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 improved with better machine vision cameras, more accurate navigation and imaging sonar integration for more robust computer vision. BumbleBees 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

For the third year, 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 in July in California; while the Singapore AUV Challenge was held in March in Singapore. Both competitions are designed with challenges that mirror industrial missions: visual recognition of objects, manipulation and acoustic localisation tasks. The Bumblebee development cycle this year has two parallel tracks: (1) to design and development the next generation Bumblebee 3.0 vehicle to compete in Robosub 2016 and (2) upgrading of Bumblebee 2.0 to Bumblebee 2.5 to patch the issues the vehicle faced from Robosub 2014.

Team BumbleBee is divided into Mechanical, Electrical and Software subteams. The team comprises students from mechanical, electrical, computer engineering and computer science of all years of studies.

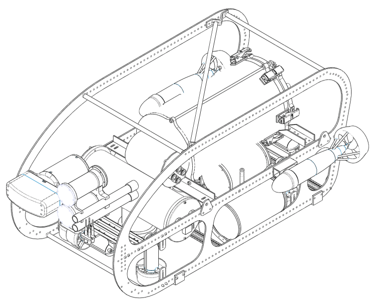

Fig. 1: BumbleBee AUV 2.5

II. Specification

Weight	50 kg
Dimensions	0.7m X 1.1m X 0.5m
Single Board Computer	Core i7 - 3610QE Aaeon EMB-QM77 8GB DDR3 RAM 512GB SATA3 SSD
Embedded System	Arduino Mega 2560 Xilinx Spartan-3 on NI sbRIO 9602
Propulsion	6 SeaBotix BTD150 2 VideoRay Surge Thrusters
Navigation	Teledyne RDI Explorer DVL Sparton GEDC-6 IMU US300 Pressure/Depth Sensor
Vision Sensors	AVT Guppy Pro AVT Guppy
Sonar	BlueView P450 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) Debian GNU/Linux x64

TABLE I: BumbleBee AUV 2.5 Specifications

III. Mechanical Sub-System

BumbleBee 2.5 features several upgrades from its original design. While maintaining its industrial Remote Operated Vehicles (ROVs) shape, enclosures for pneumatic pod and IMU have been changed.

A. Frame

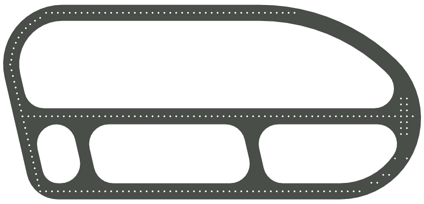

Fig. 2: Frame

The vehicle's frame is made by laser cutting aluminium sheet at Cititech Industrial Engineering and is bolted together using fasteners from Bossard. This robust and rigid frame encompasses all components while protecting them from direct impact. It also allows us to flexibly reposition components for optimal hardware stability through its unique regular drill pattern across its side.

B. External Hull and Enclosures

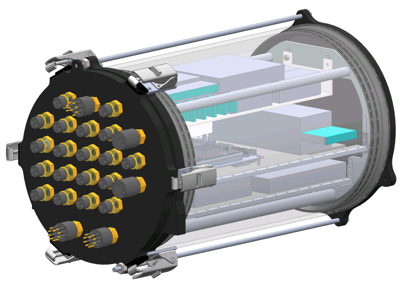

Fig. 3: Hull Assembly

The main electrical hull is made of standard size acrylic tube (250mm diameter) and it features end caps that are fabricated by Computer Numerical Control (CNC) machining of aluminium in the university's workshop. The main hull has a rapid disassembly feature that is achieved by using six draw latches to compress a face seal o-ring between the end caps. This improvement is a major breakthrough over the previous bolted flange design as it eases access to electronics within the hull.

A valve on the hull allows it to be pressurized and also monitors any drops in pressure. This feature allows the hull to be tested for any leaks before the vehicle is submerged in water. By pressurizing the hull to around 120kPa during operations, any leaks in the water would be made visible by escaping bubbles. Apart from that, a pressure sensor in the hull allows us to constantly monitor fluctuations in hull, which is a reflection of hull temperature. The hull also has a leak sensor in the case of failing pressure sensor. Leak alert is propagated to Bumblebee Control Panel which displays a warning. Through Hallin Marine's pressure testing chamber, the hull is rated to a depth of 40 meters.

Bumblebee's external enclosures house the electrical systems located outside the main hull. These comprises of the DVL housing, camera housing, acoustics housing, IMU housing and battery pods.

