damping tuned to better model AUV's real-life behaviour.

A sonar plugin was 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.

The end-to-end simulator developed allows new features to be quickly tested in a virtual environment for logic and architecture issues. This helps to speed up processes by tightening the feedback loop between writing and testing code, decreasing turnover times for more agile software development. Simulation testing allows us to quickly prototype our task specific mission logic.

MATLAB Simulator

A simplified simulator was designed in Matlab simulink using the multibody add-in.

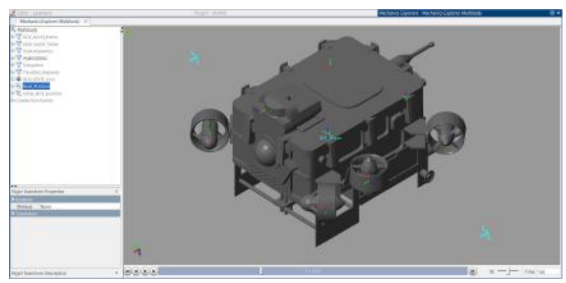

Figure 11: Matlab simulation

The use of blocks in simulink allows for rapid experimentation and tuning of different control schemes.

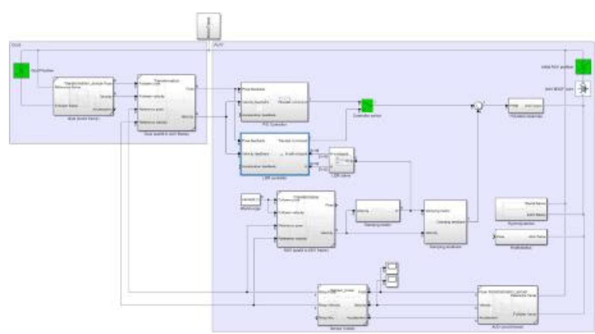

Figure 12: Simulink blocks for the simulator

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.

4. Acknowledgements

Team BumbleBee's development and achievement 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 I), including Title Sponsors - National University of Singapore (NUS), and the Platinum Sponsors - DSO National Laboratories, Future Systems and Technology Directorate. In addition, the team would also like to thank the Sport Singapore and Republic of Singapore Yacht Club for their continuous support.

5. References

[1] Y. Raaj, A. John and T. Jin, "3D Object Localization using Forward Looking Sonar (FLS) and Optical Camera via particle filter based calibration and fusion," OCEANS 2016 MTS/IEEE Monterey, Monterey, CA, 2016, pp. 1-10. doi: 10.1109/OCEANS.2016.7761077, Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7761077&isnumber=7760990

[2] Fossen, T. I. (2014). *Handbook of marine craft hydrodynamics and motion control*. Chichester: John Wiley & Sons. ISBN: 978-1-119-99149-6

Appendix A: Component Specifications

Components	Vendor	Model/Type	Specifications	Cost
Main Hull	Samco Enterprise Feimus Engineering	Custom Aluminum Milling	Custom	SGD 2700
Frame	Cititech Industrial Engineering	Custom Aluminium laser cut	Custom	Sponsored
Battery hull	SLM solutions	Custom Aluminium Selective Laser Melting		Sponsored
Waterproof Connectors	SubConn Inc. - MacArtney	Assorted Micro and Low-Profile Series	Depth rating PEEK: 300 bar	Sponsored
Thrusters	Blue Robotics	T200		SGD 237 ea
Motor Control	Tekin	RX8		USD150
High Level Control	Raspberry Pi	Model 3B+	1.4GHz 64-bit quad-core processor	SGD 52
Actuators/ Manipulators	In-house	Custom design	ABS	Sponsored
Battery	Tattu	Custom-made 4-cell battery	16000 mAh	USD 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	SGD 70
		UVQ-24/4.5-D24P-C	108W Isolated 24V-12V	SGD 90
Single Board Computer (SBC)	AAEON	GENE-KBU6 BIO-ST03-P2U1	Intel Core i7-7600U Intel® i210	Sponsored
GPU	Nvidia	Jetson Xavier	AGX Module	USD 999
Internal Comm Network	In-house	CAN / Ethernet	1000kbps / 1000Mbps	Sponsored
External Comm Interface	In-house	Ethernet	1000Mbps	Sponsored
Compass	Sparton	AHRS-8	±1.2 Gauss	Sponsored
Doppler Velocity Log	Teledyne Marine	Pathfinder DVL	600kHz Phased Array	SGD 21,550
Camera(s)	BlackFly S PoE Gigabit Camera	BFS-PGE-31S4C-C	2448 x 2048 at 22 FPS	SGD 800
Hydrophones	Teledyne Reson	TC4013	Acoustic transducers	Legacy
Sonar	Oculus	M750d	Dual-Frequency Multibeam Sonar (750KHz/1.2MHz)	SGD 28,700
Algorithm: vision			• Thresholding Particle filterMachine learning	NA
Algorithm: acoustics			• Multiple Signal Classification (MUSIC) • Localization with Short- Time Fourier Transform (STFT) based Ping Extraction	NA
Algorithm: localization & mapping			Error State Kalman Filter	NA
Algorithm: autonomy			ROS SMACH	NA
Open source software			OpenCV, ROS, Tensorflow Object Detection API	NA
Team size	28			
HW/SW expertise ratio	3:1			
Testing time: simulation	300 hours			
Testing time: in-water	0 hours			

