DESIGN AND IMPLEMENTATION OF BUMBLEBEE AUTONOMOUS SURFACE VESSEL 1.0

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***Abstract*—Bumblebee Autonomous Surface Vehicle 1.0 (BBASV 1.0) is an extension of the team's work on autonomous maritime vehicles development, guided by experience gained from the development of the Bumblebee Autonomous Underwater Vehicle (BBAUV), deployed in Robosub, another AUVSI Foundation Competition. This first iteration was developed over a short six-month design and implementation cycle, providing a baseline vehicle to be used for future development work. It features a baseline ASV system with obstacle avoidance, feature tracking, autonomous navigation and acoustic localisation capabilities.**

I. INTRODUCTION

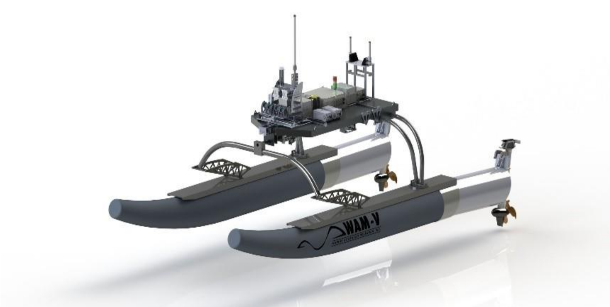

Figure 1. 3D Rendering of BBASV 1.0

Bumblebee Autonomous Surface Vehicle 1.0 (BBASV 1.0) is the product of a team of undergraduates from the National University of Singapore. (See Figure 1) To expand the scope of the team's work on autonomous maritime vehicles, support was sought in late 2015 to design an Autonomous Surface Vessel, capable of automated launch and recovery of an autonomous underwater vehicle. This was approved in mid-2016, and the team chose the participation in RobotX to be a milestone showcase of a baseline ASV. This is because RobotX aligns closely with challenges faced by the industry, encouraging teams to provide innovative solutions with real world applications. This was achieved in six months as a student driven team without any full-time academic research staff. This paper details the design choices of the mechanical, electrical, and software systems, as well as the experimental results obtained in the one-month sea testing of the vehicle before the competition. Many of the design choices are guided by the four generations of Bumblebee Autonomous Underwater Vehicle (BBAUV) developed and best practices ported over.

TABLE 1. BBASV 1.0 SPECIFICATIONS

Platform	**16' WAM-V® USV**
Single Board Computer	**Intel Core-i7 6700 IMBM-Q170A 8GB DDR4 RAM 512GB SATA3 SSD**
Embedded System	**NI sbRIO-9606 400MHz Controller NI9223 Analog Input Module 4 Teledyne Reson TC4013 Hydrophones**
Propulsion	**2 Torqeedo Travel 1003S**
Navigation	**Novatel OEM628 GPS STIM300 IMU Sparton AHRS8 IMU ODROID XU-4 Navigation Computer**
Vision Sensors	**4 Mako G-131 Camera**
LIDAR	**SICK LD-MRS400001**
Manipulators	**Festo Pneumatics Systems 17HD4063-05N Stepper Motor SR-403P Servo Motor**
Battery	**2 22.2V 10000mAh LiPo 1 12.6V 6800mAh Li-ion**
Connectors	**LEMO Connectors Samtec Acclimate™ Circulars Samtec Acclimate™ Threaded Circulars**
Software Architecture	**Robot Operating System (ROS) Gentoo GNU/Linux x64**

II. COMPETITION STRATEGY

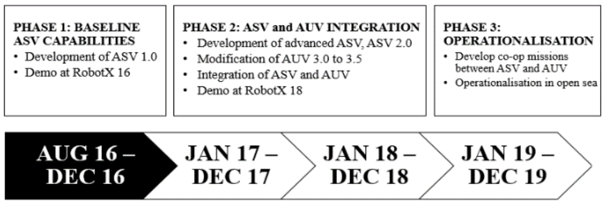

Figure 2. Three-year Masterplan

The focus for RobotX 16 as outlined in our three-year Masterplan in Figure 2 above is to demonstrate baseline ASV capabilities. Thus we have designed our strategy around mainly the surface based tasks but with limited integration of underwater based tasks. This was deliberated in consideration of the challenges involved in designing an automated launch and recovery system for an AUV vis-à-vis the tight project timeline of just six months to deliver for RobotX 16. With this as the overall strategy, the platform was designed as such to handle the challenges:

- Design the ASV to withstand weather and Sea State 3 conditions
- To operate up to 1km remotely whilst ensuring safe and reliable operation
- Sufficient battery power to run for four hours at a time to ensure continuous testing.
- Perform waypoint navigation to GPS coordinate to quickly home in to tasks
- Focus on surface based sensors for feature tracking and obstacle avoidance

III. MECHANICAL SYSTEM

The mechanical design of BBASV took into consideration the required positioning and integration of all the on-board components. Design, assembly and Finite Element Analysis was done in Solidworks. On top of that, modularity and reliability were key considerations in the design process.

