Design and Implementation of Bumblebee AUV 3.0

Goh Eng Wei, Steven Harta Prawira, Alex Foo Rong Xuan, Lim Qi Xiang,
Nguyen Dang Khoa, Tey Kee Yeow, Esther Tan, Siow Wei Han, Krishna Ramachandra,
Benaya Christo, Yang Quan Jie, Samuel Ong, Liu Shih Chiang, Vanessa Cassandra,
Joshua Yow, Akshat Dubey, Lim Jun Jie, Liu Ren Jie, Fan Jiaming,
Alex John, Tan Soon Jin, Gao Bo, Idawati Bustan and Ruth Chew

***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: AUVSI Robosub Competition and the Singapore AUV Challenge. The Bumblebee 3.0 vehicle was fully modelled in CAD and fabricated with CNC machining, laser cutting and 3D printing. This year the vehicle features many improvements such as a more streamlined mechanical structure, reliable and fault tolerant electrical system as well as more accurate navigation. Sensor fusion between the imaging sonar and the front-camera was implemented to facilitate better object tracking and recognition. Bumblebee 3.0s sensor suite includes a Doppler velocity log (DVL), an active imaging sonar, hydrophone array, inertial measurement units and two machine vision cameras. The software architecture is based on Linux, with Robot Operating System (ROS) framework as middleware.**

I. Introduction

FOR the fourth year, Team Bumblebee has 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 was held in March in Singapore. Both competitions are designed with challenges that mirror real world tasks: visual recognition of objects, manipulation and acoustic localisation tasks. Team Bumblebee is divided into Mechanical, Electrical and Software sub-teams. The team comprises of students from Mechanical, Electrical, Computer Engineering and Computer Science.

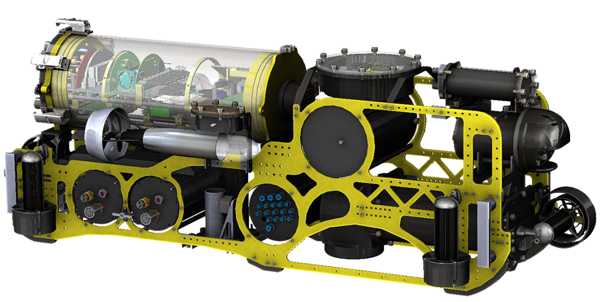


Fig. 1: Bumblebee AUV 3.0

II. Specification

Weight	52 kg
Dimensions	1.4m X 0.5m X 0.5m
Single Board Computer	Core I5-4402E Aaeon GENE-QM87 8GB DDR3 RAM 512GB SATA3 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 P900 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

TABLE I: Bumblebee AUV 3.0 Specifications

III. Mechanical Sub-system

The mechanical design of Bumblebee 3.0 takes into consideration improvable features on the previous version of the AUV. This vehicle 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 maneuverable.

A. Frame

The main frame of Bumblebee 3.0 is made from a single piece of aluminium (6061-T6). Unlike the previous version whereby the design is modular in order to accommodate future sensors and enclosures, Bumblebee 3.0 was designed for a fixed set of enclosures. This 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 savings despite having more sensors and enclosures added.

B. External Hulls and Enclosure

The main electrical hull is made of an 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 an off-the-shelf liquid coolant. The liquid is then pumped to an external reservoir which is always in direct contact with surrounding water. As a result of this, SBC temperature hardly rises above $50°C$, even under the hot tropical sun.

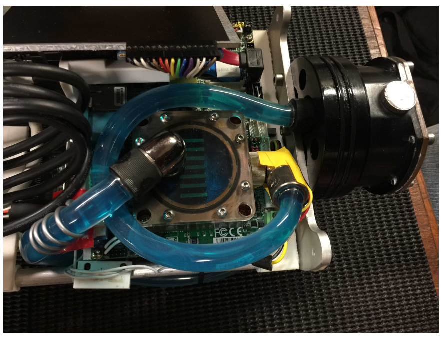


Fig. 2: Cooling System

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 and IMU. The housing is specially designed to accommodate an IMU, GPS and a single board computer. It is located directly at the top side of the AUV and away from main hull to ensure maximum magnetic isolation and to enable GPS communication on or near water surface.

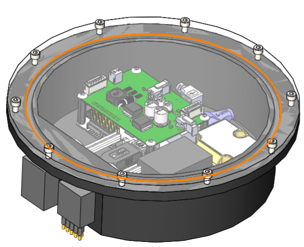


Fig. 3: Navigation Housing

D. DVL Housing

The Doppler Velocity Log (DVL) 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 consists 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 BBAUV participates in, SAUVC and Robosub. With optimization of marker size taken into design consideration, we eliminate the need to change the dropper after every competition. On the other hand, the torpedo design includes an O-ring situated at the neck of the design in order to build up sufficient pressure for maximum propulsion.

