Bumblebee Autonomous Surface Vessel 2.0 Technical Design Paper 2018 RobotX Competition

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Abstract— **Bumblebee Autonomous Surface Vessel (BBASV) 2.0 is the product of a team of undergraduates and alumnus from the National University of Singapore (NUS). As part of the team's 3-year masterplan, the BBASV will demonstrate its capabilities, along with the team's flagship Bumblebee Autonomous Underwater Vehicle (BBAUV) 3.5, in a multi-platform system during the Maritime RobotX Challenge 2018. This paper discusses the development and integration work done by the team for the past 2 years.**

I. INTRODUCTION

The Bumblebee Autonomous Surface Vessel 2.0 (BBASV) was produced from a complete overhaul of the design that was used in 2016, to complete the various tasks in the Maritime RobotX competition 2018. This document details the design and implementation of the mechanical systems, electrical systems and software systems of the machine to enable its autonomous operations while it is out at sea, as well as the incorporation of the Bumblebee Autonomous Underwater Vehicle 3.5 (BBAUV) onto the BBASV through a Launch and Recovery System (LARS) to achieve an Integrated ASV-AUV System.

II. DESIGN STRATEGY

Fresh off RobotX 2016, Team Bumblebee began their preparation for RobotX 2018 with three key objectives: upgrading the ASV hardware to handle up to Sea State 3 conditions, developing a software stack portable across different autonomous systems, as well as demonstrating an Integrated ASV-AUV System using a Launch and Recovery System (LARS). This is in line with the three-year Master Plan conceived by the team in 2016.

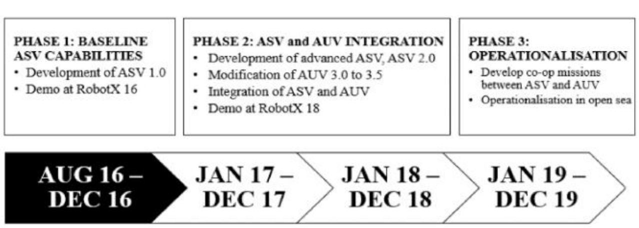

Figure 1:Development plan over three years

Hardware upgrades were focused mainly on improving the power systems, propulsion systems and sensors suite. There was a need for longer lasting batteries and stronger thrusters to handle Sea State 3. However, it was impossible to demand for both to be increased without limit since they are tightly coupled, with the thrusters being the most power consuming hardware on the ASV. As for sensors, with the limited budget, the team was prudent in the selection of the right sensors for the ASV, spending a significant amount of effort in benchmarking new hardware beforehand.

Given the stability of the software stack on the AUV, the ASV software stack was adapted and streamlined from the AUV into a common software stack. Additional components such as mapping and path planning were added for the ASV. Key components that had served well us for RoboSub, such as perception, were ported directly from the AUV with minimal changes.

Finally, the LARS development was done separately over the previous 2 years to allow the AUV to continue competing in RoboSub, before working on the integration with the ASV after RoboSub 2018. This resulted in a very tight deadline. Especially due to LARS being a relatively large system, it impacted a lot of design decisions for the other platforms, such as load carrying capacity, mounting points, simultaneous control of both ASV and AUV etc. As such, all 3 sub-teams have been making design decisions which catered for LARS since development began 2 years ago. The team also worked together tightly during the integration period to ensure that these concerns were addressed properly.

III. VEHICLE DESIGN

A. MECHANICAL SYSTEMS:

1. Antenna mast

The Antenna Mast houses most of the sensors and raises the antennas 2.5m above sea level to provide a balance between the range of the datalink, weight of the mast and the ease of assembly indoors for testing.

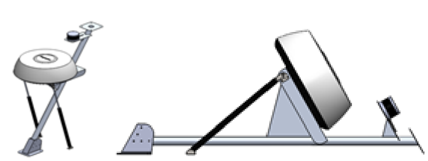

Figure 2:Antenna Mast when Upright (Left) and Folded (Right)

Designed with the intention of allowing the ASV to be transportable, the Antenna Mast had to be easily foldable. Adding on to that, the Antenna Mast is tall and holds a lot of sensors and antennas which makes folding and rising a challenge. Moreover, to increase the endurance and range of the ASV, a manual lifting and folding mechanism was desired as no power requirement is needed for the system. Hence, a gas spring was chosen. Furthermore, to prevent large deflections of the mast during operation as well as to stiffen the whole mast, a lockable gas spring was chosen as it will lock in any position and act as a rigid bar.

With the current design of the Antenna Mast, mounting of components onto the Mast is an issue as the Mast is tilted at an angle. To counter this, welded mounting planes are installed for easier mounting with the added bonus of stiffening the mounts.

2. Ball shooter

The new BBASV 2.0 Ball Shooter is electrically actuated. Designed with reliability and simplicity in mind, the BBASV 2.0 ball shooter propels the projectiles using counter rotating wheels driven by brushless DC motors. Additionally, a scotch yoke mechanism was used to convert the rotary motion from the servo to a linear motion to reload the balls.

To ensure reliable operation out at sea, all electric motors are housed in a waterproof Fibox housing. These motors are also mounted upside-down to ensure that water does not come into contact with the sensitive electrical components, and thus be able to withstand different weather conditions.

Figure 3: Prototypes for Motor Selection and Ball Compression

Prototypes were made to test the ideal ball compression as well as to select an appropriate motor for the ball shooter. Motors of varying rotations per minute (RPM) and torque were tested with a variety of distances between the 2 motors. All of which were specified based on calculations done beforehand. After much experimentation, an ideal configuration was found for optimal projectile range.

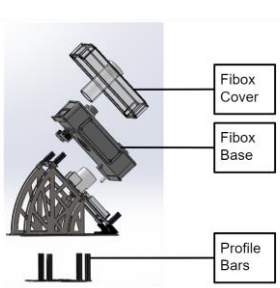

Figure 4: Disassembly of BBASV 2.0 Ball Shooter

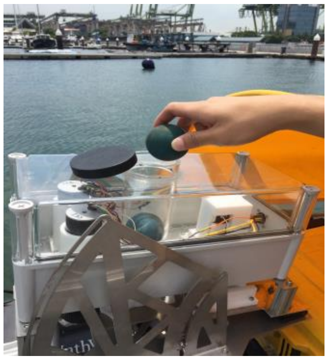

Figure 5: Loading of balls into BBASV 2.0 Ball Shooter

Adopting a plug and play concept, the only action required from the user is to load the ball by dropping them into the ball magazine. Angle markings of 5 degrees interval are incorporated into the manual aiming mechanism to allow a more convenient estimate of the angle of aim.