A. Payload Tray Integration

The payload tray has been framed with profile bars to enable quick repositioning of components. The frame ensures that the placement of critical sensors is fixed, so that minimal calibration due to repositioning is required. It also helps to re-distribute mechanical load around the payload tray; the thin sheet of aluminium on the payload tray is observed to deform slightly when a heavy object is placed on it.

From previous experiences on BBAUV, vehicle modularity can be achieved by housing different systems in separate enclosures [1]. This helps to increase efficiency because different components can be tested separately with minimal effect on other modules, especially during down-time of a particular module.

Different enclosures and components are placed strategically to maintain dynamics on the water. This is achieved through the approximation of the positions of the centre of gravity of the payload tray assembly in Solidworks.

B. Enclosures

Electrical modules on-board Bumblebee ASV are housed in IP67 [2] custom-off-the-shelf polycarbonate enclosures. This helps to ensure that electrical components are safe from harsh weather and sea conditions, and short period of immersion in an unlikely event of ASV capsize. The enclosures offer UV protection, electrical insulation and impact loading up to IK09 to maintain reliable working conditions for the delicate components within [3].

The ASV is also equipped with custom fabricated aluminium enclosures used as battery and camera housings. The housings are designed to cater for the specific needs of each the battery and camera modules. Both the battery and camera enclosures require dimensions which are not of usual custom-off-the-shelf enclosures. Viewing windows are added to the battery modules for visual monitoring.

C. Cooling System

Testing for long hours in the tropical weather in Singapore will cause over-heating of the main computer - an issue we faced with our AUV [1]. To cope with this, a liquid cooling system was been installed in the Main Electrical System.

Assorted computer liquid cooling components were purchased and assembled and can be seen in Figure 3. Firstly, a copper CPU cooling block replaces the existing fan on the Single Board Computer (SBC), absorbing heat generated from the CPU. Next, liquid coolant, driven around the cooling loop via a pump, convects heat away from the copper block. Finally, the coolant flows into a radiator positioned at the outside of the Main, dissipating heat to the surroundings through its copper fins. IP68 rated fans attached to the radiator accelerate the cooling process.

The liquid cooling system allows heat generated within to be transferred to the surrounding environment, hence mitigating the issue of high temperatures within the main system. After the cooling system is implemented, the core temperature of the CPU was maintained around 40°C during regular testing, peaking at around 50°C during periods of high load.

Figure 3. Overview of the Cooling System

D. Manipulators

BBASV features two sets of pneumatics manipulators. One of which is the hydrophones actuator, which can be seen in Figure 4. It is combination of a rotary and a linear actuator to extend the hydrophone array into the water to achieve better acoustic localisation. The design of the hydrophone array actuator is also made flexible to cater for mounting of other underwater sensors.

The other set is a payload delivery assembly of four pneumatic powered launchers. The launcher is also equipped with servo and stepper motors for pitch and lateral adjustments to maintain the target and compensate for the drifting of the ASV on the water.

Pneumatics is chosen over other actuation mechanisms primarily due to its reliability and flexibility [1].

Figure 4. Pneumatic Actuators for Hydrophone Lowering System

IV. ELECTRICAL SYSTEM

The BBASV electrical system features a combination of COTS devices and custom printed circuit boards.

With a large assortment of hardware, a well-planned out electrical architecture is required to integrate them together. The electrical architecture is broken into two portions namely Communication Protocol Architecture and Power Architecture.

A. Communication Protocol Architecture

The architecture in Figure 5 is designed to cater to the various key communication protocols used in the system for communication with the various hardware in the system.

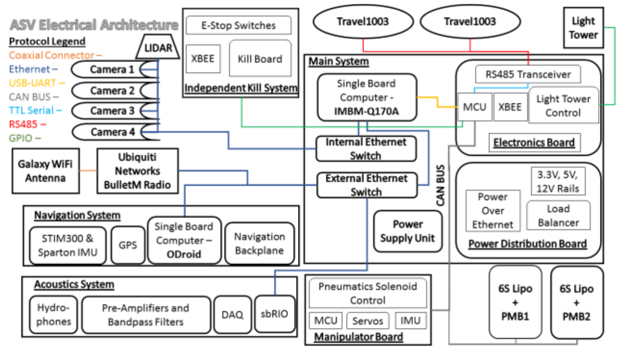

Figure 5. Overview of communication protocol architecture

Controller Area Network (CAN) and Ethernet are deployed for inter-device networking, selected based on their relative ease of implementation, high noise immunity, and flexibility to future upgrades.