- DVL Housing:
  The DVL housing is fabricated by welding 6061 aluminium tubes into a T structure. The vertical tube houses the sensor head while the horizontal tube houses the electronic box. A Subconn micro circular bulkhead is used to provide an electrical connection which is linked to the main electrical hull.
- Camera Housing:
  The camera housing is fully machined in-house and an adapter that utilizes Festo's pneumatic push-in fitting waterproof feature is used to pass through the firewire cable for minimum data loss.

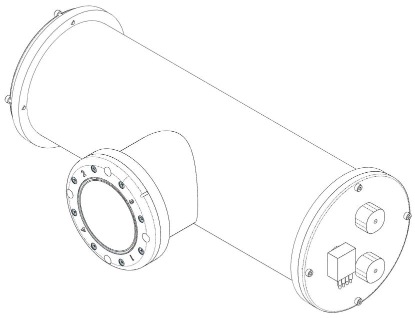

Fig. 4: DVL Housing Assembly

C. Thrusters Configuration

Bumblebee's propulsion system consists of six Seabotix BTD150 and two Videoray thrusters. Four Seabotix thrusters are used to provide movement in the z-direction (heave). The other two horizontal Seabotix thrusters are used for movement in the y-direction (sway). On top of that, the two Videoray thrusters are used to provide movement in the x-direction (surge). By controlling the thrust of various thrusters in a certain manner, we are able to achieve 6 DOF.

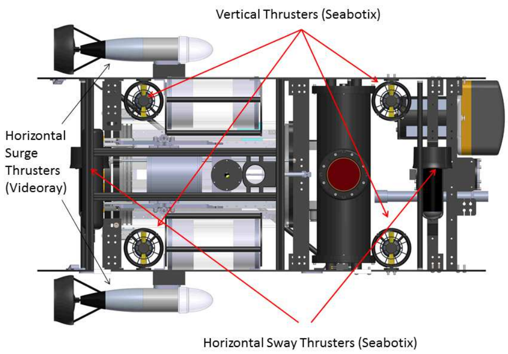

Fig. 5: Thrusters Configuration

D. Manipulators

Bumblebee is equipped with a set of 3D printed manipulators on board, consisting of a pair of grabber arms, a pair of torpedo launchers and a ball-dropper that are actuated using a pneumatics system. The compressed air for the pneumatics system is stored in a 13 cubic inch Ninja Paintball Tank. This year, some of the manipulator designs are revised. Firstly, the design of the grabber arms is improved so as to enhance their versatility in grabbing objects of different shapes and sizes.

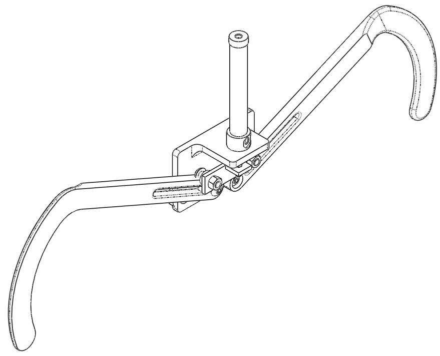

Fig. 6: Grabber

Simultaneously, compactness is incorporated in the design to ensure better integration into the vehicle. Secondly, the torpedo design involves the use of an O-ring to build enough pressure to ensure sufficient pressure for launching the torpedo. Thirdly, the ball-dropping mechanism has undergone a redesign to become more compact. All of Bumblebee's pneumatics system is supported by Festo Pneumatics Suppliers in Singapore.

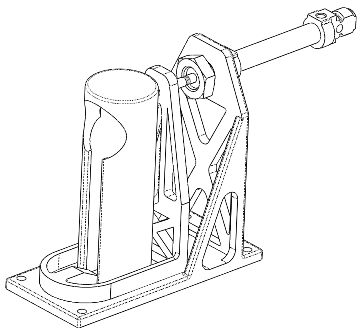

Fig. 7: Dropper

IV. Electrical Sub-System

The electrical system comprises the power, sensors and actuators, and the computer subsystems. The previous OpenUPS power subsystem has been replaced with the integration of Battery Management Boards. The sensors and actuators have been redesigned and additional ones are integrated. The main computer board hosts a quad core i7 processor for fast multicore software processing. The components are integrated on a single multi-level rack fitted into a single hull.

