Control of an Autonomous Surface Vessel (ASV) and Autonomous Underwater Vehicle (AUV) for Ocean Deployment

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Abstract— **Recently, the focus in the marine robotics field has been shifting towards cross-platform systems, with competitions such as the Maritime RobotX Challenge and Shell Ocean Discovery XPrize encouraging multi-platform systems. This paper presents the development process for the propulsion systems and teleoperation of an integrated ASV and AUV system. The main challenge in surveying open sea waters is the ability of the vehicles to station keep and move adeptly against the strong sea currents. A fully-actuated propulsion system is implemented for greater maneuvrability for the ASV. An Operator Control Station (OCS) is also implemented for teleoperation and status monitoring of the system during deployment. This design is implemented on the Bumblebee Autonomous Underwater Vehicle 3.75 (BBAUV 3.75) and Bumblebee Autonomous Surface Vessel 2.0 (BBASV 2.0), and has been operationally deployed in open sea trials in preparation for the Maritime RobotX Challenge 2018.**

I. Introduction

There has been strong interest in marine robotics in the last decade, as autonomous marine vehicles (AMV) provide the means to safer and faster ways of venturing the seas without close supervision from human operators. AMVs covers autonomous surface vessels (ASV) and autonomous underwater vehicles (AUV), and find its use in a wide range of applications, from search-and-rescue operations, to underwater scientific research and surveillance [1].

Current research has been moving towards cooperative fleets of AMVs, which allow for greater efficiency and robustness to failure compared to a single vehicle, as different sensor payloads can be distributed amongst multiple vehicles [2]. In an ASV-AUV system, this allows underwater missions to be performed faster with greater navigational accuracy, with the AUV carrying the required sensor payloads for underwater missions, while the ASV serves as a fast communication relay back to a base station [3], providing the AUV with real-time navigation information [1].. This paper focuses on the development of such an ASV-AUV cooperative system, as part of NUS Team Bumblebee’s efforts in developing autonomous marine systems.

II. Problem Statement

During ocean deployment, the vehicles will be subject to unknown external disturbances, such as water currents and wind [2], making motion control, especially dynamic positioning, a challenge in such conditions. Thus, the propulsion systems for both the ASV and AUV must be powerful enough to withstand such disturbances in open seas.

ASVs with high manoeuvrability are required to be able to track the AUV in close proximity [3]. This requires dynamic positioning, where both position and heading of the vessel is maintained concurrently, and is usually hard for vessels using a propeller and rudder, or differential drive configuration to achieve. Thus, an alternate propulsion configuration that can provide high manoeuvrability has to be explored.

As part of the support system for the ASV, a ground station, or Operator Control System (OCS) on land, for remote teleoperation of such a system also needs to be implemented for monitoring and manual control of the ASV from land.

III. Objective

The objective of this project is to design and implement a propulsion and remote control system on an integrated ASV and AUV system that is capable of dynamic positioning and adept movement under strong water currents for future deployment into open seas.

This will be done by:

1. Designing a propulsion and teleoperation system for the BBASV 2.0 to be implemented on the Wave Adaptive Modular Vessel (WAM-V) catamaran for high maneuverability and reliable communication over long distances
2. Redesigning the propulsion and power system for BBAUV 3.75 to fit in more powerful thrusters

This ASV-AUV cooperative system will be used to participate in the Robosub 2018, and Maritime RobotX Challenge 2018. They will be deployed operationally in open sea trials for a year leading up to RobotX 2018..

IV. Design

A. AUV-ASV Cooperative System

A basic tethered ASV-AUV platform is to be implemented for deployment in Hawaii waters for RobotX 2018 (refer to Figure 1). Cooperative motion and navigation of the two vehicles are to be conducted through exchanging positional data via the tether. A launch-and-recovery systems (LARS) is also implemented on the ASV to release the AUV into the water, and reel back the tether and the AUV using a winch for recovery of the AUV.