IV. Electrical Sub-system

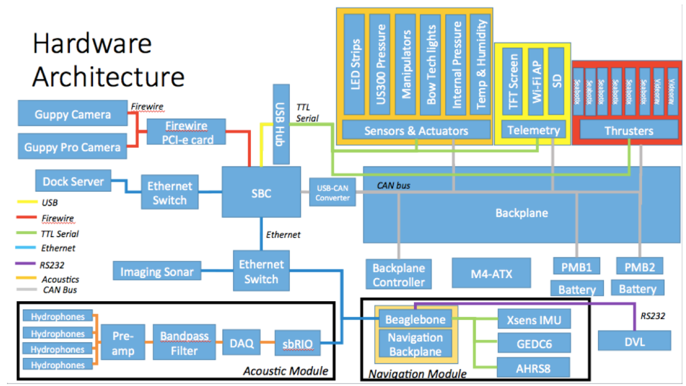


Fig. 4: Hardware Architecture

This year Bumblebee 3.0 electrical system underwent a major revamp of design featuring 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.

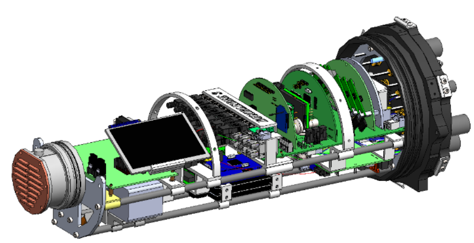


Fig. 5: Electrical Rack

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.

- Power Monitoring and Management:
  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.

- Power Distribution:
  The power system utilizes a M4 ATX power supply to generate three voltage rails (12V, 5V, 3.3V) to power the SBC together with the sensors and actuators. A Y-PWR provides load balancing hot-swap capabilities for the batteries. Batteries can be swapped out one by one without powering down the SBC.The electronics are isolated from the noisy thrusters via an isolated DC-DC converter, preventing instability in the electronics due to the inductive loading from the thrusters.

B. Backplane

The main purpose of the electrical backplane is 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 channeled to the DC-DC converter, the M4-ATX, and finally channeled 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-shelf Pololu Simple Motor Controllers and Tekkin 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.

The Sensor and Actuator board was designed to obtain sensor data such as depth from the US300 pressure sensor and also temperature, humidity, and internal hull pressure. It is also responsible for from the board and control all of the pneumatic manipulators as well as the LED strip indicator.

The data will then be shared on the CAN bus and passed onto the Telemetry board to be logged in a memory module, and to be shown on a 5” LCD screen that is attached on the vehicle. The Telemetry system also has a Wifi XBee to allow

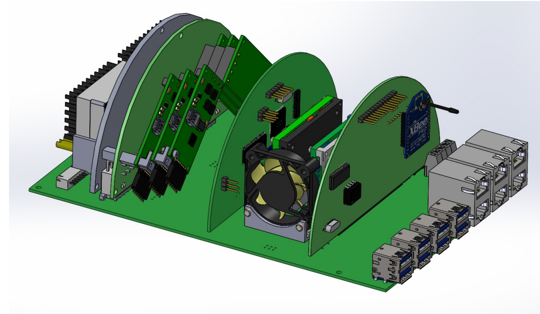


Fig. 6: Daughter Boards

for external mobile devices to connect to the CAN network. The SBC also collects the data from the CAN bus, parses it and displays it in the Software Control Panel.

An Atmega2560 MCU is integrated to each of the daughter boards and backplane for dedicated processing. Each daughter board has a similar CAN circuit to establish reliable communications between 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 are able to exchange data in a peer to peer fashion, without additional wiring overheads between devices.

E. Computer System

Bumblebee’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 Atmega328P is integrated on the backplane to allow translation of 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 dockside via a 1000 Mbps Ethernet tether. The vehicle is networked to a Gigabit switch that connects to NI sbRIO 9606 and surface router.

F. Navigation Sensors

- Sparton AHRS8 IMU:
  The Sparton AHRS-8 (Attitude Heading Reference System) is used to provide geomagnetically referenced heading data. The IMU is isolated using the new navigation enclosure as well as calibrated against magnetic interference.
- STIM300 IMU:
  The Sensonor STIM300 IMU is a tactical grade inertial measurement unit. Providing accurate inertial data at 2GHz, it functions as the primary source of body frame measurements for the navigation system. The sensor forgoes the traditional magnetometer triplet for inclinometers.