3. Thruster Configuration

Learning from the experience during the RobotX 2016, the team has decided to use 4 Minn Kota Riptide RT80 thrusters placed in a vectored configuration to achieve a holonomic drive.

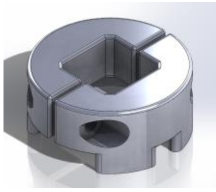

Figure 6: Thruster clamp

The team decided to reuse the transom mount from the previous iteration for the Minn Kota thrusters as they are designed to allow the thrusters to be lifted out of water when they are not in use. Moreover, this reduced the development time necessary to integrate the thrusters onto the ASV. However, after fabrication of the mount, the team discovered that due to the way the Minn Kota thrusters was designed, the thrusters could rotate about the transom mount despite the high clamping force applied. As such, a Thruster Clamp (Figure 6) was designed to stop the rotation of the thruster even after an extended period of operation.

Figure 7: Shroud clamp and thruster shroud

The thrusters also feature a thruster shroud (Figure 7), which protects the propeller from foreign objects and the tether of the AUV from being shredded by the propeller. Since the Minn Kota thrusters were originally not designed to have a shroud, a custom shroud clamp (Figure 7) was designed to securely mount the shroud in place to prevent the shroud from being displaced and causing damage to the propeller.

4. Centralized main housing & Shelter

For the ASV to operate reliably, housings and sensors need to be secured onto the payload tray while withstanding the waves and winds. Profile bars were mounted onto the payload tray using the existing mounting points intended for straps, which provide a strong backbone on the otherwise thin payload tray.

The main housing of the ASV was designed to house most of the electronics on the platform with the intention to protect the electrical components from the sea environment. A pelican case has been modified for the Main Housing, which was an improvement in the reliability as compared to BBASV 1.0. This allows for immediate troubleshooting when there is a need to access the inside and inspect the electronics.

As the internals of the Main housing is a sealed environment, the heat generated by the electrical components cannot be easily dissipated out of the system. A liquid cooling system was thus integrated into the Main housing which takes the heat generated from the power supply, single board computer and other components, and discharges it from the system through the radiator to the external environment.

Apart from the Main housing, other housings such as the telemetry housing, the navigation-acoustic housing and the on board kill were also made. Each are uniquely designed based on their individual requirements.

Figure 8: ASV shelter

The ASV shelter (Figure 8) was designed to reduce heating of the components on the payload tray by providing shade from the sun, as well as provide some protection from the rain. The shelter was made from tough waterproof marine-grade canvas stretched across 2 semi-circular stainless-steel pipes, which provides sufficient strength and rigidity to withstand strong winds and handling. Quick-release pins were used to secure the structure to the payload tray, which allows easy removal for transportation. Zips were included on the canvas to allow for easy access of the housings onboard the payload tray without removing the entire shelter. The transparent cut-out near the telemetry housing allows viewing of the telemetry screen data without removing or unzipping the shelter.

5. Launch and Recovery System

The LARS was designed with the aim to launch and recover the AUV autonomously from the ASV. It is made up of 2 key components; the winch and the tether railing.

Figure 9: The winch (left). Tether Railing (right).

To simplify the LARS, the Falmat cable was chosen due to its capability of withstanding high tensile loads. With this in mind, a simple motor with a gearbox was used to rotate a spool with the Falmat cable as shown in Figure 9 was tested to hold a weight equivalent to that of the AUV. Furthermore, due to the close proximity of the ASV to the AUV, a short length of cable was used to connect the two vehicles and a level wind was forgone to simplify the mechanism as there was no need for cable management.

The tether railing is designed to guide the ASV-to-AUV tether for the underwater ring recovery task, to sustain the weight of the AUV and other external forces from the sea environment as well as to ensure that the AUV is properly secure to the ASV when the ASV is moving.

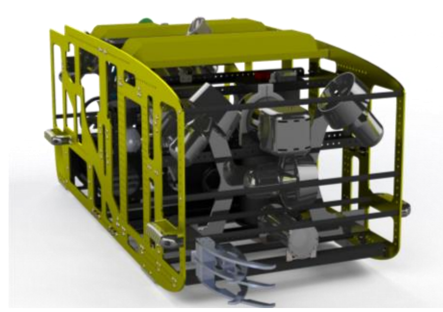

Figure 10: Redesigned BBAUV 3.5

On the BBAUV 3.5, the frame was redesigned for LARS operations and to improve the vehicle stability and provide protection from external impacts to fight the harsh sea environment of Hawaii. It features common mounting platforms and angled mountings of components which optimised space while keeping within dimension and weight requirements.

B. ELECTRICAL SYSTEMS:

1. *Electrical Architecture*

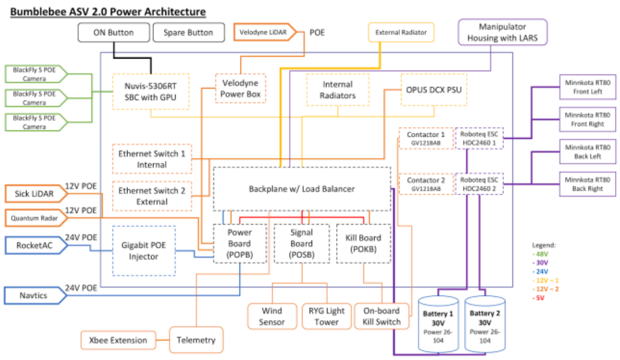

Figure 11: Power Architecture

The overall electrical system of the ASV is split into multiple housings, namely the Navigation and Acoustics housing, Telemetry housing, Manipulator housing and the Main housing. The Main housing contains the electronics which are the backbone of the whole electrical system and are categorised into 3 sub-systems: Power Distribution, Sensors and Thruster Controls, and Kill system.

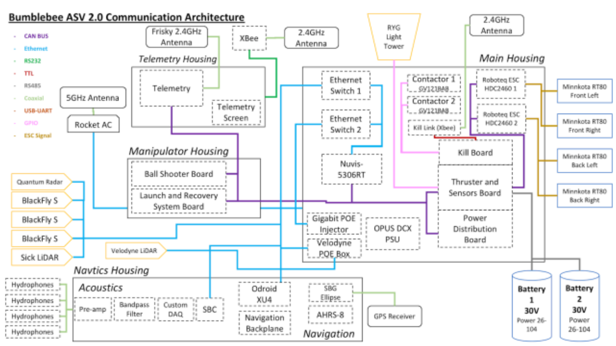

Figure 12: Communication Architecture

Ethernet and Controller Area Network (CAN) are our primary methods of communication between the high-level and low-level components. These interfaces provide ease in adding new peripherals as well as the ability to communicate between the two maritime systems.