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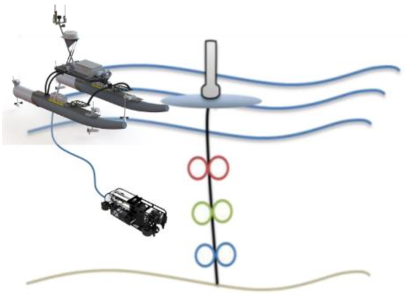

Figure 1. AUV deployment for underwater mission by ASV

For the propulsion and teleoperation of the ASV-AUV system, the design is split into three sub-systems:

1. ASV Propulsion System

Receives commands in autonomous and manual modes and controls the thrusters accordingly

2. ASV Operator Control Station (OCS)

Allows for manual teleoperation of the ASV, and displays hardware status of electronics on the ASV. Handles failsafe measures to stop the ASV in appropriate scenarios for safety

3. AUV Propulsion System

Receives commands and controls the thrusters accordingly

B. ASV Propulsion System

The previous generation of the BBASV used a differential steering configuration. Propulsion systems using differential steering or rudder and propeller configurations are known as under-actuated systems [3], where the vehicle has fewer actuators than its degrees of freedom. This makes it difficult to achieve station-keeping under environmental disturbances [4], like waves from the lateral direction, since it is incapable of controlling all its degrees of freedom simultaneously.

A fully-actuated thruster configuration is thus chosen to achieve omnidirectional movement to execute tasks requiring both independent control of vessel position and heading simultaneously [4]. This can be implemented with additional bow thrusters or azimuth thrusters (rotatable thrusters) [5]. However, due to the slow response of azimuth thrusters in changing its steering angle, a thruster configuration that uses thrust vectoring with fixed thruster positions is preferred. Four thrusters are mounted on the vehicle (as shown in Figure 2), two at the front and two at the back, and are all mounted at an angle of 45 degrees to achieve vectored thrust.

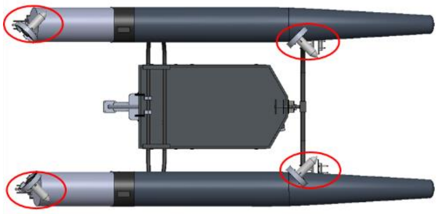

Figure 2. Thruster Layout on the WAM-V vessel (bottom view)

The thrusters are controlled using an electronic speed controller (ESC), which receives commands from a microcontroller on a custom PCB. The microcontroller chooses between manual and autonomous thruster commands from the control link or on-board computer respectively, and changes the visual light indicator accordingly. The overall system is depicted in Figure 3 below.

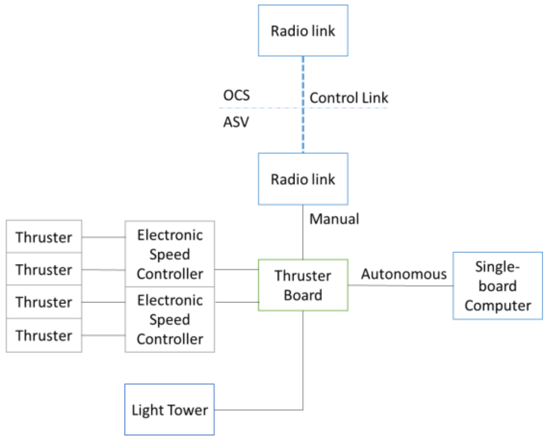

Figure 3. ASV Propulsion System Overview

C. ASV Operator Control Station (OCS)

The ground station, or operator control station (OCS), is designed according to key functions of a ground station identified by Ding & Wang [6]:

- *Status Monitoring:* Motion control and real-time display of vehicle heading and path, and other hardware statuses
- *Mission Controlling:* Path planning and manipulator operation
- *Data Processing:* To parse, store and playback data
- *Robotic Debugging:* Check sensor data and debug algorithms

Direct radio transmission from a ground station provides a more limited signal range, but is used in place of satellite transmission which incur high costs from leasing satellite bandwidth. The overall structure of the wireless communication system is depicted in Figure 4 as dotted lines.

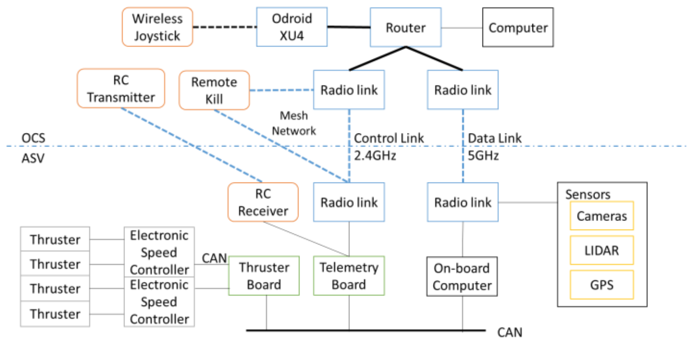

Figure 4. Wireless communication system between OCS and ASV

The control link is responsible for transmission of essential data and movement commands for manual control of the ASV.