- Teledyne RDI Explorer DVL:
  The Doppler Velocity Log (DVL) is a form of Acoustic Doppler Current Profiler (ADCP) that uses doppler shift to calculate the lateral velocities. The 600 KHz Explorer DVL was chosen for its small form factor as well as optimum trade-off between resolution and range. The shallow water tracking upgrade was purchased to aid testing in traditional swimming pools and similar environments.

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 boast 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.

V. Acoustic Sub-system

Bumblebee 3.0 acoustic sub-system uses four Teledyne TC4013 hydrophones, integrated with custom analog and digital boards. The MUSIC (Multiple Signal Classification) algorithm is used to localize the acoustic pinger. The acoustic sub-system features a redesign of the software to improve the performance and robustness of the algorithm.

A. *Hardware System*

The hardware setup for the acoustic 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.

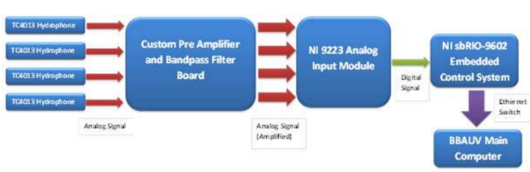


Fig. 7: Hardware Flow Diagram

- 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 hydrophone mount is designed in SolidWorks and fabricated precisely with laser cutting.
- 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:
  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 redesign of the software architecture to fully utilize the software resources available. This results in an improvement in the speed of the algorithm. 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.

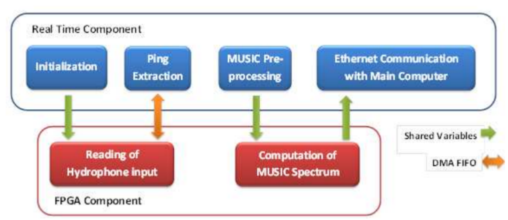


Fig. 8: Software Flow Diagram

The usability and robustness has been improved of the acoustic sub-system. The sbRIO-9606 publishes any faults with the FPGA to the main computer, making it easier for the layman to detect problems with the system. The system can also automatically detect faults in the hydrophones and compensate accordingly, allowing the system to operate even in the event of 1 hydrophone failing, making it more robust.

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 band pass filtering, Fast Fourier Transform (FFT) 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 division of the software tasks between the processor and FPGA allows the algorithm to complete each cycle of processing in under 800ms, while not compromising the accuracy and robustness of the system. This allows BBAUV to make movements much more quickly when localizing to the pinger.

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

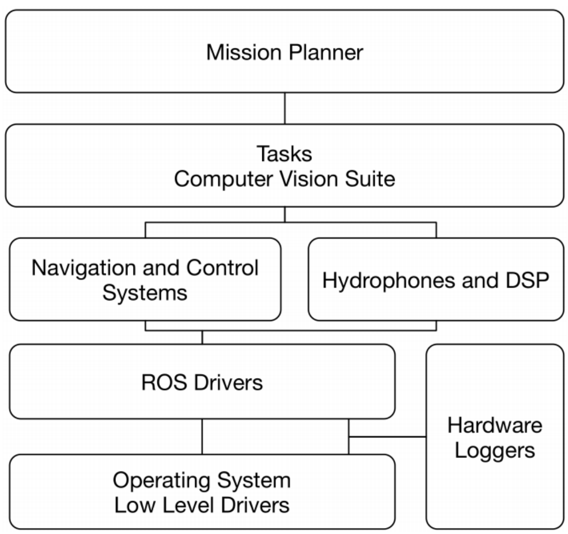


Fig. 9: Software Block Diagram

Bumblebees 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 standardized 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.

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

Sensors	Interface	Rate
Sparton AHRS-8 IMU	RS232	100Hz
STIM300 IMU	RS422	2GHz
Teledyne RDI Explorer DVL	2xRS232	7Hz
Pressure Sensor	Current loop sensing via ADC	20Hz

TABLE II: Navigation Sensors

The navigation sensor suite consists of a 9 axis Sparton IMU, 6 axis STIM300 IMU, a DVL and a barometric pressure 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 sensors is fused to obtain independent state data. An error state Kalman Filter is used to obtain much higher accuracy than each sensor is able to 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 behaviors in the state equation setup. Since error variables are used as the state vector, nonlinearities can be canceled. In addition, motion assumptions are not necessary in formulating the state equations. The absence of these motion assumptions greatly enhances the reliability of the filter.

C. Control System

Six PID (Proportional Integral Derivative) control loops are used to control the vehicle's 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 fulfill the PID Controller requirements.

The PID control loops have been improved for dynamic allocation of actuator limits, reducing saturation between PID loops that command the same set of actuators.

