Design and Implementation of Bumblebee AUV

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***Abstract*—Bumblebee Autonomous Underwater Vehicle (BBAUV) is the product of a team of undergraduates from National University of Singapore (NUS). This vehicle is designed for two competitions: the RoboSub Competition and the Singapore AUV Challenge. The Bumblebee vehicle was fully modelled in CAD and fabricated with CNC machining, laser cutting and 3D printing. This year, Bumblebee has been refined with changes to its software implementation algorithms. This includes the implementation of optical flow, changes to the vision pipeline, and integration between imaging sonar and camera for more robust computer vision. The Bumblebee sensor suite includes a Doppler Velocity Log (DVL), an imaging sonar, a hydrophone array, an Inertial Measurement Unit, two machine vision cameras and a depth sensor. Its software architecture is built upon Robot Operating System (ROS) and the complex vision algorithms have been implemented in OpenCV.**

I. Introduction

Team Bumblebee designed and built an Autonomous Underwater Vehicle (AUV) for two annual competitions: the AUVSI International RoboSub competition and the Singapore AUV Challenge. RoboSub is held every July in California; while the Singapore AUV Challenge is held in March in Singapore. Both competitions are designed with challenges that mirror industrial applications: visual recognition of objects, manipulation and acoustic localisation tasks. The Bumblebee 3.0 platform was first completed last year January. This year the team's focus is on software development and ensuring reliable vehicle hardware performance up to open sea conditions. Team Bumblebee is divided into Mechanical, Electrical and Software sub-teams. The team comprises of students from mechanical, electrical, computer engineering and computer science of all years of studies.

Fig 1: Bumblebee Auv 3.0

II. Specification Of Bumblebee AUV

Table I

This table outlines the capabilities of the bumblebee AUV 3.0

Bumblebee AUV 3.0	
Weight	52 kg
Dimensions	1.4m X 0.5m X 0.5m
Single Board Computer (SBC)	Core i5-4402E Aaeon GENE-QM87, 8GB RAM, 512GB SSD
Embedded System	sbRIO-9606 400MHZ controller NI9223 Analog input module
Propulsion	6 SeaBotix BTD150 2 VideoRay Surge Thrusters
Navigation	Teledyne RDI Explorer DVL Sparton GEDC-6 IMU US300 Pressure/Depth Sensor STIM300 IMU
Vision Sensors	AVT Guppy Pro AVT Guppy
Sonar	BlueView M900 Imaging Sonar 4 Teledyne Reson TC4013 Hydrophones
Manipulators	Festo Pneumatics Systems
Power Supply	22.2V 10000mAh LiPo Battery (x2)
Underwater Connectors	SubConn Micro and Low Profile Series
Software Architecture	Robot Operating System (ROS) Gentoo GNU/Linux x64

III. Mechanical Sub-system

The mechanical design of Bumblebee AUV 3.0 takes into consideration improvable features on the previous version of the AUV. This version is completely new and fabricated from ground up. Only certain sensors and thrusters are reused to conserve development costs. Design and FEA analysis are done in Solidworks. The final product is an AUV that is more streamlined, compact and manoeuvrable.

A. *Design Strategy*

The main frame of Bumblebee AUV 3.0 is made from a single piece of aluminium (6061-T6). Unlike the previous version whereby the design is generic to accommodate future sensors and enclosures, the design process of Bumblebee AUV 3.0's main frame begins after all enclosures and sensors have been designed. This method ensures that the frame will be made to accommodate all enclosures and will be at its most compact form. The result is a specialized compartment for each enclosure and sensor, with weight saving despite having more sensors and enclosures added.

B. External Hulls and Enclosure

The main electrical hull is made of acrylic tube of diameter 200mm. Sealed with both face and radial O-rings, the hull is pressurised to provide a buffer in case of leakage. The electrical rack is directly attached to the bulkhead end cap and is removed together during servicing. One of the main features of the hull is an active cooling system. A custom-designed cooling system draws heat away from the SBC with the use of off-the-shelf liquid coolant. The liquid is then pumped to an external reservoir which is always in direct contact with surrounding water. Because of this, SBC temperature hardly rises above 50ºC, even under hot tropical sun.