There are two modes of remote teleoperation of the vehicle:

- *Via RC controller directly to the ASV:* For operator's ease of movement to travel with the ASV during launch and recovery. To be sent directly from controller to a 2.4GHz receiver
- *Via wireless joystick through the OCS control link:* Allows for long range control via the directional antenna. Operator can pilot the vehicle via camera

stream and joystick when it is beyond line-of-sight

The telemetry board on the ASV, and Odroid on the OCS will be programmed to send teleoperation commands and receive hardware status data to the OCS over the control link.

D. AUV Propulsion System

The propulsion system for the previous generation vehicle BBAUV 3.5 is found to be robust and adept in movement in pool tests and competitions. Thus for BBAUV 3.75, only the thrusters need to be upgraded to be more powerful to be sea-worthy and move against strong ocean currents. This requires a redesign of the custom thruster board PCB to interface with new electronic speed controllers (ESC) for the new thrusters.

V. Hardware implementation

A. Hardware Choices

1) ASV Propulsion System

The Minnkota Riptide RT80 is used as a saltwater electric trolling motor that provides up to 80lbs of thrust. It was chosen for its high thrust after characterization of several trolling motors were conducted to obtain the thrust curves of each motor. The RT80 is driven by the Roboteq HDC2460, which is a dual-channel brushless electronic speed controller (ESC), and is capable of supporting large current draws from the thrusters up to 150A. Thruster data such as current draw and error flags can be retrieved from the HDC2460 ESC via Controller Area Network (CAN) for status monitoring.

2) ASV Operator Control System

The XBee-PRO DigiMesh 2.4 is used for radio communication for the control link. At 2.4GHz, the signal range is calculated from the Fresnel Zone radius:

$$r = 17.32 * \sqrt{\frac{d}{4f}}$$

Which yields d = 0.800km, for f = 2.4GHz and r = 5 (where boat elevation of 3m which accounts for 60% of r for clear transmission, r = 5).

A 10dBi directional Yagi-Uda antenna is used on the OCS side for high gain while pointing towards the ASV. An 8dBi monopole antenna is installed on the ASV, so that it can transmit and receive adequately regardless of its current heading. The Logitech F710 wireless gamepad is used as a wireless controller to pilot the ASV via the OCS.

3) AUV Propulsion System

For sea-worthiness, the current Seabotix BT150 brushed thrusters used on the BBAUV 3.5 are changed to more powerful Aquilanova thrusters to fight strong ocean currents. The Aquilanova thrusters are chosen for its high efficiency, ability to operate at 24V, with the AUV's current 6S lithium-polymer batteries, and adequate thrust. These parameters were obtained from charaterisation tests conducted to obtain the thrust curves and current draw of several underwater thrusters.

The Electronic Speed Controller (ESC) used to interface with the thrusters is also changed to the Tekin RX8 GEN3 ESC to move from brushed for the Seabotix brushed thrusters to brushless ESCs. The Tekin RX8 GEN3 is chosen for its ability to reverse immediately for AUV motion control and drive low kV underwater motors.

B. Prototyping

To interface the Minnkota thrusters directly to the ESC, the control panel of the Minnkota motors were removed and the two motor cables were connected directly to the ESC instead. The ESCs were commanded via CAN using the CANOpen protocol. During prototyping, an Arduino CAN shield was used to send CAN messages to the Roboteq ESC to run, kill and retrieve thruster information from the ESC.

C. Hardware Characterisation

The performance of key hardware components were characterised to ensure that they fit our requirements. Thruster characterization was done for both ASV and AUV thrusters using a custom thruster measurement jig with a load cell to measure the thrust curve and current draw of the thrusters at different speeds. Range tests were conducted for different radio modules and antennas at Pandan Reservoir, to test their signal strength at varying distances over a large water body. Hardware choices were made according to the performance results of these characterization tests.