2. *Backplane and daughter board*

To optimise the space inside the main housing while ensuring that the sub-systems are able to have the same access to all the different power and communication rails, the team decided to follow the same concept of having a backplane and daughter board system (which was implemented on the BBAUV 3.5 and was proven to be very stable and reliable). Similarly, the three daughter boards utilise the same connectors with a standardised pin mapping. Plastic locking pegs were used to prevent the boards from loosening due to the extreme vibrations of the ASV.

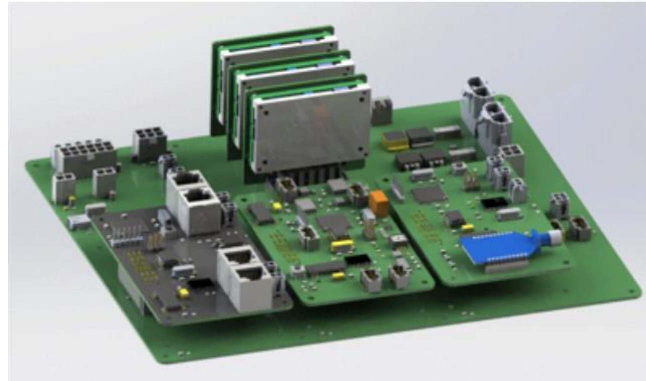

Figure 13: Backplane and daughter boards

The backplane also houses the load balancing circuit, the isolated DC-DC converters, and also provides the required power distribution to both onboard and external devices. Like the daughter board concept, each of the isolated DC-DC converters could be plugged onto the backplane. Furthermore, to improve ease of maintenance, the same custom PCB was utilised for all three converters, which output different voltages, by allowing multiple configurations during component assembly. The same connector with standardised pin mapping was also used for the isolated DC-DC converters to connect to the backplane.

In this iteration, a reliable Quad-FTDI circuitry was integrated onto the ASV backplane, providing the interface to reprogram the firmware of multiple daughter boards with a single USB cable. This improvement gives the team a channel to easily identify and swap out faulty daughter boards, while also allowing on-the-fly programming, increasing the reliability and usability of the electrical system.

3. *Control, Data and RC link, Kill System*

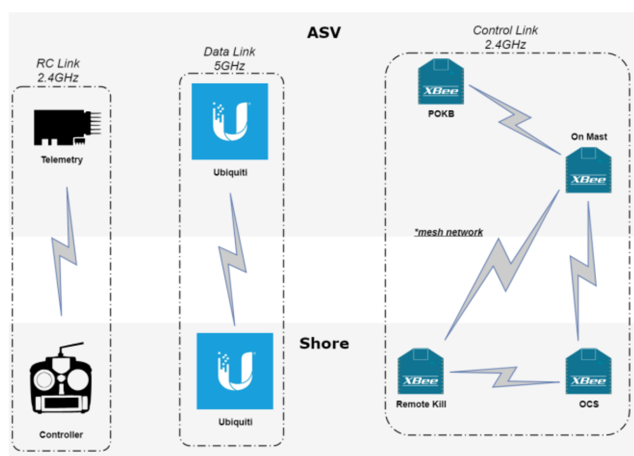

Figure 14: Wireless link in the ASV

The Operator Control System (OCS) houses the on-shore communication links to the ASV. The communication links are split into two separate wireless interfaces. The data link is a high-speed link used mainly for streaming of sensor data such as the video feed from the cameras on the ASV. The control link is a robust long-range link which is used to send hardware statuses and provide safety features such as manual teleoperation as well as an emergency stop for the ASV. The control link is formed using Xbee communication modules. The modules form a dynamic mesh network where messages can be relayed from one Xbee to another to reach its destination. A 10dBi directional antenna on the OCS maximises the range of the control link to provide a larger safety net.

The Kill Board handles kill signals from the on-board kill switch, remote kill switch and software through CAN. Upon receiving a kill signal from any one of the three sources, the Kill system switches releases the contacts to instantaneously cut the power provided to the thrusters.

4. Sensor and Actuator system, Thruster upgrade

To ensure the manoeuvrability of the ASV in harsh sea conditions, the thrusters were upgraded from two Torqeedo Travel 1003S thrusters to four Minn Kota Riptide RT80 thrusters.

A pair of Roboteq HDC2460 Electronic Speed Controllers (ESC) are used to control the Minn Kota Riptide RT80. The Sensor and Thruster Contol board interfaces the Roboteq HDC2460 ESC via CAN using the CANOpen protocol, apart from monitoring internal humidity and temperature, battery information and controlling the light tower which indicates the ASV operation mode.

5. Power control system

With the multitude of sensors and peripherals on board, it required multiple power outputs to provide for these devices. The need to individually reset these devices was realised from previous experiences as some devices needed to power cycle for it to re-initialise and work as desired. From perusing the Application Report titled “Integrated Load switches versus Discrete MOSFETs” by Texas Instruments, the decision was made to use load switches over discrete components. This decision reaped benefits which include, prevention of a negative voltage spike when the input voltage is stepped, no inrush current when the control signal is toggled, as well as an in-built overcurrent protection measure.

This was implemented in the new Power Control Board, which manages power to the onboard peripherals and sensors. Each power control circuit is implemented using a load switch, which can be toggled by the microcontroller onboard. With a fuse connected in series to each load switch to provide additional overcurrent protection. These load switches were tested with an electronic load while drawing the expected current from the peripheral. The board manages the following peripherals: PoE Injector, Velodyne LiDAR, Sick LiDAR, Quantum Radar and the Navigation/Acoustics system.

6. Manipulators - Ball shooter

The ball shooter consists of three electrical actuators: Two 42mm frame-sized brushless DC motor (BLDC) and a single servo motor. The BLDCs are controlled via YEP 80A Electronic Speed Controller (ESC) by HobbyKing. A separate lithium-polymer battery was used to power the BLDCs instead of the main battery, while the servo receives 5.5V regulated voltage drawn from one of the ESCs. This design was used to reduce the load on the load balancer because each motor requires at least a peak current of 10 Amps to compress and shoot the projectile.

A custom PCB board was designed to control the actuators on the ball shooter. Due to the inductive loads (actuators), the board adopts an isolation design where the input power and output signals are isolated from the microcontroller and CAN communication channel.