The deployment of CAN in the system eliminated the single point of failure; a major design improvement from older generations of BBAUV which required the SBC to play the role of the master between communicating devices. With CAN, hardware devices can exchange data in a peer to peer fashion over a robust differential CAN bus without additional wiring overheads between devices.

The deployment of Ethernet is used to support up to 1000Mbps of data transfer for data heavy transmission due to the multitude of devices utilising Ethernet. The Power Over Ethernet (POE) variation is implemented to supply power to the external modules concurrently and reduced the wiring on the system.

B. Power Architecture

The power architecture in Figure 6 is centred around the power supply unit and the custom power distribution board (PDB) to supply the electronics on the ASV with a reliable power source.

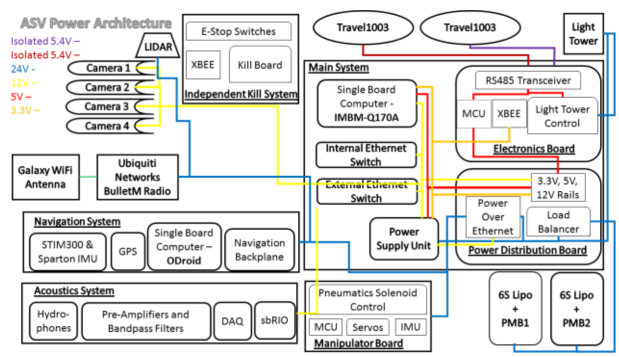

Figure 6. Overview of power architecture

C. Power Management

1. Battery Modules

Two 22.2V battery modules of 10Ah each power the main electrical system. Each module is equipped with their custom Power Monitoring Board (PMB) designed to withstand a maximum current of 30A. The PMBs are used to monitor the voltage and capacity of the batteries. They are also used to control the power input into the main system. Should there be a large current draw or a sudden drop in the battery voltage level, the PMB is capable of emergency shutdown and automatically cuts power to the main system. This enhances the safety of using LiPo battery packs and prevents over discharge.

The modules facilitate charging of the batteries without disassembly. A battery charging box was designed for quick deployment of mobile charging stations. This battery charging box supports parallel charging of two battery pods of up to 25A per channel simultaneously taking only 20 minutes for a full charge cycle.

2. Power Distribution Board (PDB)

The PDB is custom designed to provide various voltage rails (24V, 12V, 5V, 3.3V) through Power Over Ethernet (POE) and wiring. The PDB also provides load balancing and hot-swap capabilities for the batteries, enabling battery changes without powering down the SBC.

D. Visual Indicator System

An EZ-LIGHT TL50BL Beacon Tower Light for outdoor applications is used as the visual indicator of the ASV's vehicular state. Each mode is indicated using steady lights as follows [Table 2]:

TABLE 2. VISUAL INDICATOR COLOURS

Colour	Green	Yellow	Red
Mode	Autonomous	Manual Operation	E-stop Active

E. Manipulator System

The manipulator system is designed to accomplish the task for Detect and Deliver as well as Acoustic Pinger-Based Transit. An on-board microcontroller receives commands from the SBC via CAN, and acts accordingly. A high current H-bridge driver chip is used to drive the stepper motor. An On-board automotive grade Inertia Measurement Unit (IMU) constantly monitors the pitch of the vehicle and provides feedback to the microcontroller for pitch adjustment; this ensures that the shooter is always aiming at the target accurately regardless of the vehicle's pitch due to waves.

F. Propulsion System

The propulsion system comprises two Torqeedo 1003S electric outboard motors. Each motor is capable of 68 lbs of static thrust, which steers the ASV using differential thrust. They were chosen as motor control and retrieval of electrical status information on the motor and battery can all be done without any additional hardware modifications. To do this, the tiller which is usually used to control the motor was removed, and a microcontroller was introduced to interface with the motors' integrated on-board computer via RS485. A library was written to decode the proprietary Torqeedo protocol. A separate relay is used to turn on and off the thrusters. In the initial design, the motors were not electrically isolated from the electrical system and shared a common ground. This caused damage to the motors as well as the RS485 interface ICs. The design was modified for galvanic isolation of the motors from the electronics preventing further damage.

The microcontroller takes in commands from either the on-board SBC for autonomous operation, or the Operator Control System (OCS) on land for manual operation using a joystick via a wireless Xbee module. As a safety feature, the microcontroller stops the thrusters once the manual control link is lost to prevent losing control of the ASV. Manual control is recovered once the control link is restored.