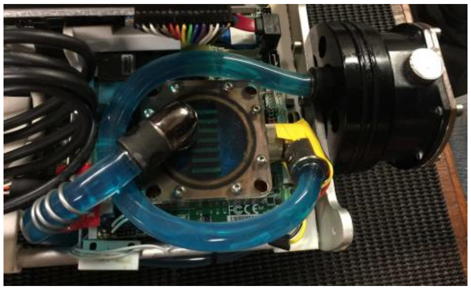

FIG 2: COOLING SYSTEM

C. Navigation Housing

The navigational housing is a new addition to the collection of enclosures on the AUV this year. It serves as the module responsible for navigational processing and interfaces with sensors such as the DVL (Doppler Velocity Log) and IMU (Inertial Measurement Unit). The housing is specially designed to accommodate two IMUs and a SBC. It is located directly at the top side of the AUV and away from main hull to ensure maximum magnetic isolation.

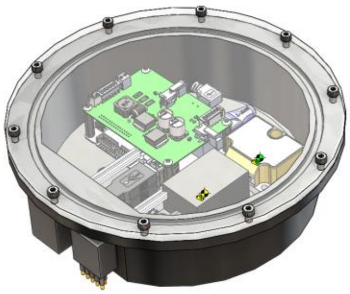

FIG 3: NAVIGATION HOUSING

D. DVL Housing

The Doppler Velocity Log is sealed in a three- part housing. The main hull contains the electronics chassis while a unique endcap houses the phased array transducer. The parts have been optimally designed to attain minimal weight while ensuring sufficient space for a safe bending radius of connectors.

E. Actuator

The actuators consist of a torpedo launcher, marker droppers and a grabber. Pneumatic actuation is selected for its powerful yet reliable performance. The dropper design has been improved from last year to take into accounts of two annual competition Bumblebee AUV 3.0 participates in, SAUVC and RoboSub. With synchronization of marker size taken into design consideration, we eliminate the need to change the dropper after every competition. The torpedo, on the other hand, has an O-ring situated at the neck of the design to build up sufficient pressure for maximum propulsion.

F. Grabber

This year the grabber was designed to pick up the tubes rigidly, instead of the magnetic grabber from last year. The grabber is actuated with our on-board pneumatics system, allowing it to grab and retract. The position of the grabber is also mounted such that it maximises the field of view of the camera.

FIG 4: GRABBER

G. Thruster Measurement Jig

This year a thruster measurement jig was designed to benchmark both our Videoray and Seabotix Thruster. With this jig, the thrust and current curve of both thrusters can be obtained. The data would then be used to fine-tune the control system, and allow better power management of the electrical system on board the AUV. The results are currently still preliminary, and testing is still on-going for more accurate results.

FIG 5: THRUSTER MEASUREMENT JIG

IV. Electrical Sub-system

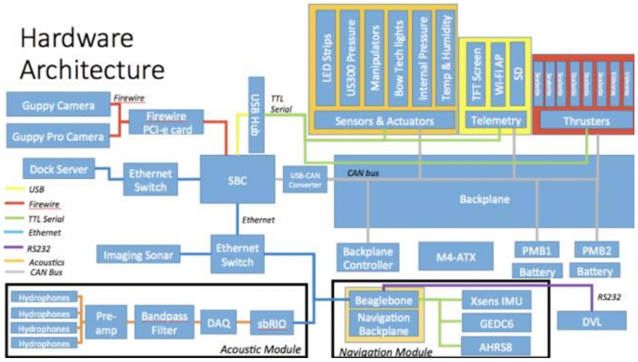

Fig 6: Hardware Architecture

Bumblebee AUV electrical system underwent a major revamp of design in 2016, which features a custom designed backplane that represents the core of the electrical system, routing all the powers and signals to the individual sub systems via a custom PCB. Mounted on the backplane are custom-designed daughter boards, including thruster board, sensors and actuators board and telemetry board. The main computer board is also upgraded to host a new 4th generation Intel Core i5 processor. The components are carefully placed to optimize electrical connections with the aid of Solidworks Electrical 3D CAD. This year, the primary focus is to stabilise the electrical system, ensuring smooth operations.