7. Manipulators - LARS

Together with the mechanical team, the motor used was selected from MOOG Inc based on the amount of torque and precision required. The motor comes with two possible methods of communication: CANOpen and RS485. Considering the team’s experience with RS485 circuitry on the Torqeedo related hardware as well as the slight incompatibility between CANOpen and the CAN bus on the ASV, the final decision was to use RS485 as the main form of communication between the electronics. Using a sniffer program to figure out the handshakes between the hardware, A custom library was made to simplify the LARS controls for software development purposes. The firmware was written with close cooperation with the mechanical and software team, as the motor motion must be able to match the demands from movement of the AUV as well as the mechanical limitation on the LARS.

Another custom PCB was specifically designed to handle LARS. Likewise, proper power regulation and isolation circuitry was implemented to improve the robustness of the electrical signals. An inductive proximity sensor was also implemented such that the motor would stop if the AUV was recovered past a safety margin, preventing the motor from pulling past it’s limit and stalling.

8. Acoustics upgrade

The acoustics sub-system underwent a significant overhaul. Migrating away from the sbRIO based system used previously to a Data Acquisition (DAQ) board designed in-house and an ARM based SBC running a Linux-based OS for signal processing and localization. The major focus in this redesign was reduced costing, scalability and flexibility. The six-channel ADC allows the use of more hydrophones as required and the DAQ features a Xilinx FPGA for higher performance, lower latency signal processing. The DAQ uses High-Speed USB for communication with the SBC where further processing is done. Using USB enables interoperability with different SBCs and allows flexibility in choosing a processor with the required computational power. Using a Linux based system also eases development and enables more complex and higher-level features.

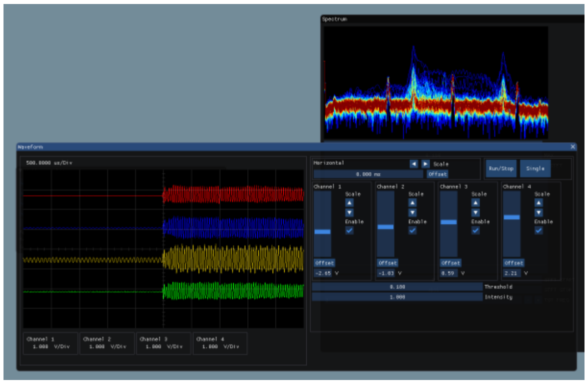

Figure 15: Acoustics UI

The signal processing and software suite also underwent significant changes. While the principle of operation, signal processing and localization algorithm remained largely the same, using the reliable and robust MUSIC algorithm for direction of arrival (DOA) estimation, the software stack was redesigned and heavily optimized to harness the multi-core ARM processor. The increased DOA estimation speed would imply a lower latency and higher possible ping rate for more accurate localization. The software stack also features a remote-control toolkit, allowing near real-time monitoring of signal characteristics, acoustic conditions and system performance.

C. SOFTWARE SYSTEMS:

1. *Software Architecture*

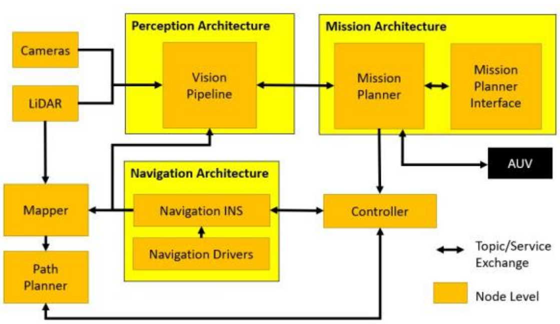

Figure 16: Software architecture of the ASV

The ASV software architecture is largely similar to the BBAUV 3.5 [2], designed to minimize coupling between components and maximize cohesion between components. The structure of ported components like perception remains unchanged which can be found in the published RoboSub 2018 paper [2]. The main form of communication with AUV is through the Mission Planner. The AUV's software architecture can be found in [2].

2. *Controls*

In order to take advantage of the vectored thrust configuration, the controls system in the AUV was modified to suit the ASV. With a PID controller for each degree of freedom, the ASV is able to move in any direction on the 2D plane.

Three types of manoeuvres were specifically designed to tackle the various challenges. Firstly, dynamic positioning is the most basic form of control for the vehicle which allows the vessel to move to and stay at a targeted setpoint. This manoeuvre also gives the vessel the ability to do fine movement which is required for high precision tasks such as the Detect and Deliver task. Secondly, path tracking allows the vessel to follow a path from one point to another while avoiding obstacles which are randomly scattered around the course. Lastly, encirclement allows the vehicle to circle around an object of interest while facing the object. This is useful for tasks that requires the vehicle to identify the object.

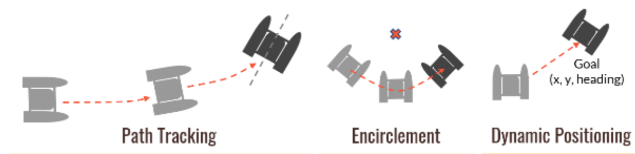

Figure 17: Three types of manoeuvres

3. *Navigation*

The navigation sensor suite consists of a 9 axis Sparton IMU and a SBG Ellipse-N INS. All the sensors are interfaced and integrated with the rest of the system over the ROS IPC framework. The data from each sensor is fused to obtain independent state data. Due to the inconsistency of the satellite positioning or momentary signal outages, extended Kalman Filter is used to fuse the GNSS and IMU output, improving the reliability of the final positioning output. Utilising the filtered output from the sensor suite, the ASV is able to localise itself in the global frame. The current system uses the Universal Transverse Mercator which is a 2-dimensional coordinate system since the ASV does not require the 3rd dimension of altitude. This simplifies the process of frame transformation.

Through thorough benchmarking, the strengths and weaknesses of each sensor is identified, allowing the navigation software to leverage on the strengths of all the sensors and apply the most optimal algorithm to further improve the sensor output. The combination of these design considerations creates a much more accurate and reliable navigation system.

4. *Mapping*

The map itself is based on a simple occupancy grid. It uses the Bressenham algorithm to mark occupied and free space. The map takes in data from both the SICK Lidar and PUCK lidar and uses the collected data to draw out a rough occupancy grid. A relatively coarse grid size of 1m x1m was chosen as it was found to be sufficient for the purposes of path planning. The GPS and IMU data are used to transform the point clouds onto the correct place in the occupancy grid. Furthermore, to handle moving objects, a decay was placed on every grid, allowing previously occupied grids to be reidentified as free space. Dilation of the map was also done according to the dimensions of the vehicle, to allow ample space for manoeuvres.