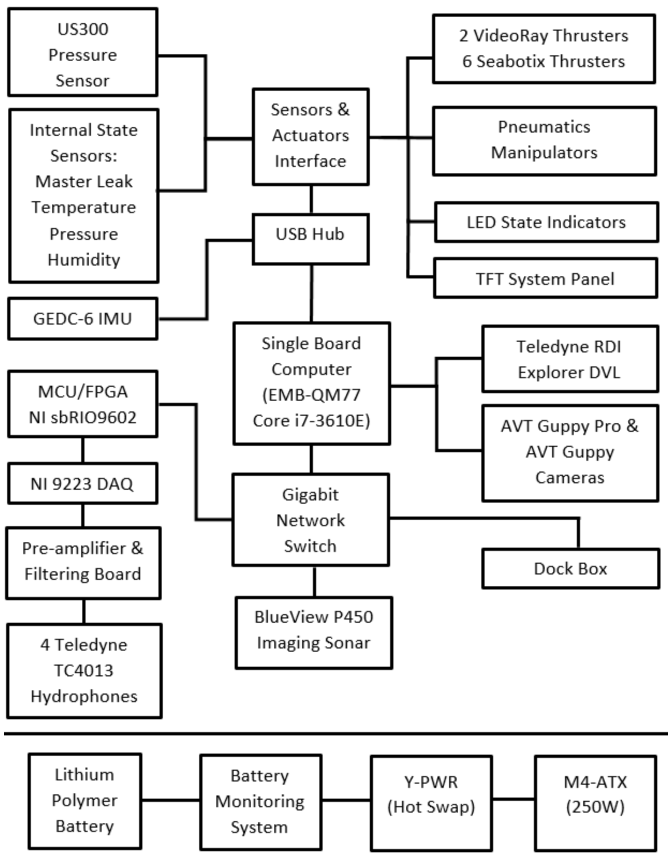

Fig. 8: Electrical System Block Diagram

A. Camera System

This year, our vehicle features a major upgrade to the system with the incorporation of new 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 previous vision system faced constantly changing colour reproduction and automatic exposure which caused major issues for our thresholding of the various colours in object detection and identification. Our previous cameras were based on webcams and paled in comparison to the Guppy cameras which boasted far 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.

B. Power System

The vehicle is powered by two 10000 mAh LiPo (lithium polymer) batteries extending testing time to approximately 210 minutes before requiring a recharge.

i. *Power Monitoring and Management:*
Each LiPo battery is installed into 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.

ii. *Power Distribution:*
The power system utilizes a M4 ATX power supply to generate three voltage rails to power the SBC and 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.

C. Sensors and Actuators

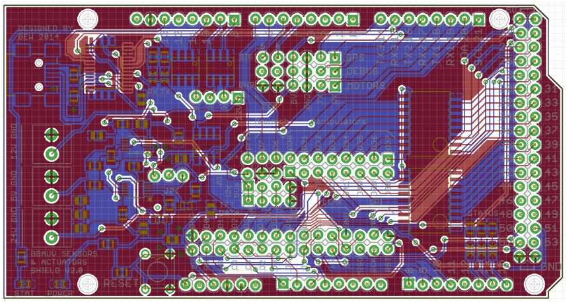

Fig. 9: Sensors and Actuator Board Design

BumbleBee 2.5 presents a redesigned and custom fabricated Printed Circuit Board (PCB) for the sensors and actuators shield. The Arduino Mega 2560 microcontroller developmental board is based on the previously used ATMega 2560 microcontroller. The previous shield design was continued because it provides quick swap of the microcontroller which is crucial for modular debugging during port or component damages.

New sensors such as internal pressure and humidity sensors are added onto the sensors and actuators board, to the existing suite of the GEDC-6 IMU, depth and temperature sensors. This board also interfaces the six SeaBotix thrusters and the pneumatic manipulators. The current thrusters are enhanced by including actuator controls to the electronic speed controllers operating on the two VideoRay surge thrusters.

In addition, LED strips are integrated as state indicators, while a TFT LCD screen display provide visual feedback on the system sensor status. These indicators are especially useful for understanding the vehicle's current state during autonomous runs.