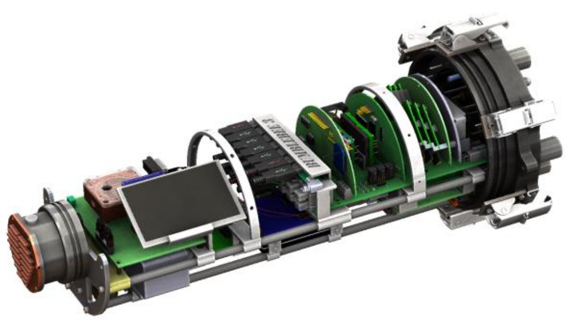

Fig 7: Electrical Rack

A. Power

The vehicle is powered by two 10000 mAh LiPo (lithium polymer) batteries extending testing time to approximately 210 minutes before a recharge is required. The onboard power monitoring, management and distribution is as follow,

- <u>Power Monitoring and Management:</u>
  Each LiPo battery is enclosed inside a battery pod which allows for both charging and discharging. Within the pod, the batteries are connected to PMB (Power Monitoring Boards) which monitor vital power statistics such as current, cell voltage and capacity. The custom fabricated PMB has been designed to withstand a maximum current of 30 A. This system allows tracking of power statistics of the batteries and is more reliable than the previous off-the-shelf OpenUPS system. A battery charging box has been designed for quick deployment of mobile charging stations. This battery charging box supports parallel charging of two battery pods of up to 25 A per channel at one go.

- <u>Power Distribution:</u>
  The power system utilizes a M4 ATX power supply to generate three voltage rails(12V,5V,3.3V) to power the SBC and the sensors and actuators. The electronics are isolated from the noisy thrusters via an isolated DC-DC converter and isolators, preventing instability in the electronics due to the inductive loading from the thrusters.

B. Backplane

The main purpose of the electrical backplane is for power and data distribution. A load balancer circuit in the backplane allows the two batteries to be hot-swappable to make it easier to change on-the-go. The power from the battery is then channelled to the DC-DC converter, the M4-ATX, and finally channelled back to the backplane to be distributed to the rest of electrical components.

The backplane also provides the interface to different electrical peripherals. The backplane uses the Controller Area Network (CAN) protocol to communicate to the other daughter boards. Power Over Ethernet (POE) injector circuit allows communication to imaging sonar, acoustics, and navigation module.

There are other additional features implemented in the backplane, such as voltage and current monitoring, and the ability to disconnect power to selected peripherals via a software interface.

C. Daughter Boards

The Thruster Board comprises of off-the-shelves Pololu Simple Motor Controllers and Tekin ESCs custom mounted onto the board. The Sensor and Actuator board was designed to obtain sensor data from the board and control all the actuators. The board is responsible for dynamic control of the thrusters.

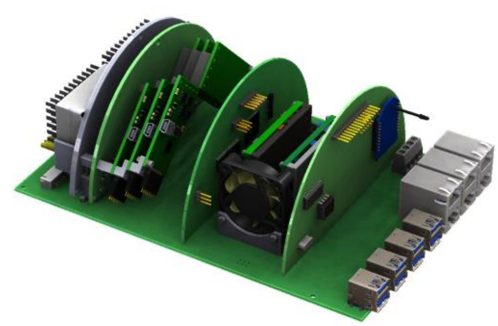

Fig 8: Backplane And Daughter Boards

D. CAN Bus

The CAN protocol is implemented this year to communicate with all the daughter boards, backplane and SBC. The deployment of CAN in the Bumblebee System eliminates the single point of failure. By enabling this network, hardware devices can exchange data in a peer to peer fashion, without additional wiring overheads between devices.

E. Computer System

Bumblebee AUV's software system is powered by an Intel Core i5-4402E processor on an Aaeon GENE-QM87 motherboard along with a 512 GB SATA SSD (Solid State Drive).

A dedicated microcontroller is integrated on the backplane to allow translation of USB Serial signals to CAN to communicate with all the daughter boards and backplane. In addition, VGA and USB ports are exposed to allow external debugging of the software systems.