5. Path planning

Path planning on the ASV is done on demand to prevent excessive use of resources. As such, it was integrated as a ROS service, executing when there is a client's request rather than constantly running in the background. After extracting the grid data from the mapping component, the data is pre-processed to produce a 2D array where each grid holds states of either occupied by an obstacle, a free space that can be traversed or unknown. After specifying a start point and end point, it runs the A star algorithm on the pre-processed map to generate a path which avoids all obstacles between the two points for the ASV in real time.

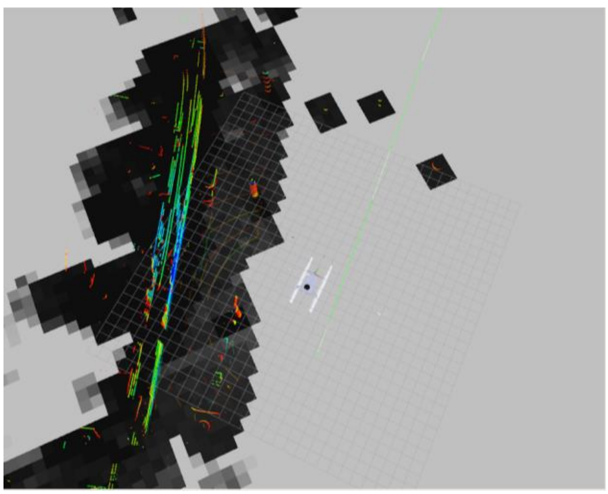

Figure 18: The map and path (green line) generated

6. Vision – Lidar Segmentation

Two algorithms were evaluated for lidar segmentation. The first being a variant of DBSCAN in 3D which accounted for decreasing density of points radially and the second being Euclidean distance based segmentation performed on a 2D plane. The Euclidean distance based segmentation seemed to outperform DBSCAN on a 3D. This was used in combination with a simple RANSAC based line detector to perform detection of planes.

For detecting totems, a simple detector based on the least squares method is used. It takes the 3D points and tries to fit them to a cylinder model. The system determines whether an item is cylindrical or not based on the R-squared value of the fit.

7. Vision – Deep learning for machine vision

A deep learning model for object detection, specifically totems, was used for its effectiveness against different lighting and environmental conditions. For RobotX 2018, transfer learning was applied to the Mobile SSD v2 model. This model was chosen for its high frame rate and decent results. Running this model on our onboard GTX1050 produces outputs of 20 fps, which is the maximum as our cameras are capped at 20 fps. This allows the vehicle respond immediately to any objects detected. The data collection and training methodology follows the one used for Robosub 2018 [2]. The resulting model achieved a mean average-precision (mAP) of 92.5%, over 7 classes, on our test set.

Figure 19: Deep learning model in action

8. Vision – Sensor fusion with particle filter

The particle filter algorithm developed to fuse camera and SONAR data on the AUV [2] was extended to the ASV's LiDAR and cameras. The slight difference is that LiDAR can provide 3D information, so the initial variance in the z axis does not need to be huge.

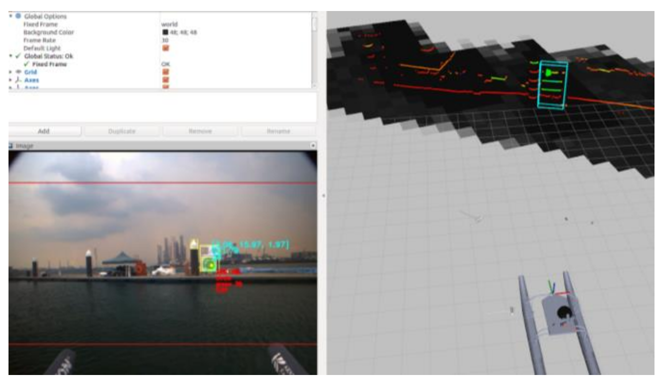

Figure 20: Particle filter in action

Particles are stored in world coordinates and given higher weights in areas corresponding to real objects. Sampling then causes the particles to converge about the correct position. By projecting these particles into the camera, information like the colour or type of object can be matched to the 3D position.

9. Vision – Shape detector

First, Maximally Stable Extremal Regions (MSER) algorithm was used to extract regions of interest (ROI). Within each ROI, edges are extracted from the region of interest and the Hu moments of the edges are computed. Hu moments was chosen as it is a shape descriptor, invariant to translation, rotation and scale. This allows the vehicle to approach the symbol from any angle and still be able to determine the shape of the symbol.

10. Simulator

A simulator was developed upon Open Source Robotics Foundation's (OSRF) Virtual Maritime Robotx Challenge (VMRC) simulator, which already provides environments modelled after the competition venue and simulates on-site conditions. The vehicle model and a portion of the software stack, namely the navigation, controls, mapping and path planning modules, were integrated with the simulator, to enable testing of algorithms without actual sea trials.

Several modifications made include enabling the vectored thruster configuration of the ASV and simulating sensors output using Gazebo plugins.

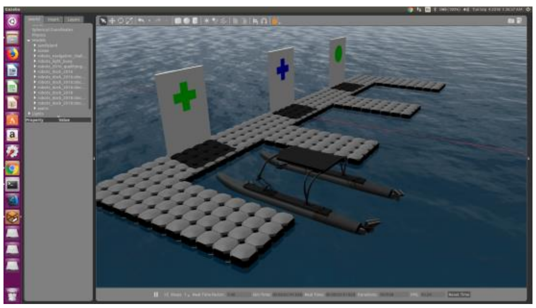

Figure 21: Gazebo Simulation of ASV

11. User Interfaces

To ensure that the surface vessel remains reliable at all times, user interfaces are required for status checks and timely interventions. We have 2 in-built UIs, the mapper UI and the control panel.

The mapper UI is a real time monitoring and control application which aims to help users monitor and control the position of the surface vessel at all time. Users are presented with various navigation status as well as satellite map overlaid to allow them to be aware of the environment surrounding the ASV. The ability to control the vessel right from the UI also enables the user to react quickly and steer the vehicle away from danger when needed.