D. Navigational Sensors

i. *Sparton GEDC-6 IMU:*
The Sparton GEDC-6 IMU (Inertial Measurement Unit) provides critical inertial data at a rapid rate of 100 Hz. The IMU's proprietary algorithms ensure the output of correct data despite the presence of electromagnetic interference generated by the BumbleBee's suite of electronics and thrusters.

ii. *Teledyne RDI Explorer DVL:*
The DVL (Doppler Velocity Log) is an active sonar system that tracks the velocity of the instrument via a four-beam solution directed at 30 degrees nominal from the sensor's 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 squares 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.

iii. *Navigation:*
The data provided by the navigational sensors are fused together via trigonometric equations to generate a global position vector. The odometric data obtained from this vector allows precise navigation to a given spatial coordinate.

E. Computer System

BumbleBee's software system is powered by an Intel Core i7-3610QE quad core processor on an Aaeon PCM-QM77 motherboard along with a 512 GB SATA SSD (Solid State Drive). This upgrade from the previous 16 GB SSD accommodates more software data and rosbag data collected.

A USB hub interfaces the embedded sensors and actuators as well as other serial devices, i.e. two PMBs and the GEDC-6. The imaging sonar is connected via Ethernet with a PoE (Power over Ethernet) connection to the SBC, dedicating imaging sonar bandwidth to the main computer. 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 9602 and surface router.

F. 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, allowing greater output in specific degree of freedoms. Velocity controllers for the surge and sway domains have been implemented for more precise maneuvering of the vehicle during mission runs. A control system tuning User Interface was designed to assist in software tuning of the control parameters.

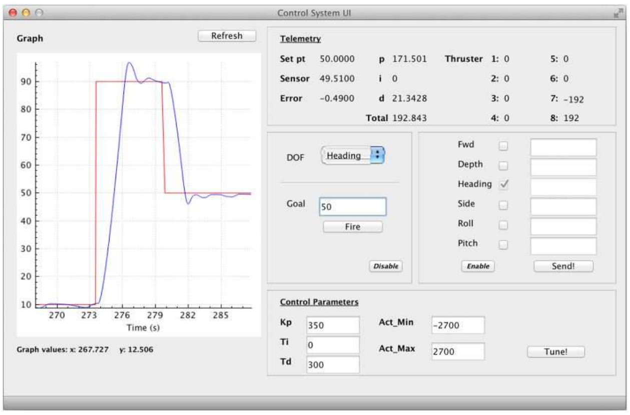

Fig. 10: PID tuning UI

V. Acoustic Sub-System

BumbleBee'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 a redesign of the software to improve the performance and robustness of the algorithm.

A. Hardware

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. 11: Hardware Flow Diagram on Acoustic Sub System

i. *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 on SolidWorks and fabricated precisely using laser-cutting technology.

ii. *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.

iii. *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 ($\pm 10V$) on up to 4 different channels.

iv. *NI sbRIO 9602*
Lastly, the signal is processed by the National Instruments sbRIO 9602 to compute the Direction of Arrival (DOA) of the signal. The sbRIO 9602 has a 400MHz PowerPC processor paired with a Xilinx Spartan-3 Field Programmable Gate Array (FPGA) with 2M gates.

B. *Software*

The Acoustic subsystem this year 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.

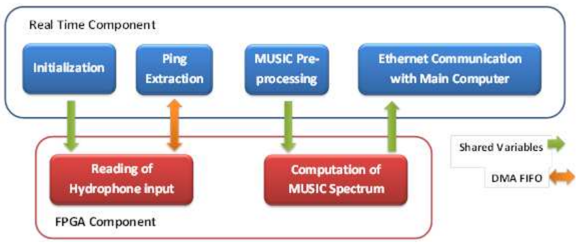

Fig. 12: Acoustic Sub-System Software Architecture

The usability and robustness has been improved of the acoustic sub-system. Error codes allow the main computer to gain insight on the functioning of the acoustic sub-system without having to access the program directly, allowing for easier debugging. 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

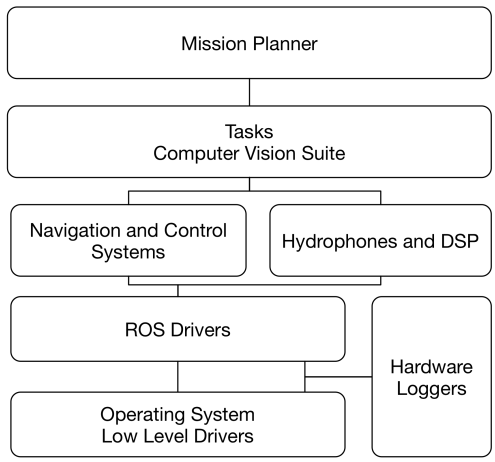

Fig. 13: Software Block Diagram

Bumblebee AUV'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 standardized medium for package management, serialization and over the network message passing between processes by utilizing a graph architecture. One of the biggest advantages that this offers is that we can run processes outside the