The computer is connected to the topside Operator Control Station via a 1000 Mbps Ethernet tether. The vehicle is networked to a Gigabit switch that connects to NI sbRIO 9606 and Operator Control Station.
whereby the design is generic to accommodate future sensors and enclosures.

F. Navigation Sensors

- <u>Sparton AHRS8 IMU:</u>
  The Sparton AHRS-8 (Attitude Heading Reference System) provides critical inertial data at the rate of 100 Hz. The sensors' proprietary algorithms ensure correct data output despite the presence of electromagnetic interference generated by the Bumblebee's suite of electronics and thrusters.
- <u>STIM300 IMU:</u>
  The Sensonor STIM300 IMU provides inertial data at a rapid rate of 2GHz. This high performance and reliability IMU is equipped with 3 MEMS gyroscopes, 3 accelerometers and 3 inclinometers. The IMUs accuracy is maintained over temperature range, and it is insensitive to vibrations and shock.
- <u>Teledyne RDI Explorer DVL:</u>
  The DVL is an active sonar system that tracks the velocity of the instrument via a four-beam solution directed at 30 degrees nominal from the sensors ceramic head. The velocity readings obtained are combined with tilt and altitude measurements, then resolved into the three orthogonal x, y and z axes via a least square fit solution. These resolved readings are further filtered through a direct three-degree of freedom Kalman filter, which serves to attenuate noise. The calculations output a more accurate positional coordinate of the vehicle.

G. Vision

For Computer Vision, Bumblebee 3.0 has two machine vision cameras interfaced over firewire as follows:

- Front Camera: Guppy Pro F046C with Edmund Optics 4.5mm fixed focal length lens
- Bottom Camera: Guppy F146C with Edmund Optics 4.5mm fixed focal length lens
- Firewire interface: PCIe 4 port 1394a (Firewire) from Allied Vision Technologies

The Guppy cameras boasted superior performance due to their camera sensors with better field of view (with the 4.5mm focal length lens), lower image noise and higher dynamic range. The Guppy cameras are also more readily configurable allowing full access to the camera parameters (such as shutter, exposure, white balance) to be tuned.

H. Operator Control Station

The Operator Control Station (OCS) is designed to be an integrated, portable communication hub which is easily deployed and user friendly. Communication between the vehicle and shore can be easily established with just a push of a button, and robust military ethernet connectors provides a reliable communication link. The OCS also does not compromise on its integrity. With a custom panel fitted with minimally IP65 components and a 11Ah Lithium-ion battery, it is designed to operate more than 10 hours even in rainy weather conditions. The OCS was also designed with Autonomous Surface Vessel control link/data link interoperability which will not be covered in this paper.

V. ACOUSTIC SUB-SYSTEM

Bumblebee AUV's acoustic sub-system uses four Teledyne hydrophones, integrated with custom analog and digital boards. The MUSIC (Multiple Signal Classification) algorithm is used to localize the acoustic pinger. This year's acoustic sub-system features an improvement in the hardware as well as optimization of the software to improve the its performance.

A. Hardware System

The hardware setup for the acoustics subsystem on BBAUV consists of 4 Teledyne TC4013 hydrophones, integrated with custom analog and digital boards. The setup is shown in the figure below and each component is further elaborated.

FIG 9: REDESIGNED HYDROPHONE MOUNT

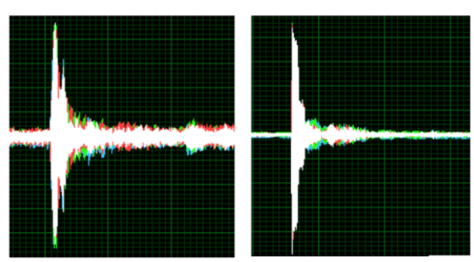

FIG 10: HYDROPHONE SIGNAL (LEFT PREVIOUS OLDER MOUNT, RIGHT NEW MOUNT)