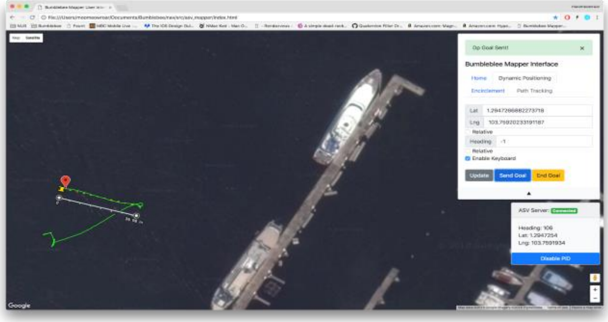

Figure 22: The Mapper UI displaying route travelled by the ASV

The team also ported over the control panel interface which was used in the AUV. This interface focuses more on hardware status, actuation controls and sensors updates. Fine control over hardware systems are also provided, such as the option to kill power to certain sensors. This allows the user to attempt to correct hardware issues without accessing the vehicle physically.

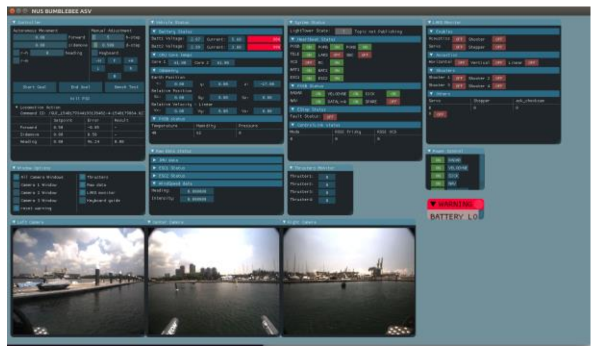

Figure 23: Control Panel Interface

IV. EXPERIMENTAL RESULTS

A. ROBOTX PREPARATIONS

The vast majority of the hardware systems were benchmarked and completed by the end of 2017. However, due to the Team's commitment to RoboSub 2018, the team could only spare manpower and time to conduct sea trials for the ASV once a week for the first half of 2018. After RoboSub 2018, the schedule was increased to at least 3 times a week, whilst juggling the limited manpower since it was during regular school term leading up to RobotX 2018.

B. ANTENNA MOUNT SIMULATIONS

A simulation was done to ensure that the Antenna Mast could withstand the sea conditions.

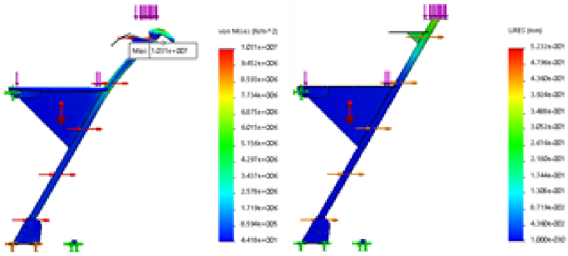

Figure 24: Simulation of Antenna Mast Under Wind Speed of 10m/s

Unfortunately, the top plate of the Antenna Mast broke off during transit as shown in Figure 25. After much analysis, a possible cause of the top plate breaking off was due to resonance. However, in this current iteration, the damage occurred just before shipping off the ASV and redesigning the antenna mast within the short period of time was not feasible. Hence, frequency simulation must be done in the future to discover the first modal frequency of the Antenna Mast, which is also the natural frequency. Future iterations of the Antenna Mast will be designed with a high natural frequency to prevent environmental factors from causing such damage again.

Figure 25:Damage to the Antenna Mast

C. MAIN HOUSING HEAT FLOW SIMULATION

Flow simulation with two fluids was conducted in Solidworks to ensure that the setup was sufficient to cool the various components, and the results showed that the average total temperature in the Main housing was 36 degrees Celsius with peak temperature of 59 degrees Celsius.

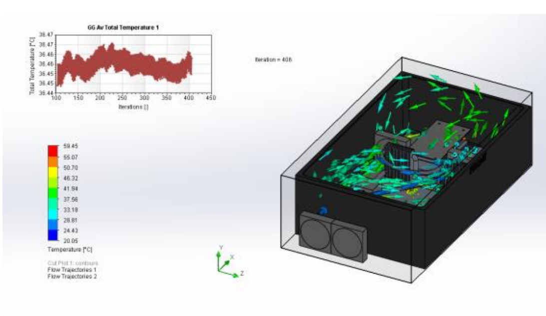

Figure 26: Airflow simulation in the main housing

D. BALL SHOOTER TESTING

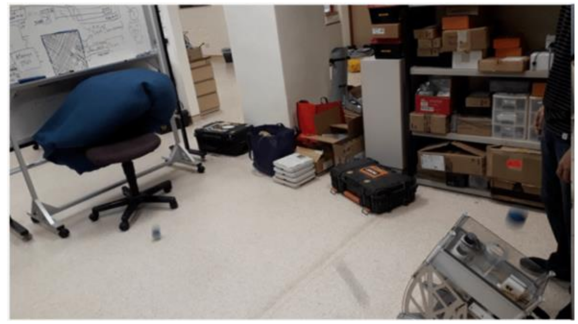

Figure 27: Test setup for the Ball Shooter

A static performance test was performed on the ball shooter. To simulate the small target hole used in the detect and deliver task, a 9-inch by 9-inch square was drawn on the whiteboard and was shaded in with diagonal black lines. Tests were conducted where four projectiles were fired in succession, the test is only successful when all four balls landed in the shaded region of the target. The white patches are indicative of the spots where the projectiles hit the target. Where two or more projectiles lands within a similar area, this results in the topmost white patch being bigger as seen in Figure 27. A total of twenty balls were then shot after the initial calibration and was tuned to the point where all twenty balls could land within the targeted area.

E. LARS SIMULATION

Extensive stress and deformation analysis as well as topology optimization study was done on all the key components of the LARS (Refer to Appendix VII.E).

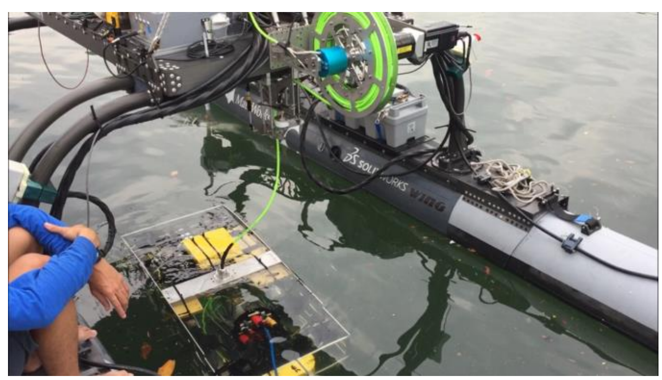

Figure 28: LARS deployment

However, there is still room for improvement for the LARS. Due to the decision to forgo a cable arranger, issues such as the tether unreeling itself in the spool in the absence of tension and tightly stuck tether from the reeling process arose during testing. To counter these issues, a shroud like structure will be mounted outside of the reel and will not move with respect to the reel, and a cable guide will be installed to force the cable to be fed lower before reeling back in more uniformly.