D. Printed Circuit Board Design

1) ASV Thruster Board

The custom PCBs on the BBASV 2.0 are designed to be modular, consisting of one main backplane, with several plug-and-play daughter boards. The thruster board takes in thruster commands from autonomous and manual sources, and commands the ESC accordingly. The thruster board also houses several other functions. The circuitry implemented on the thruster board are as follows:

TABLE 1
ASV Thruster Board Circuit Functions

Circuit	Function
ATMega 2560 Microcontroller	General processing
Controller Area Network (CAN)	Thruster control & monitoring
RS485 Transceiver	Battery Monitoring
RS232 Transceiver	Anemometer reading
Humidity & Temperature Sensor	Humidity & Temperature reading

PCB Layout guidelines followed are as follows:

- *4-Layer PCB Design:* Used for a low EMI design to isolate high speed traces from low-speed traces with internal power planes The layers in the 4-layer stack (from top-to-bottom) are as follows: high-speed signal layer, ground plane, power plane, and low-frequency signal layer
- *High-Speed Interface Layout:* Differential routing for the RS485 and CAN signals use short symmetrical traces, with sufficient keepout from neighbouring traces and components, and an adjacent ground plane underneath
- *Transient Voltage Protection:* For transient voltages produced by the battery which could affect the RS485 control lines going to the batteries

After the PCB is fabricated, the PCB is populated with components and tested part by part, to ensure that each part works before soldering the next part, and for easier debugging if any part were to have issues

Figure 5. Fully populated ASV thruster board

2) *AUV Thruster Board*

Similar to the ASV hardware architecture, the custom PCBs for BBAUV 3.75 are to be modular, consisting of one main backplane, with several plug-and-play daughter boards. Thruster control is to be implemented on the thruster board, which includes the following parts:

TABLE 2
AUV THRUSTER BOARD CIRCUIT FUNCTIONS

Circuit	Function
ATMega 2560 Microcontroller	General Processing
CAN circuitry	Communicate with rest of electronics
Power connectors	Distribute power from battery to ESCs
Digital isolators	Isolate PWM signal going towards the ESC
Power regulator	Regulate BEC output from the ESC to 5V

The main consideration when doing PCB layout for the AUV thruster board, is the positioning of the ESCs to maximise space and be clear from wires and connectors in the tight space within the AUV hull. After several placements were test-fitted in Solidworks, the following arrangement as in Figure 6 was decided upon, where all power connectors are placed flushed to the top of the board for sufficient clearance from the ESCs.

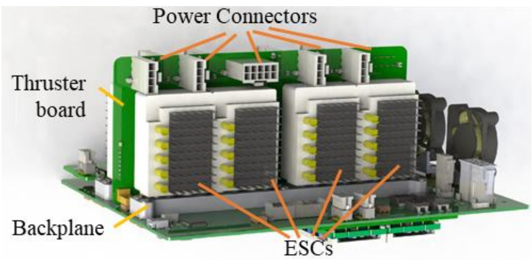

Figure 6. 3D Placement of AUV Thruster Board with ESCs and backplane

Power traces that carry current from the batteries to the ESCs are drawn as polygons on the outer planes rather than the internal planes for better heat dissipation. The width of these power traces are calculated with a trace calculator, setting current at 60A and trace thickness at 2oz/ft2.

E. *ASV System Integration*

After the ASV thruster board is tested standalone and working well, it is then integrated and tested with the rest of the system. After all PCBs for the ASV are fabricated, assembled and tested together, connectors and cables are assembled within the hull

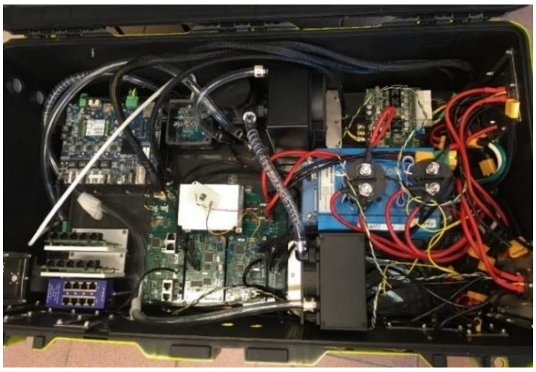

Figure 7. Cable Assembly in ASV main hull

Tests are done incrementally during integration, to resolve problems from integration between different components. Eventually, a full system test of the electronics and propulsion system was conducted to run two thrusters simultaneously underwater at the NUS SRC Swimming Pool.