G. Independent Kill System

The kill system was designed per the safety requirement to have an independent physical emergency stop system. The system has both wireless remote and also in vehicle emergency stop which will instantaneously disconnect power from the vehicle's motors. The kill system caters for the following technical specifications of the Travel 1003S.

- Operating Voltage: 30V
- Maximum Current Draw: 50A

In addition, as the thrusters will each be mounted at the back of the pontoon, which is a considerable distance away from the payload tray where the kill system is planned to be mounted, a custom cable extension is made to connect the kill system to both thrusters.

The system went through 3 rounds of design iteration. The first iteration used automotive MOSFETs to cut the power. However, the MOSFETs were assessed to not be able to withstand the initial current spike from the inductive load. The second iteration used automotive relays to cut power. This worked well, but a flaw was discovered in the schematic during system integration. Power was cut on the GND line, and that included the signal GND. This forced the signal return path into the noisy main GND line, resulting in the damages to the RS485 communication bus of the motors. In the third iteration, power is cut on the 30V line instead as shown in Figure 7

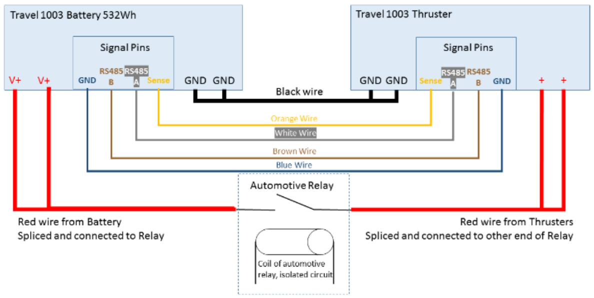

Figure 7. Implementation of Kill System, cutting the power line avoids the problem of noisy ground return path

The wireless remote kill uses the same communication module as the OCS. The system is designed to cut power should the wireless remote kill lose signal for safety considerations.

H. Wireless Communications

Communication with BBASV is performed over three links as follows [Table 3]:

TABLE 3: DIFFERENT COMMUNICATION LINKS

Control Link	**Xbee Pro 900HP (900MHz)**
Independent Kill Link	**Xbee Pro 900HP (900MHz)**
Data Link	**Ubiquity BulletM Radio (2.4GHz)**

The links were selected based on considerations for data rate and range. The control link utilises Xbee Pro 900HP on 900MHz allowing for better range at lower data rates given the lower bandwidth required to transmit control commands. Same consideration applies to the independent kill link which send low bandwidth heartbeat and kill command messages to the receiver on board the vessel. The Xbees utilise Digimesh to enhance robustness and redundancy of the nodes by connecting all of the Xbee devices in a mesh network. This allows for multi-hop messages should a direct link fail.

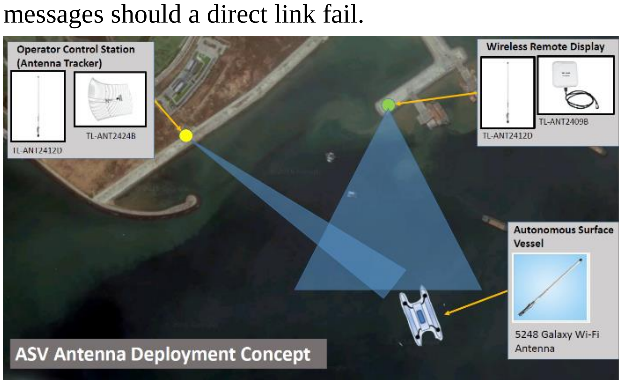

Figure 8. Implementation of the Data Link network

The Data Link on the other hand requires heavy transfer of data as well as image/LIDAR streams. The BulletM Radio was selected to allow for higher data transfer rates but at the price of range. To compensate this, higher gain antennas were deployed on the ASV as well as the OCS. The BulletM utilises Time Division Multiple Access to minimise collisions due to the hidden node problem. This is especially with the ASV being a long distance point to point link and may contend with the Wireless Remote display. The Data Link network comprise of the ASV as the Access Point, the Operator Control Station and the Wireless Remote Display as client nodes.

1. Operator Control Station

The purpose for the Operator Control Station (OCS) is for the user to retain manual control the vehicle, and data transfer from the ASV to other land terminals. It serves as a control link and a data link between the operator on shore and the vehicle. On the control side, the operator would be able to utilise a joystick to control the movement of the vehicle.

2. Wireless Remote Display

A Wireless Remote Display was designed to provide feedback to the judges of task completion. Leveraging on the same Data Link, this reports the results of tasks to the judges. Information received will be processed and displayed on a screen to the judges.