F. THRUSTER SELECTION TESTING

The selection of thrusters was made after profiling several different thruster models, notably Minn Kota Riptide RT80 and Newport L-series 86lb, with a custom thrust measurement jig. The Minn Kota Riptide RT80 was chosen due to its high thrust and moderate current draw. Refer to the Appendix D Figure 35, for the graphical results.

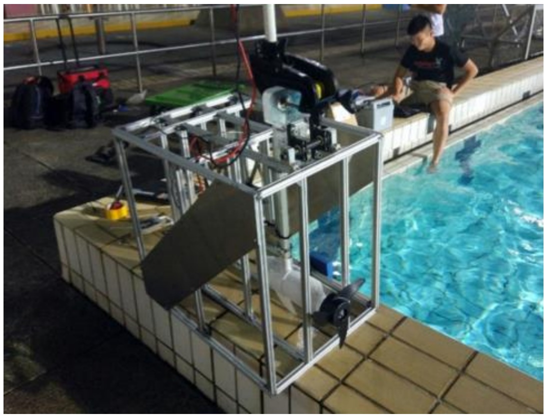

Figure 29: Thrust measurement jig

G. WIRELESS LINK BENCHMARKING

During the selection of the radio module, the performance of multiple radio modules over a large water body was benchmarked. This was done by testing the packet loss and throughput of the radio modules transmitting at 3m elevation across a reservoir. The Xbee modules managed to sustain a throughput of 3kbps and packet loss of 5% at a distance of 2.2km across the diagonal of the reservoir. The RC link is implemented to provide manual control of the ASV on the hardware level. Onboard receivers will take the inputs of throttle, roll, pitch and yaw from a drone controller, resolving them into vectors to move the ASV.

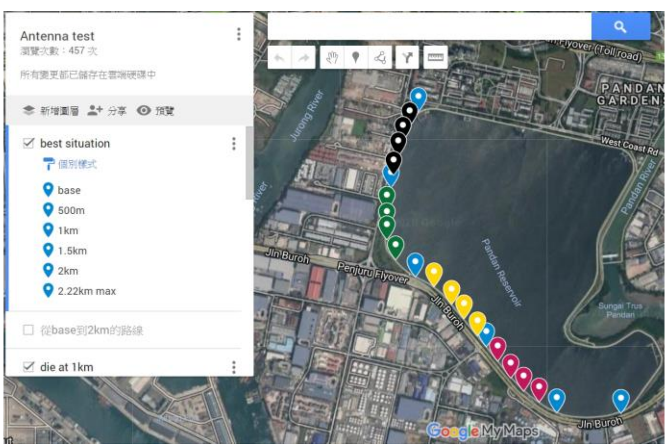

Figure 30: Wireless link benchmarking at Pandan reservoir

H. NAVIGATION SYSTEM TESTING

A field test was conducted to benchmark the performance of 2 different GNSS receivers, SBG Ellipse-N and Novatel OEM628. The test was done by walking consistently along the outermost track and plot the coordinates on Google Maps to measure as accurately as possible the deviation of the coordinates. Both GNSS receivers seem to have a maximum deviation of 1m as seen in Figure 31. However, there was a significant delay in the data output by the OEM628 receiver of about 15s which could be detrimental as the ASV is constantly moving at a high speed.

Figure 31: Field test with GNSS receivers (SBG Ellipse-N in red line and Novatel OEM628 in yellow)

V. ACKNOWLEDGEMENTS

Bumblebee Autonomous Systems would like to thank everyone who gave their generous support to the team, for their unwavering belief in us and for their contributions which allows us to continue producing quality platforms that will shape the future of maritime autonomy in Singapore. The team would like to express our deepest gratitude to our sponsors, including our Title Sponsor - NUS, and our Platinum Sponsors - FSTD, DSO National Laboratories, DEME, MacArtney Underwater Technology, and ST Engineering. The full list of our sponsors can be found in Appendix VII.C.

VI. REFERENCES

Journal Papers:

[1] Alek Kaknevicius. (2015, December). Integrated Load Switches versus Discrete MOSFETs. *Journal.* [Online]. pp 1-19. Available: http://www.ti.com/lit/an/slva716/slva716.pdf

[2] Bumblebee Autonomous Systems. (2018, Jul.). Design and Implementation of BBAUV 3.5.[Online]. pp. 1-15. Available: https://www.robonation.org/sites/default/files/NatlUSingaporeBumblebee_TDR_RS18.compressed.pdf

VII. APPENDIX

A. SITUATIONAL AWARENESS

A common question that our team always have when running the system autonomously is “What is it doing?”. The team has always been innovating with ways to learn system behaviours.

For both vehicles, the software architecture was designed with explanation interfaces in mind. The perception module publishes a camera feed overlaid with debugging contours and texts, for the user to understand what the robot is seeing and intervene if needed. The map the robot constructs and the path it follows are also published. Such debugging windows are important for the user to trust that the robot is going to make a right decision.

The method of displaying this information to the user is important as well, and the approach for each vehicle is elaborated below.

ASV:

Since we can always connect to the ASV, the team chose to utilise user interfaces to aid us in telling what the ASV is doing. There are 2 main UIs.

Figure 32: ImGUI based control panel

The first UI is our ImGUI based control panel (Figure 32), which provides hardware status and camera feeds. This facilitates the identification of hardware faults, such as a loss of GPS signal, allowing the operator to quickly address such problems.

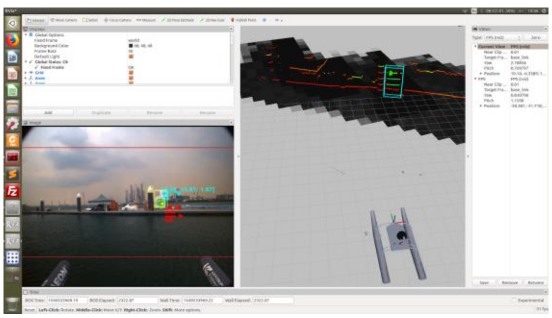

Figure 33: RViz visualising data

The second UI that is used would be RViz (Figure 33), to understand how the ASV perceives the environment. RViz is an open source 3D visualizer that enables the user to visualize raw sensor data, the robot model, and the robot's interpretation of the world in terms of maps and paths.