AUV that can control the system when its in water as well as connect to processes running inside a deployed AUV which 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

The navigational sensor suite consists of a 9 axis IMU, a DVL and a barometric depth sensor. Provisions have been made for the integration of a GPS receiver as well. The sensor data from the Doppler Velocity Log (DVL) is fused with the data from the 9 axis IMU and depth sensor is fused to obtain independent state data. An error state Kalman Filter is used to obtain more accuracy than each sensor is able to provide independently. It 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 canceled. 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.

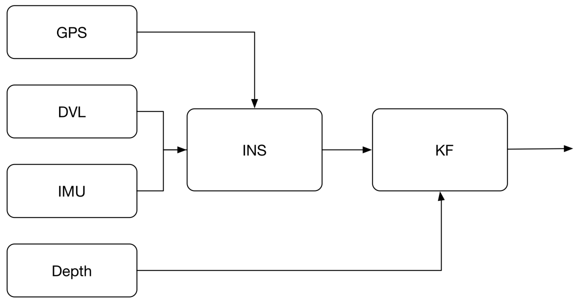

Fig. 14: Navigation Block Diagram

C. Computer Vision

Our basic vision processing framework consists of color thresholding, contour detection, morphological transformation and histogram equalization. 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. In addition, dynamic selection of threshold based on information such as contrast, brightness or entropy of certain channel. For image classification, contour features such as convexity, eccentricity and ellipticity are particularly useful to distinguish various shapes.

This year we have also explored several image processing techniques to achieve better image segmentation and object tracking in Robosub water condition. More focus is given on preprocessing of raw image captured from the camera to rectify problems such as specular reflections, poor visibility and color cast. For instance, gamma correction and dark channel prior are employed to handle hazy water condition that causes loss of details. Having learned from previous Robosub experience, instead of relying on a single method to identify object of interest, current vision algorithm utilizes ensemble of classifiers to achieve successful segmentation in varying water condition. A combination of edge detection, color thresholding and saliency detection provides consistent tracking of delorean and train despite loss of color intensity by light attenuation.

As most vision algorithms call for constant fine tuning of parameters to obtain maximum efficiency, utility tools such as ROS dynamic reconfigure client and rosbag tool to make possible rapid development of our vision algorithms. Besides that, we also write utility library for more comprehensive analysis of bag files obtained from daily practice run. With the utility library, we are able to possess a better grasp of minute informations such as effect of each vision filter.

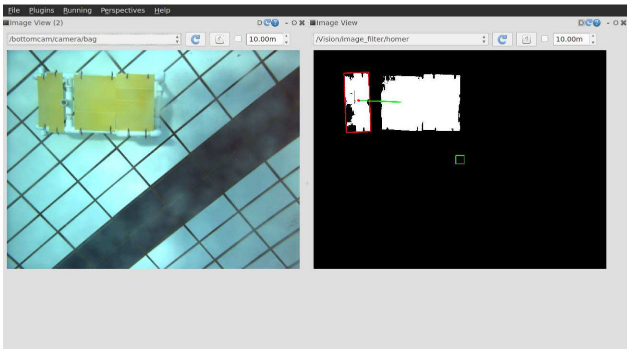

Fig. 15: Processed Image on ROS

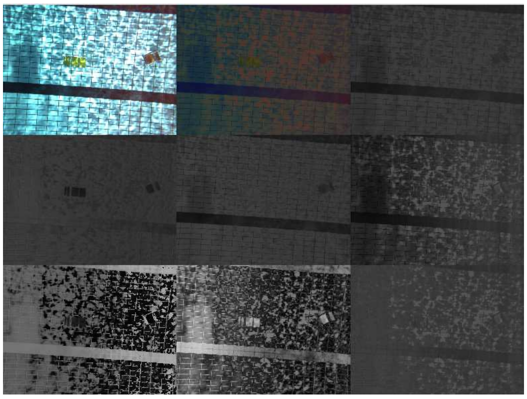

Fig. 16: Analysis of different channels of image frame after preprocessing

D. Imaging Sonar

This year, a new framework has been devised for better localization and tracking of targets in the forward space. A new multi-sensory fusion approach is used, involving the camera, sonar and vehicular POSE and velocity. Previous approaches for tracking targets involved HSV thresholding and contour detection in the camera space, but were susceptible to noise due to poor visibility.