I. Vision System

BBASV has 4 machine vision cameras interfaced over POE as follows:

- Front Camera: 2x Mako G-131 POE Camera, with the possibility of expansion into stereo cameras
- Side Camera: 1x Mako G-131 POE Camera
- Underwater Camera: 1x Mako G-131 POE Camera

In BBAUV, the interfacing of firewire cameras was problematic due to the amount of additional hardware needed and susceptibility of the firewire signals to interference. Due to these issues, POE cameras were deployed instead for BBASV. The Mako cameras communicating over Ethernet made adding and removing cameras highly flexible and integration of the hardware was straightforward. The system easily supported the 4 Mako cameras.

The SICK LD-MRS400001 LIDAR is also deployed on BBASV as part of the vision sub-system. It is able to provide 800 data points at distances up to 50m, at a frequency of 15Hz.

J. Navigation System

The ASV has 4 main navigational sensors on board:

- Novatel OEM628 GPS Receiver capable of L1/L2 GPS and GLONASS with Antcom G5 L1/L2 GPS Antenna
- Sensonor STIM300 Inertial Measurement Unit
- Sparton AHRS-8 Inertial Measurement Unit

K. Acoustic System

The design of the acoustic system in BBASV has been adapted from the acoustic system of BBAUV. Through years of developments, a reliable system is developed to ensure real-time processing and accurate localisation of the vehicle [1] [4].

1. Hardware

Four Teledyne Reson TC4013 hydrophones are used to receive signals from the pinger. Their compact size of 9.5mm in width allows them to be placed within a spacing of 1.5cm, which makes them an ideal choice for phase difference based algorithms.

A custom-built preamplifier and band pass filter improves Signal to Noise Ratio (SNR) and avoids aliasing incurred by sampling high frequency components above Nyquist frequency.

The NI 9223 analog input module features 4 channels, simultaneous, differential ADC that is capable of sampling at 1MS/s/ch.

The NI sbRIO 9606 processor board allows data to be processed at high speed with its 400MHz PowerPC microprocessor and runs algorithms in real time, enabled by the embedded Xilinx Spartan-6 LX45 Field Programmable Gate Array (FPGA) component. It communicates to the SBC via an Ethernet connection.

2. Software

Multiple Signal Classification (MUSIC) is a phase difference based algorithm which has high resolution and low computational requirement [5] [Figure 9]. It is ideal to be deployed in an embedded platform performing active acoustic localisation which demands real-time processing of data. The workload has been divided between the real-time processor and the FPGA, with the processor handling less computationally intensive tasks such as digital band pass filtering, Fast Fourier transform, and communication to SBC. The FPGA handles the time-critical tasks such as MUSIC spectrum computation and reading of samples from the ADC [Figure 10].

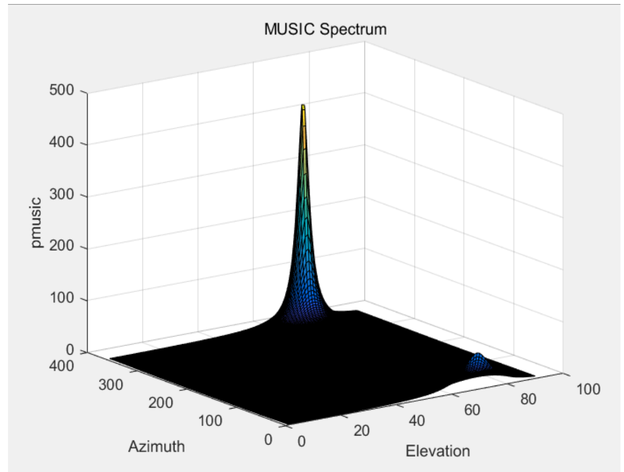

Figure 9. MUSIC spectrum drawn in MATLAB, a sharp peak in the spectrum indicates the algorithm capable of resolving two closely separated angles

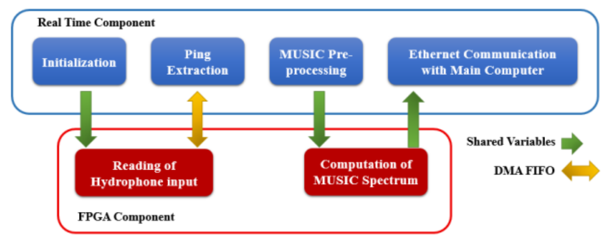

Figure 10. Algorithm flow of acoustic system, the good separation of real-time processor and FPGA enable low latency and accurate results

3. Improvements from previous iteration

Further refinement was done over the last iteration of the software algorithm, enabling the achievement of a low overall computational time of around 100-200ms and increased accuracy in results. In the previous iteration, the number of hardware computational units in FPGA had to be decreased for successful compilation of FPGA codes, resulting in mathematical inaccuracy. In the latest iteration, an improved algorithmic structure and logic flow to re-distribute the FPGA resources to an optimal level, enabled a significant reduction of FPGA resource usage. This produced better results, while still leaving room for future expansion.