AUV:

In tethered mode, the AUV operator can utilise the 2 UIs mentioned as well. However, during autonomous runs, the AUV is often untethered and we will be limited to only using visual cues. Our AUV is equipped with LED lights (Figure 34) that tells us what the vehicle is doing at that point in time. Since the AUV has the ability to determine the task it is doing, the different coloured lights inform us of the task it has decided to do. With this indicator we can confidently know what the AUV is doing at any point in time. The debugging feeds can be retrieved after an autonomous run to review the AUV's decisions.

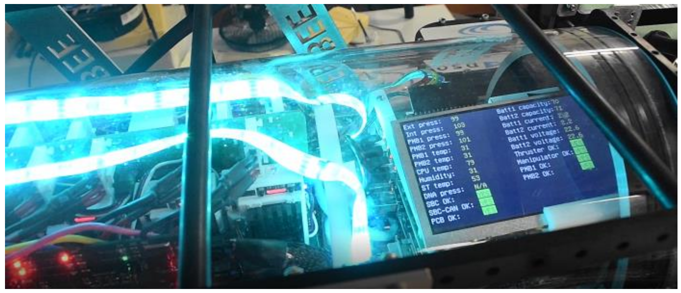

Figure 34: LED strips inside the AUV

B. SPECIFICATION TABLE FOR THE BBASV 2.0

Platform	16' WAM-V□ USV
Single Board Computer	Nuvis-5306RT 32GB DDR4 RAM, Intel i7-6700TE NVidia GTX1050Ti
Propulsion	4 x Minn Kota RT80 Saltwater Transom-Mount Motor
Battery	2 x Torqeedo Power 26-104 battery 2,685 Wh
Navigation	Novatel OEM 628 GPS receiver with Antcom G5 L1/L2 GPS antenna Eclipse2-N: Miniature INS/GPS Sparton AHRS8 Inertial Measurement Unit Odroid XU4 Single Board Computer
Wireless Communications	Control link – 2.4GHz Xbee based on Digimesh Remote Kill link – 2.4GHz Xbee based on Digimesh Data link – 5.8GHz Ubiquity Rocket 5 AC Prism RC link - Frsky Taranis X9D+, Frsky X8R-II Receiver
Perception Sensors	3 x Blackfly S Camera for 180° panoramic vision SICK LD-MRS LIDAR for immediate collision avoidance Velodyne VLP-16 LIDAR for crowded environment mapping Quantum Radar for long range collision avoidance and sea navigation
Acoustics	Hydrophone array based on Teledyne reson TC4013 hydrophones NI9223 Analog input module NI sbRIO-9606 400MHz controller with Xilinx Spartan-6 LX45 FPGA High resolution Multiple Signal Classification algorithm for DOA calculation
Software Architecture	Robot Operating System (ROS) Ubuntu Linux 16.04 LTS x86_64

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Seagull (By Kim Tuck Huat Boat Builder)

Tekin

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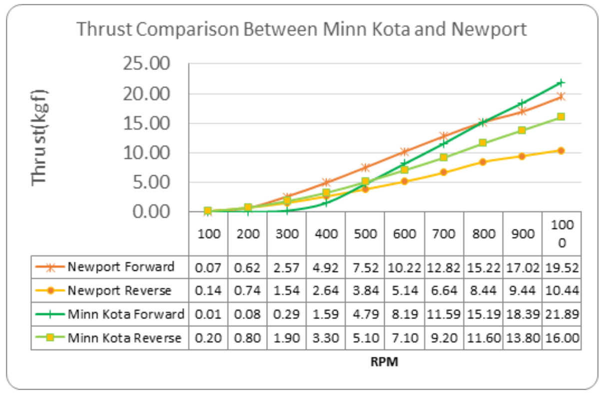
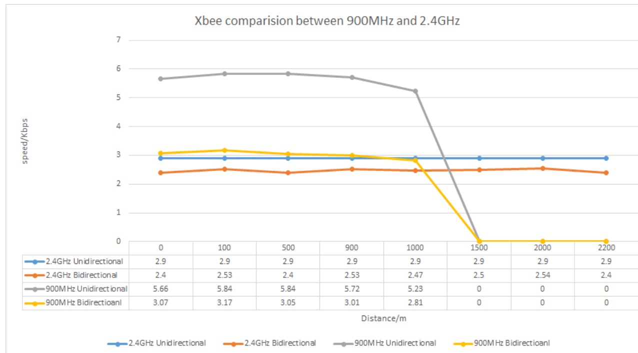
D. GRAPHICAL ANALYSIS



	100	200	300	400	500	600	700	800	900	1000
Newport Forward	0.07	0.62	2.57	4.92	7.52	10.22	12.82	15.22	17.02	19.52
Newport Reverse	0.14	0.74	1.54	2.64	3.84	5.14	6.64	8.44	9.44	10.44
Minn Kota Forward	0.01	0.08	0.29	1.59	4.79	8.19	11.59	15.19	18.39	21.89
Minn Kota Reverse	0.20	0.80	1.90	3.30	5.10	7.10	9.20	11.60	13.80	16.00

Figure 35: Thrust profile of Minn Kota RT80 vs Newport L-series 86lb



	0	100	500	900	1000	1500	2000	2200
2.4GHz Unidirectional	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
2.4GHz Bidirectional	2.4	2.53	2.4	2.53	2.47	2.5	2.54	2.4
900MHz Unidirectional	5.66	5.84	5.84	5.72	5.23	0	0	0
900MHz Bidirectioanl	3.07	3.17	3.05	3.01	2.81	0	0	0

Figure 36: Xbee range benchmarking

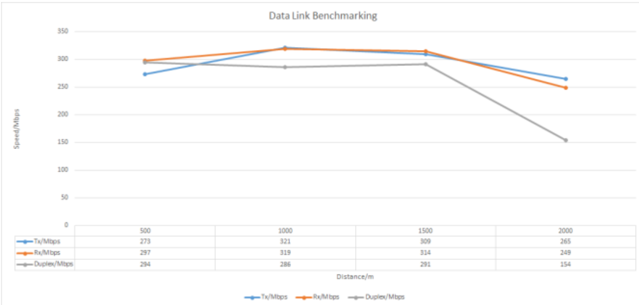


Figure 37: Data link range benchmarking

E. LARS COMPONENTS DEFORMATION ANALYSIS