VI. SOFTWARE IMPLEMENTATION

For teleoperation system for an ASV, input signals from the operator's joystick has to be parsed at the OCS and sent across the control link to the telemetry board, which resolves the thrust vectors and sends the thruster values to the thruster board to command the ESCs to move the thrusters. This is done by the firmware on the OCS, telemetry board and thruster board

A. *ASV Thruster Board Firmware*

The ASV thruster board is responsible for thruster control to the ESCs via CAN, and other peripheral sensors, and light tower control. This firmware does the following functions:

1) *Thruster Control & Monitoring*

Accepts thruster commands and communicates with the Roboteq HDC2460 ESC via CANopen. Incoming CAN messages are parsed for thruster commands from the single-board computer (SBC) and OCS, and the appropriate CAN commands are sent to the ESC for thruster control. Motor status such as current draw and error flags are also queried at regular intervals via CAN.

2) *Battery Monitoring*

Retrieves battery information, such as battery capacity, voltage and current draw, by communicating to the Torqeedo Power 26-104 Marine Batteries via RS485 communication, using Torqeedo's proprietary communication protocol.

3) *Anemometer Reading*

Reads the direction and intensity of wind published by the Windsonic anemometer in ASCII format

4) *Humidity & Temperature Sensor*

Get Humidity & temperature values via I^2C

5) *Light Tower Indicator*

Update the light tower according to the current control mode of the ASV:

TABLE 3
LIGHT TOWER INDICATOR FOR CONTROL MODE

Control mode	Light tower colour
Autonomous	Green
Station-Keep	Flashing green
Manual	Yellow
Emergency kill activated	Red

B. *ASV Telemetry Board Firmware*

The telemetry board collates hardware statuses from the ASV via CAN, for debugging and mission control purposes. It displays this data on an LCD screen on-board the ASV and sends it back to the OCS via the control link. Firmware for the Telemetry Board carries out the following functions:

1) *LCD Screen Display:*

Parse relevant statistics and heartbeats from CAN, and display it on an LCD Display for hardware debugging on the vehicle

2) *Read RC Transmitter:*

Read RC receiver signal from the FrSKY D8R-XP receiver using Combined pulse position modulation(CPPM) protocol. Duty cycle of each channel is read by taking the time from one falling edge to the next falling edge using an interrupt.

3) *Control Link via XBee*

Parses incoming packets for teleoperation of ASV, or for forwarding other commands to the CAN bus. Sends all hardware status data from CAN bus on to control link

4) *Resolve thrust vector and control mode*

Resolves incoming manual controls from surge, sway, yaw to vectored thrust value for each thruster. A simple sum of each direction value is used to give the thruster speed for each thruster as follows:

$$speed1 = - surge - sway - yaw$$
$$speed2 = - surge + sway + yaw$$
$$speed3 = surge - sway + yaw$$
$$speed4 = surge + sway - yaw$$

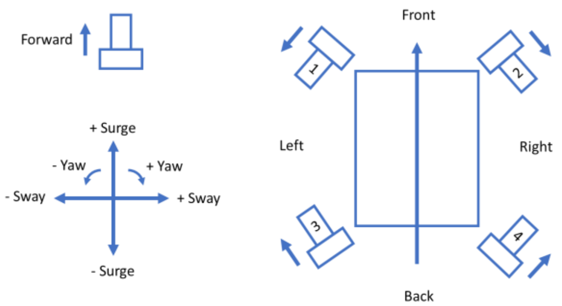

Figure 8. Thruster direction & thrust vector resolution

C. *OCS Remote Software*

The Logitech F710 wireless gamepad is interfaced on the Ubuntu OS on the Odroid XU4 in the OCS via its wireless USB receiver, in the Robot Operating System (ROS).

Joystick input is read and mapped to individual thruster values, and sent over the control link at 10Hz. Buttons on the joystick can also toggle the control mode and estop. These command messages are framed in the same way as the CAN packets on the ASV electronics, for easy parsing on the ASV side, and is sent to the serial port and through the control link.

D. *Fail-safe Features*

For additional safety, fail-safe protection is implemented on the ASV to stop the thrusters if any of the hardware fails or communication link is lost. All PCBs and communication links regularly send a heartbeat onto the CAN bus every 500ms to show that it is still active. If the heartbeat of any component is not received for a period of 3 seconds, the vehicle will station-keep or stop accordingly.

VII. TESTING & FINAL PRODUCT

A. *Testing*

A rigorous test plan is devised to ensure that the requirements of the project were being met at all stages of development. This minimises problems and makes debugging easier when integration is done. Different types of tests are devised for different stages of implementation, from unit tests for stand-alone units, performance tests to characterise the performance of key components, integration tests for cross-unit functionality, and system tests for the entire system.