D. Computer Vision

Our basic vision processing pipeline can be divided into 4 main stages: preprocessing, enhancement, detection and tracking. It is a major challenge operating on underwater footages that have non-uniform illumination and color degradation; thus we preprocess our images with homomorphic filtering to remove flickering effect, gamma correction and Gray-World algorithm to recover original color of the images. Saliency region detection enables us to operate on objects that pop-up to the human vision system and this information is used as a primary filter to remove artifact noises and other features in TRANSDEC.

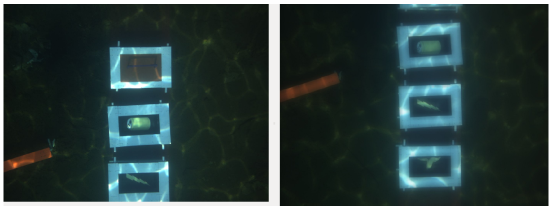


Fig. 10: Homomorphic filter

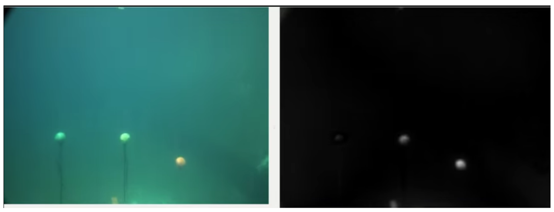


Fig. 11: Salient Region Detection

One of the mainstay of our object detection framework is thresholding. Though color thresholding is susceptible to underwater perturbations, selecting optimal color space such as HSV, LUV or LAB for thresholding may yield better result depending on the object of interest. Lastly, we track the object of interest in the competition using a particle filter as previous algorithms often neglect prior knowledge and past observations which are accounted for by the particle filter. 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. In order 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.

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 analyze 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 color. The particles are then resampled, with those having higher weightage more likely to be selected and repopulated.

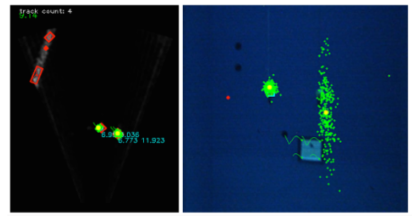


Fig. 12: Tracking two buoy in 3D. Larger uncertainty in the rightmost buoy

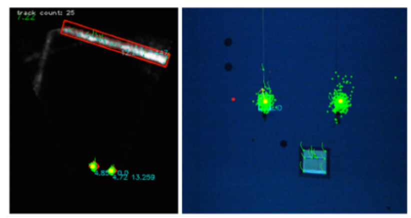


Fig. 13: Particle filter converges due to drop in uncertainty in from camera image

F. Control Panel

Bumblebee 3.0 features a new control panel written as an immediate mode GUI. Written in C++ and rendered as an OpenGL texture, we have been able to achieve significant reduction in CPU utilization and easier customization of the interface.

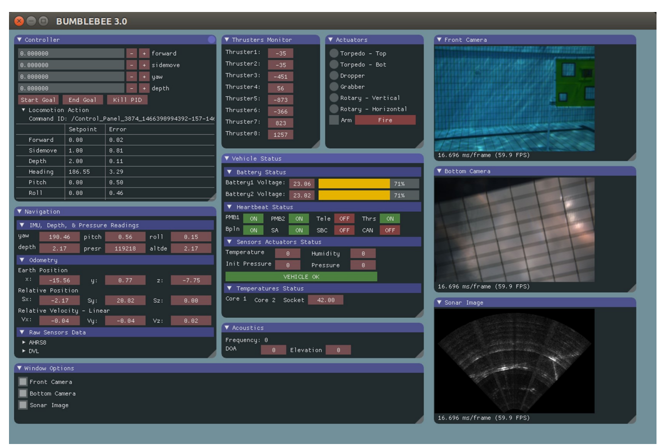
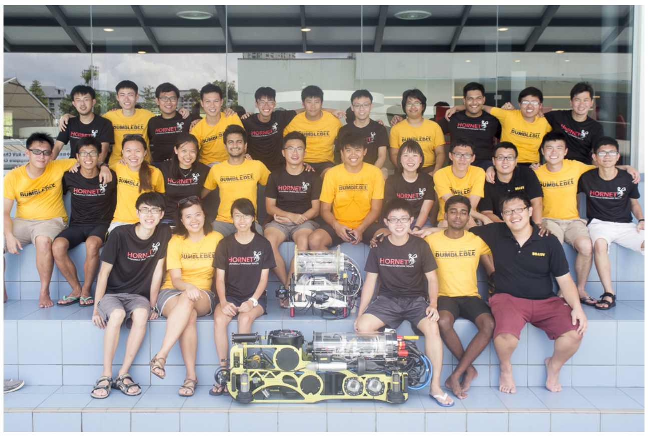


Fig. 14: Control Panel

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.



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.

Platinium Sponsor
DSO National Laboratories: For cash support and technical guidance
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, 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