- Teledyne TC4013 Hydrophones:
  4 compact 9.5 mm Teledyne TC 4013 hydrophone are arranged in a square array with inter-element spacing of 1.5 cm. This prevents spatial aliasing associated with phase-difference based algorithms. The mounts were redesigned such that they are mechanically isolated from the vehicle, as well as each other. This significantly reduces the noise received by the hydrophones, especially when the vehicle is moving. It also increases the channel-to-channel isolation, which improves the accuracy of the DOA estimation.
- Custom Preamplifier and Bandpass filter board:
  A Custom Preamplifier board is used to amplify the signal from the hydrophones to a suitable voltage for Analog- to-Digital conversion. The signal is low-pass filtered to remove the DC components to allow the signal of interest to be amplified without clipping. It is then high-pass filtered to remove high frequency noise above the Nyquist rate as these may cause aliasing when converted to digital form. The signal is then passed through a Low-Noise Amplifier to amplify the signal to suitable amplitude so that the resolution of the Analog to Digital Converter is maximized.
- NI9223 Analog Input Module:
  The NI9223 Analog Input module then converts the signal to digital form. The NI9223 can sample at a rate of 1MS/ch/s with 16-bit resolution (10V) on up to 4 different channels.
- NI sbRIO 9606:
  Lastly, the signal is processed by the National Instruments sbRIO 9606 to compute the Direction of Arrival (DOA) of the signal. The sbRIO 9606 has a 400MHz PowerPC processor paired with a Xilinx Spartan-3 Field Programmable Gate Array (FPGA) with 2M gates.

B. Software System

The Acoustic subsystem features a software architecture which fully utilizes the software resources available. This results in an improvement in the speed of the algorithm compared to previous years. Also, by pushing the MUSIC algorithm down to a lower level processor, CPU resources on the main computer of BBAUV can be dedicated to other tasks.

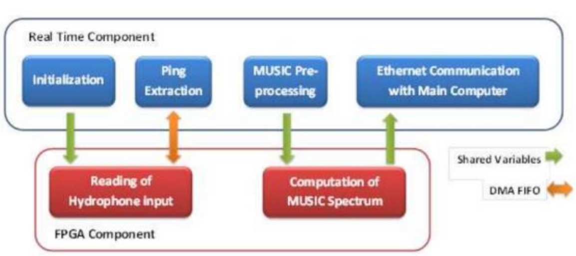

FIG 11: SOFTWARE FLOW DIAGRAM

The acoustic software this year incorporates the use of Short-time Fourier Transform (STFT) to identify the pinger signal and extract its phase information for use with MUSIC. This preprocessing step can identify the desired pinger signal from multiple sources, and extract the phase information of the direct path signal only. This reduces interference from multipath effects and improves the resulting DOA estimation.

The software architecture this year divides the tasks to be completed between the processor and the FPGA. The processor handles less computationally intensive tasks like the STFT and communications with the main computer. The FPGA handles computationally intensive tasks or time-critical tasks like the computation of the MUSIC spectrum and the sampling of the analog signal from the hydrophones.

The algorithm has also been optimized further to reduce the computation time of each cycle to under 500ms. This reduces the latency of the DOA estimation after receiving the pinger signal, allowing BBAUV to localize much quicker.

Statistical analysis is done on the hydrophones to determine if the readings are faulty. The mean of readings is checked to ensure the signals are grounded properly. The variance is also checked to ensure that the minimum background noise is being received at the hydrophones. If the readings from one hydrophone are determined to be faulty, its identity is sent to the main computer and the readings from that hydrophone are ignored in the computation of the Direction of Arrival. This allows the acoustic system to continue operating even in the case of a failure in one hydrophone channel.

VI. SOFTWARE SUB-SYSTEM

Bumblebee's software stack runs on the open source message passing interface, Robot Operating System (ROS) which in turn runs on top of Linux. ROS provides a standardised medium for package management, serialisation and over the network message passing between processes by utilizing a graph architecture. One big advantage is that we can run processes outside the AUV that can control the system when it is in water. Remote connection to processes running inside the AUV also makes real time debugging feasible.