B. *Final Product*

BBASV 2.0 has been deployed at the Republic of Singapore Yatch Club (RSYC) since 26th February 2018, for bi-weekly testing in preparation for RobotX 2018. Teleoperation of the ASV has been smooth via the RC transmitter, while intermittent issues have been fixed for teleoperation via the OCS.

Figure 9. BBASV 2.0 docked at the Republic of Singapore Yatch Club (RSYC) for open sea trials

The ASV has been able to attain a top speed of 1.9m/s while moving at full throttle inside the marina. The ASV has also been demonstrated to be able to do omnidirectional movement in any direction while maintaining heading. This provides the manoeuvrability the ASV needs to station-keep and track the AUV effectively in open seas.

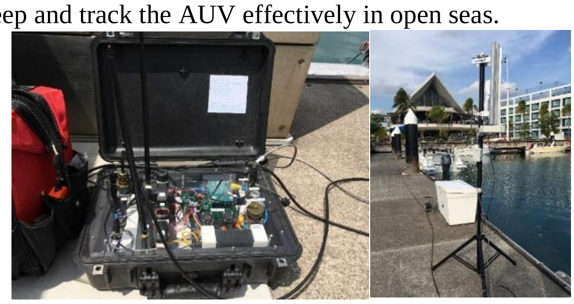

Figure 10. OCS (left) and antenna setup (right)

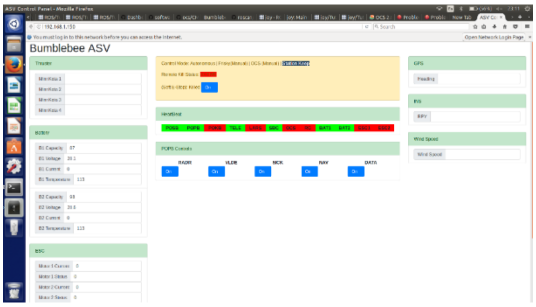

Figure 11. Hardware status monitoring via web interface on OCS

The OCS (Figure 10) has been deployed and used for teleoperation of the ASV and hardware status monitoring via a web interface during testing (Figure 11). The signal strength at long range has not been tested, since the ASV has not been allowed out of the marina without a permit. However, the control link has been stable within the marina, at a maximum distance of 100m, even when the ASV is not in line-of-sight with the OCS. Previous range tests at Pandan Reservoir also yielded a minimum line-of-sight range of 2.2km over water

The performance of the thrusters and ESC for the AUV has been benchmarked to be suitable for the requirements, and the PCB designs for the AUV have been completed and sent for fabrication. However, the PCB has not arrived back at the time of submission of this paper

VIII. Future Work

In this project, BBASV 2.0 and BBAUV 3.75 were developed separately for sea-worthiness. Moving forward, the next step towards ASV-AUV integration is a launch-and-recovery system (LARS) where the AUV is deployed to and recovered from the ASV. The full capabilities of this ASV-AUV system is to be demonstrated at the Maritime RobotX Challenge 2018 in Hawaii, USA, in Dec 2018.

For the ASV, the limitations of direct radio communication to a ground station is evident when designing the OCS. Further work can be considered to implement satellite communication on the ASV to allow the ASV to travel further distances into the sea and be out of line-of-sight to the OCS.

To further increase the thrust of the thrusters for long haul operations, petrol outboards can be considered in future iterations rather than electric trolling motors, to provide a larger propulsion force.

IX. Conclusion

This paper presents the development process of a propulsion and remote control system on an integrated ASV and AUV system that is capable of adept movement under strong water currents for future deployment into open seas. A fully-actuated ASV propulsion system using four angled thrusters is implemented, which demonstrated dynamic positioning capabilities by doing omnidirectional movement while maintaining heading, giving the ASV greater manoeuvrability in rough waters. An operator control system (OCS) is deployed, with a tested communication range of 2.2km, that is capable of teleoperation of the ASV and displaying hardware statuses of the ASV from a web interface. The propulsion system for an AUV is also designed to enable the AUV to operate in strong water currents when deployed from an ASV in open seas. BBASV 2.0 is currently deployed at a marina for sea testing, while the final designs for BBAUV 3.75 have been sent out for fabrication, but are experiencing manufacturing delays. Hopefully, this ASV and AUV system will be able to demonstrate its full integrated capabilities n strong water currents at the Maritime RobotX Challenge 2018 in Hawaii.

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