Appendix B: Outreach Activities

Ever since our humble beginning in 2012, Team Bumblebee has continued to grow and 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.

Public Showcase and Exchange

Bumblebee was fortunate to be invited as a host for a caffeination session during RobotX Forum 2019 to share the community about our RobotX experience. We shared our experiences in project and team management, which led us to our championship title in RobotX 2018.

Figure 13.1: Caffeination Session with Bumblebee @ RobotX Forum 2019

Lab Tour and Sharing Sessions

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

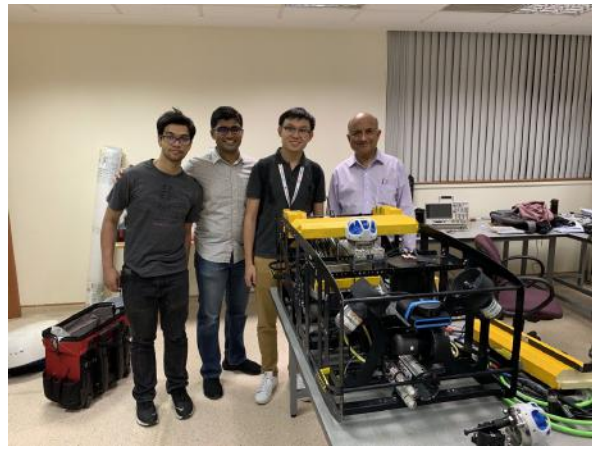

Figure 13.2: Lab visit by a Professor from Florida

Despite the 2020 pandemics, 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.

Industrial Partnership and Appreciation

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

Figure 13.3: Industrial Visit to SLM Solution

SLM Solutions is one of our latest sponsors, who have assisted us in metal 3D printing of battery hulls used in our AUV 4.0.

Collaboration with local secondary school

Figure 13.4: Collaboration with local school

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.

Recruitment of New Members

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, named "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.

Figure 13.5 Online recruitment session

Hornet Training Program

Figure 13.6 Team Hornet working on their Hornet 5.0 vehicle

Since its inception 5 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 (SAUVC). The main aim of this programme is to challenge the freshmen to explore and implement bold designs instead of replicating what others and predecessors have done.

Appendix C: Team's Sponsors

Title Sponsor

NUS (Faculty of Engineering, School of Computing, Advanced Robotics Centre, Engineering Design and Innovation Centre, Department of Mechanical Engineering, Department of Electrical and Computer Engineering): For their cash support, equipment procurement, and academic support in our project.

Platinum Sponsor

- DSO National Laboratories: For cash support and technical guidance
- FSTD: For cash support

Gold Sponsors

DEME Group, MacArtney Underwater Technology, FESTO, Wurth Electronics, Cititech, Kentronics Engineering, Aaeon Technologies, SLM Solutions

Silver Sponsors

ST Engineering, Bossard, Mathworks, Southco, SolidWorks

Bronze Sponsors

Edmund Optics, Richport, Samtec

Supporting Organisations

Republic of Singapore Yacht Club (RSYC), Sports Singapore