In order for this fusion to work, a pre-calibration step is performed to find the relationship between the sonar, camera and vehicular dynamics. This step solves for unknowns as part of a model involving the vehicle's POSE, camera's intrinsic matrix and 3D sonar coordinates derived from the sonar image and depth sensor of a fixed calibration object.

With the above unknowns solved, we can project the sonar coordinates of any object into the camera space. If the object depth is unknown, the sonar's 20 degree vertical field of view can be used. Since the object's being tracked are stationary, it's position is a function of the Angular (Yaw) and Tangential (Vehicle) velocity as seen in Figure 16, hence the correct object can be selected. This is then projected to the camera as seen in Figure 17. From there, the multiple spaces are fused using a Recursive Bayesian Inference filter, and the final target point of interest is obtained.

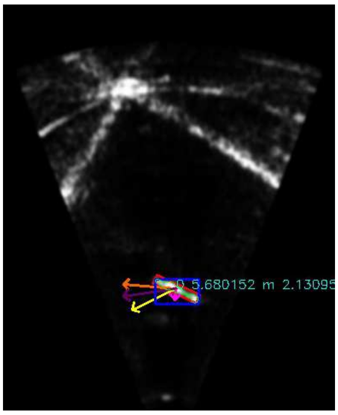

Fig. 17: Optical velocity fused with Angular (Yaw) and Tangential (Vehicle) velocity.

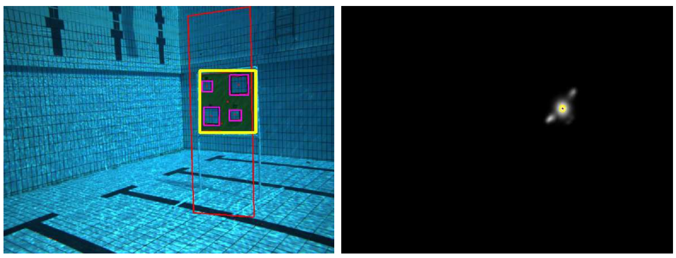

Fig. 18: Sonar plane is projected onto the camera plane and fused using a Recursive Bayesian filter.

VII. Vehicle Status and Testing

BumbleBee 2.5 has been undergoing extensive pool tests at Queenstown Swimming Complex in preparation for RoboSub 2015. Prior to the integration of the vehicle, the mechanical subsystem was thoroughly leak tested; the electrical components were bench tested; the software subsystem was constructed and tested on recorded data from previous runs.

VIII. Conclusion

Bumblebee 2.5 has undergone rigourous 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 carried over to the next generation Bumblebee 3.0 which will see deployment for next year's Robosub. Our team has evolved considerably also with better organisational structures and greater capacity for development. We are confident that Bumblebee 2.5 is ready to meet with the challenges of Robosub 2015.

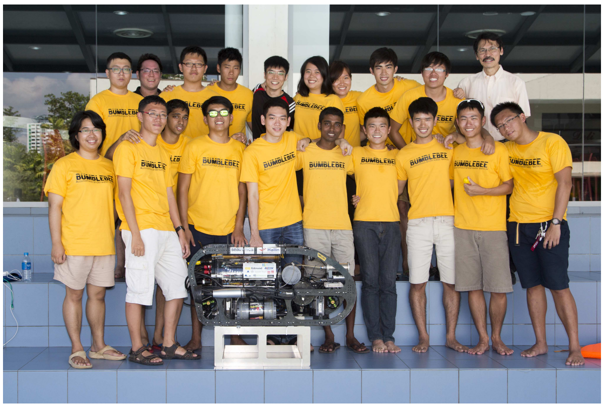

Fig. 19: Team Bumblebee 2015

IX. 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 sponsorship, equipment procurement, and academic support in our project.

Platinum Sponsor
Superior Energy Services(Hallin Marine): For supporting the early developments in our project with cash sponsorship and air tickets from 2012 onwards.
Seatronics: For the continued loan of Explorer DVL, BlueView Imaging Sonar and underwater connectors.
Cititech: For fabrication support of our mechanical parts and competition obstacles

Gold Sponsors
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Silver Sponsors
Teledyne Reson, Macartney Underwater Technology, Allied Vision Technologies, Edmund Optics, Sparton

Bronze Sponsors
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Supporting Organisations
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