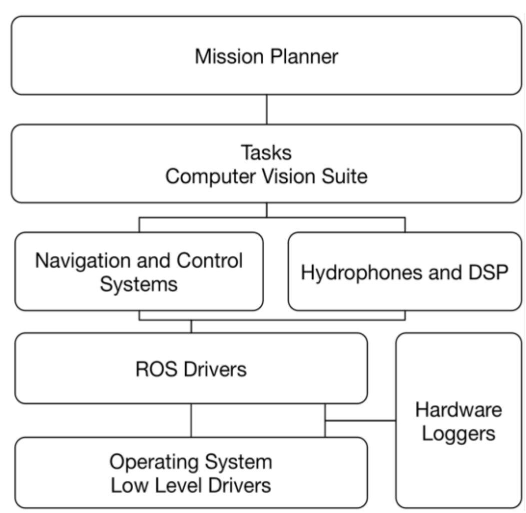

FIG 12: SOFTWARE FLOW DIAGRAM

The various processes that need to be run are hence written as nodes of a graph. The system is headed by the mission planner which has the authority to start, stop, monitor the progress of and time each individual task. Each task node contains its own internal state machine to perform its various tasks. This allows easy flow control and avoids the use of jump statements and other convolutions for complex logical sequences.

A. Mission Planner

The mission planner is implemented using Finite State Machines and a graph walking algorithm. Finite State Machines are used because each task in the mission sequence can be represented as its own individual states with known inputs and a deterministic set of outcomes. The mission planner is a high-level process and therefore written in Python for ease of modification and compatibility with various libraries that may be used. The mission planner has the capability to dynamically load modules and generate linked state machines on the fly.

B. Navigation

Table II

THIS TABLE OUTLINES THE COMMUNICATION PROTOCOLS OF THE NAVIGATION SENSORS ON BOARD THE AUV

Bumblebee AUV 3.0		
Sensors	**Interface**	**Rate**
Sparaton AHRS-8 IMU	TTL Serial	100Hz
STIM300 IMU	RS422	2Ghz
Teledyne RDI Explorer DVL	RS232	7Hz
Pressure Sensor	Current loop sensing via ADC	20Hz

The navigation sensor suite consists of a 9 axis Sparton IMU, 6 axis STIM300 IMU, a DVL and a barometric pressure depth sensor. All the sensors are interfaced and integrated with the rest of the system over the ROS IPC framework. Provisions for integration of GPS receiver have been made. The data from each sensor is fused to obtain independent state data. Error state Kalman Filter is used to obtain much higher accuracy than each sensor can provide independently. This is notably more robust and suitable for dynamically changing states than the traditional full-state KF, which has inherent assumptions of vehicle motion behaviours in the state equation setup. Since error variables are used as the state vector, nonlinearities can be cancelled. In addition, motion assumptions are not necessary in formulating the state equations. The absence of these motion assumptions greatly enhances the robustness of the filter state equations in handling various vehicle manoeuvres.

This year, we have included the velocity tracking from optical flow using the two cameras to aid the Kalman Filter. We use the Lucas-Kanade method as the camera frame is assumed to move with a homogeneous velocity. In comparison to dense optical flow, this method uses less computational power. The filter then removes the angular velocity component from the image frame.

Optical Flow is useful during DVL outages in low altitude scenarios (picking up objects). In real world applications when the water is muddy or low light conditions the filter is disabled due to no features being tracked.

C. Control System

Six PID (Proportional Integral Derivative) control loops are used to control the vehicles six degrees of freedoms. The PID controllers are designed with the following considerations:

- Low pass filter for the derivative component to reduce the exponential effects on sensor noise
- Variable period time sampling for more accurate integral and differential computation
- Weighted set points to reduce transient effects in set point changes
- Integrator windup protection for when actuators are unable to fulfil the PID Controller requirements.

The PID control loops have been improved for dynamic allocation of actuator limits, allowing greater output in specific degree of freedoms.

D. Computer Vision

It is a major challenge operating on underwater footages that have non-uniform illumination and colour degradation. Our basic vision processing pipeline can be divided into 4 main stages: pre-processing, enhancement, detection and tracking. Pre-processing focuses on illumination normalization using gamma correction, while enhancement recovers the original colour of the images with the Shades of Grey algorithm.