Redundant code was removed and a more modular design is adapted to allow easier debugging and understanding of algorithm flow.

Previous iteration requires the vehicle to stop and listen for pings. In this iteration, Listening-on-the-move is now possible, enabling the vehicle to localise faster. To overcome the noise produced during movement, the simple thresholding technique was abandoned, matched filter and mean filter were employed for ping extraction from the noisy signals received instead.

V. SOFTWARE SYSTEM

A. Software Architecture

As seen in Figure 11, the software architecture for the ASV was designed based off the existing architecture for BBAUV [1]. We make use of Robot Operating System to perform durable inter-process communications and enforce structure on individual task nodes and communication protocols.

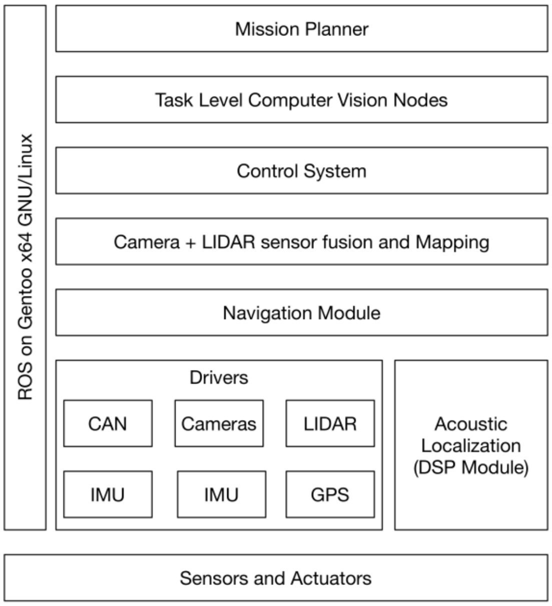

Figure 11. Software architecture

Each of the task nodes are written to work independently from each other for ease of testing. The use of independent task nodes combined with the networked nature of ROS also lets us to run the nodes outside the ASV.

B. Mission Planner

The mission planner is a high-level task node that manages other nodes. It is given a mission plan when initialised from which it calculates an optimal plan to follow. The calculated plan includes the path to take, tasks to activate and transitions to follow up tasks. It can start, stop and run tasks concurrently and to detect failure and react accordingly. Detecting failure is done based on hard positional bounding boxes, cascading timers and input from the task nodes themselves.

For coping with the increased dynamic and unpredictable nature of the RobotX tasks, the mission planner can recalculate the plan based on input received from computer vision nodes; for example, taking different routes and tasks based on the input from color codes on buoys.

The mission planner is state machine based and written in Python for ease of change at field tests. It makes heavy use of the ROS smach and smachros libraries.

C. Navigation

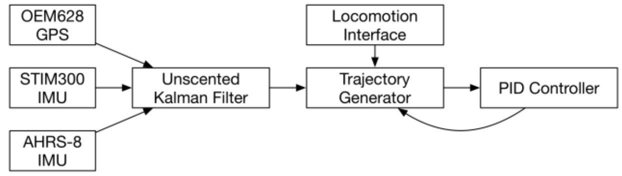

Figure 12. INS architecture

The inputs from the navigation hardware suite are sensor fused into the local navigation frame that can be utilized for doing computer vision tasks. (see Figure 12) We use an unscented Kalman filter with the following state vector:

$$[\mathbf{p}\ \mathbf{v}\ \mathbf{a}\ \mathbf{q}\ \boldsymbol{\omega}\ \boldsymbol{\omega}_{\mathbf{b}}]$$

where each of them are three vectors for position, velocity, linear acceleration, quaternion attitude, angular velocity and the gyroscopic bias respectively. The true heading to magnetic north is then obtained from the AHRS-8 which has a magnetometer as opposed to the STIM300 and then fused with the state.

It is worth noting that BBAUV featured an external, fully modular navigational module consisting of its own networking and an ODROID XU4 as the single board computer [1]. The original design consideration noted ease of transition and plug and play capabilities to new platforms and we have indeed reused the same module for the ASV.

Unscented filtering was chosen for its increased robustness to noise in the more dynamic and unstable sea conditions as opposed to the error state filter that the AUV featured. Although UKF is computationally more expensive, it is not a bottleneck considering our hardware on board.