FIG 13: PREPROCESS AND ENHANCEMENT (LEFT BEFORE, RIGHT AFTER)

One of the mainstay of our detection stage is thresholding. While selecting the thresholds in optimal colour space such as HSV, LUV or LAB may yield decent result, this method is highly susceptible to underwater perturbations. In contrast, saliency region detection is less vulnerable to these disturbances. Saliency region detection enables us to operate on object that pop-up to the human vision system and this information is used as a primary filter to remove artefact noises and other features in Transdec.

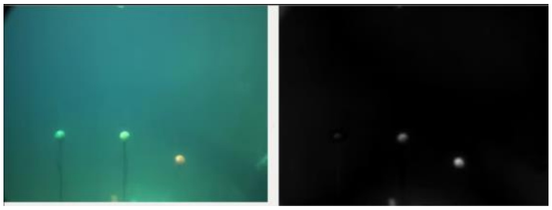

FIG 14: SALIENT REGION DETECTION

Lastly, we track the object of interest using a particle filter to make use of past observations. This solves the problem of false detection that may cause the vehicle to temporarily lose track of the original object.

E. *Imaging Sonar*

A multi-sensory approach to tracking and localization is adopted, using the camera, sonar and vehicle pose and velocity. For the sensor fusion to work, a calibration step is performed to obtain the relationship between sonar, camera and vehicular dynamics. This step involves computing the coordinate transformation matrix between the sonar and camera, and between camera and vehicle. This allows us to map a 3D point from sonar frame to camera frame.

Before tracking and localization, various filters and thresholding techniques are used on the sonar image to extract objects of interest, before applying feature tracking methods such as Lucas-Kanade tracking on these objects. Since sonar only outputs range R and azimuth θ, the tracked object has uncertainty in elevation φ. Hence, we transform and project that search space into the camera image using sonar/camera transformation matrix. From there, we can analyse this reduced search space in the camera image and find the object of interest.

Once we determine that an object is to be tracked, we initialize a particle filter with the 3D position and velocities of the object in the sonar frame, with low uncertainty in R and θ, but higher uncertainty in φ. The particle update model is based on vehicular dynamics, obtained from DVL and IMU. This is done to enhance the robustness of the sensor fusion.

Once the update step is done, these 3D points are projected into both sonar and camera image. Each particle is assigned a weightage based on several heuristics, such as intensity and optical velocity of the sonar pixel, the object dimensions and camera pixel colour. The particles are then resampled, with those having higher weightage more likely to be selected and repopulated.

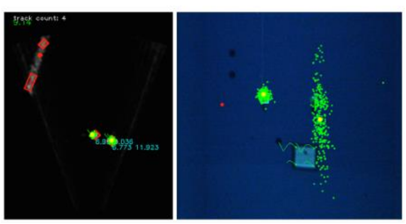

FIG 15: TRACKING TWO BUOYS IN 3D. LARGER UNCERTAINTY IN THE RIGHTMOST BUOY

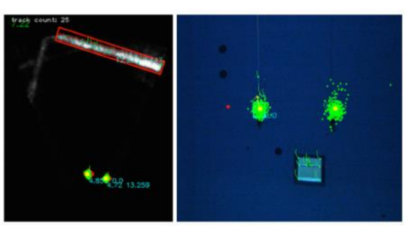

FIG 16: PARTICLE FILTER CONVERGES DUE TO DROP IN UNCERTAINTY IN CAMERA IMAGE

F. *Control Panel*

This year the control panel has been retuned and base on ImGUI. The new control panel boasts less CPU usage, faster update rate and a user-friendly, customizable interface in which windows can be collapsed to focus on the necessary parameters.

FIG 17: CONTROL PANEL

VII. CONCLUSION

Bumblebee 3.0 has undergone rigorous testing and evaluation to achieve the robust performance and capabilities it has today. Concurrently, the many lessons learnt in the design of this vehicle will be continually iterated upon to develop a better vehicle each year. Our team has also evolved considerably with better organisational structures and greater capacity for development.

FIG 18: TEAM PHOTO OF BUMBLEBEE TEAM

VIII. ACKNOWLEDGEMENT

Team BumbleBee would not have been where we are today without the following people and we would like to thank them for giving us the chance to compete in RoboSub:

Title Sponsor

- *NUS*: For their cash support, equipment procurement, and academic support in our project.

Platinum Sponsor

- *DSO National Laboratories*: For cash support and technical guidance
- *ST Engineering:* For cash support
- *Cititech*: For fabrication support of our mechanical parts and competition obstacles

Gold Sponsors

- Seatronics
- Superior Energy Services (Hallin Marine)
- MacArtney Underwater Technology
- FESTO
- IKM Subsea Singapore
- KOMTech
- Kentronics Engineering
- Soon Lian Holdings

Silver Sponsors

- NUS Temasek Hall,
- NUS Raffles Hall
- Bossard,
- Teledyne Reson,
- Allied Vision Technologies,
- Edmund Optics,
- Sparton,
- National Instruments,
- DF Robot,
- Mathworks,
- Aaeon Technologies

Bronze Sponsors

- SolidWorks,
- Richport,
- Bloomfoss,
- Sterling Comm Intl Pte Ltd

Supporting Organisations (Resources)

Advanced Marine and Acoustic Research Lab, Sports Singapore, NOAA Southwest Fisheries Science Center (SFSC)

Supporting Organisations (Equipment)

SECO Tools, Deep Sea Power and Lights, Southco, Tekin, Digikey, SeaBotix, Wurth Electronics, Diab Group, Pololu, Samtec

IX. APPENDIX – OUTREACH ACTIVITIES

Team Bumblebee strongly believes in public outreach and we try our best to engage people from different communities. Through exhibitions and lab tours, we explain and showcase our technology, so that more people can better understand our vision.

A. *Public Showcase*

This year, we participated in the Tech Saturday Upsized organised by Infocomm Media Development Authority (IMDA), which aims to bring fun-learning tinker stations, cool demos and gadgets and free workshops to all ages.

Through this showcase, we shared with different people what autonomous systems are all about, igniting passion in the young to do robotics.

FIG 19: BUMBLEBEE AUV AT TECH SATURDAY UPSIZED 2017

We also participated in a University Showcase, which we exhibited our AUV to Junior College students and industrial guests, sharing with them what autonomous system are about.

FIG 20: EDIC SHOWCASE AT NUS

B. *Sponsors Appreciation*

This year, Team Bumblebee held a sponsor's appreciation ceremony, inviting academic staffs, sponsors and industrial partners.

Through this event, we shared our development plan for the next 3 years, to give people a better understanding of our project.

We also presented token of appreciations to each of the sponsors and academic staffs who had helped us one way or another. Our Team believe in giving back to those who assisted us in making our vision possible.

FIG 21: OUR TECHNICAL LEAD PRESENTING A TOKEN OF APPRECIATION

C. Hornet

This is the second year since we ran our Hornet Program, which is opened to the engineering faculty in National University of Singapore.

Through this program, we taught students how to build a low-cost AUV, and provided them with the necessary materials. Eventually, they would participate in Singapore AUV Challenge, and have a taste of what building AUVs are like.

Those who are interested and would like to pursue robotics are then welcomed to join the Bumblebee Team.

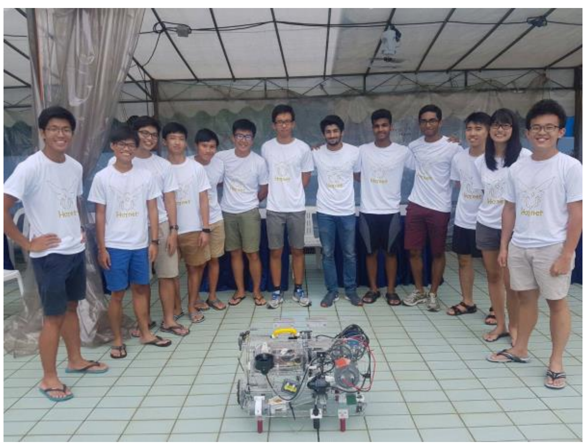

FIG 22: TEAM HORNET AT SAUVC 2017