D. Control System

The control system for the ASV consists of two closed loop Proportional Integral Derivative (PID) controllers minimizing errors in the δx (surge) and $\delta\theta$ (heading). For any given path, we sample the instantaneous error or deviation from the path and continuously act on it. (See Figure 13) The system takes its set-points from the vision system and its inputs from the INS system. This also enables the control system to take inputs from a variety of path planning algorithms but is optimized for $RTT^{\star}$.

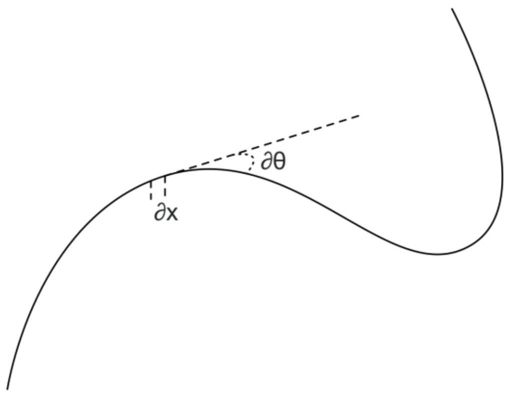

Figure 13. Following a trajectory

Set-point weighting and integral windup protection is built into the PID loops to increase stability of the system. Due to the inertia of the ASV, the PID loops are tuned to be overdamped to prevent excess uncontrolled overshoot. Real world constraints on the actuators (windup time for the motors) is considered and tuned for.

The PID controller is tuned by hand at a real testing location as opposed to automated tuning as we have had more success with the former. Our intuitive and helpful control system tuning UI from BBAUV can be used with the new control system as well.

E. Computer Vision

1. Symbol Detection

Our symbol detection consists of two main stages - detection and classification. (See Figure 14) In the detection stage, we use Maximally Stable Extremal Regions (MSER) to extract regions of interest from the image. MSER is chosen due to its robustness to scale and perspective change. MSER is performed on the saturation channel of HSV image, as the target symbols have much higher colour saturation compared to their surroundings. After detecting all MSER regions, filtering is done based on pixel size and aspect ratio.

The filtered set of MSER regions are passed to the classification stage. In this stage, we extract the largest area contour from each region of interest and compute its seven Hu moments. Hu moments are shape descriptors which are invariant to translation, rotation and scale. The computed Hu moments are compared with the Hu moments of known templates.

To eliminate false positives, persistence checking over 10 consecutive image frames is employed. Pixel coordinate of false positive tend to fluctuate radically across consecutive frames, while pixel coordinate of valid target is relatively more stable.

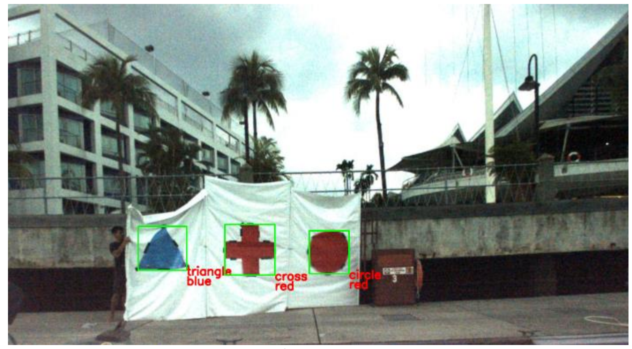

Figure 14. Detection of shapes using computer vision

2. Buoy Detection

Salient region detection is first used to segment the foreground from the background. The buoys, amongst with other obstacles, will show up distinctly in the resultant saliency map. Binary thresholding is done on the saliency map to obtain a thresholded image. To only detect buoys of certain colour, original RGB image is converted from camera into HSV colour space and threshold it based on the required colour. The two thresholded images are then combined to form the final thresholded image for the required colour.

Several techniques are employed to eliminate false positives, such as filtering based on contour area, aspect ratio of detected Region of Interest (ROI), and angle of rotation of the minimum area rectangle enclosing the detected contour.

F. Control Panel

The BBASV 1.0 Control Panel leveraged on the user interface that was designed for BBAUV 3.0 [Figure 15].

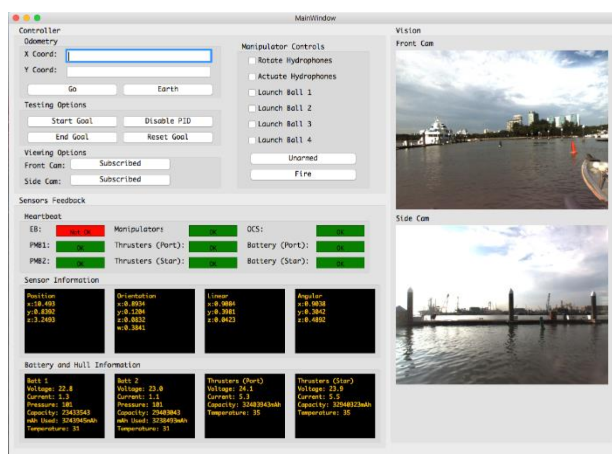

Figure 15. BBASV Control Panel v1.1

With the control panel, operators of the ASV would be able to view real time telemetry information from the ASV for both monitoring as well as troubleshooting. The control panel is capable of control of the vehicle as well via the Control Systems. As the code is currently written in Python, high CPU usage is required to run it. Plans have been made to rewrite the control panel in C++.

G. Simulation

For RobotX, it was necessary to build a map of the scene to perform various tasks such as obstacle avoidance, and to extract the 3D coordinate of obstacles detected in the camera. In our case, the map is unknown, hence it is necessary to continuously build it over time. The algorithm was developed around Simultaneous Localisation and Mapping (SLAM).

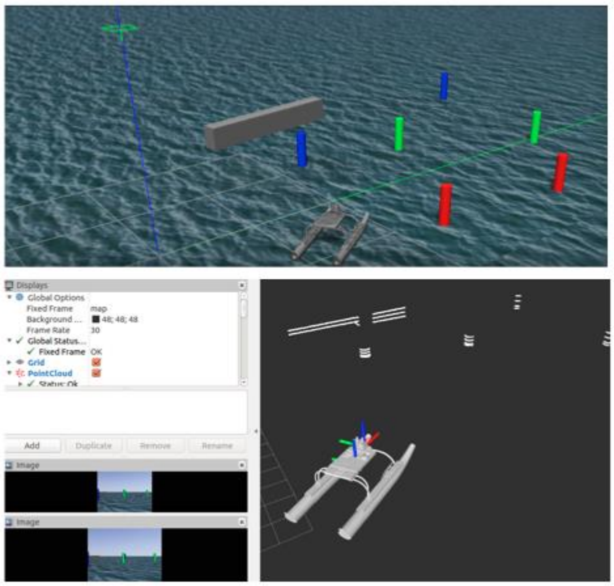

Figure 16. Simulation of Obstacle Avoidance

To develop it, the setting was built up in a simulation environment (Gazebo), where dynamics of the vehicle is modelled. (See Figure 16) A simulated stereo camera and LIDAR was then placed on the boat. Algorithm was developed to ensure that the ground truth pose of the boat, and the pose determined by SLAM were closely matched. After a baseline performance was achieved in simulation, real world data was added in. There was a lot more noise and the sensor data was sparser, hence the weights of the filter were tuned to work.

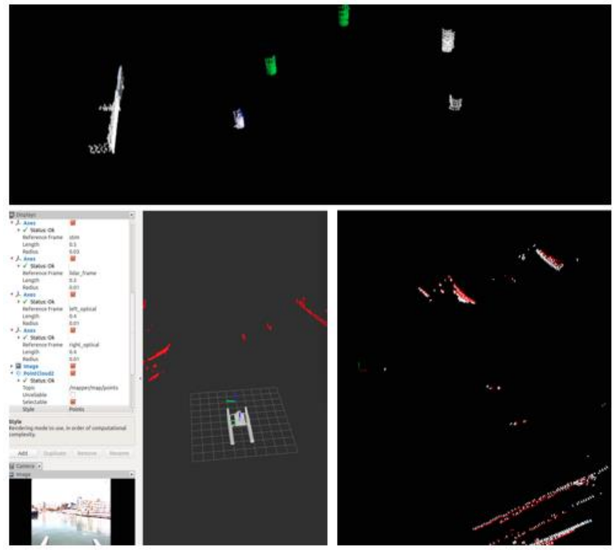

Figure 17. Simultaneous Localisation and Mapping with LIDAR

The algorithm works based on a particle filter based approach, where the incoming LIDAR data is correlated with an existing map that is actively being built, by minimizing the distance and surface normal of the data (see Figure 17). This is done at 10FPS in one thread, and another thread takes a brute force ICP approach to superimpose the existing data against the old map and down sampling it. Hence, we can continuously localize the robot at high speed, and build the map up at a slower speed. This was an approach taken from several existing algorithms such as gmapping.

VI. CONCLUSION

BBASV has undergone much testing and evaluation to achieve the baseline capabilities of today. Concurrently, the many lessons learnt in the design of this vehicle will continually be iterated upon to develop a better vehicle for version 2. We are confident that BBASV is ready to meet with the challenges of RobotX 2016 and to mark a milestone in our three year Masterplan.

VII. ACKNOWLEDGEMENT

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