NU Marine, RobotX Technical Design Paper, 2022

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***Abstract*—In the future, various tasks currently performed by human beings will be carried out by autonomous systems. One such task is boat navigation. This paper describes the design of an autonomous surface vessel (ASV) for the RobotX competition[1], developed by The University of Newcastle's NU Marine team. The ASV is equipped with sensors and employs a set of algorithms which enable the system to safely navigate without human intervention. The system design strategy includes the integration of a suite of sensors, mechanical hardware, and software architecture.**

I. Introduction

The international Maritime RobotX Competition is a biennial event which offers undergraduate students the opportunity to apply their skills to robotic systems operating in the maritime environment. Hosted by RoboNation, the 2022 competition will take place at the Sydney International Regatta Centre. Teams are required to develop and build an autonomous system using the Wave Adaptive Modular Vessel (WAM-V) as a base platform. The vessel produced by each team is given the opportunity to compete in a series of challenge tasks that mimic the potential requirements of real-world autonomy. NU Marine is a student team comprised of passionate undergraduate engineers from The University of Newcastle competing in the RobotX Competition in 2022.

II. Design Strategy

The COVID-19 pandemic saw the NU Marine team evaporate, leading to minimal knowledge transfer, missing or broken hardware and a limited understanding of how the boat was previously configured. The 2022 team gained access to the hardware in early February and quickly pursued baseline functionality.

This required subsystems to be developed from the ground up, while attempting to leverage off the sparse previous knowledge base and experience of past team members. The end goal for the 2022 team is to cultivate a strong technical foundation and facilitate knowledge transfer to enhance the team in future years. The platform development approach was to achieve a solid hardware and software foundation as quickly as possible and increase functionality throughout the year. This allowed for continuous capability enhancement while time permitted, whilst still conforming to the original goal of producing a simple, robust platform capable of reliable autonomy.

III. Platform Design

As with all mechatronics projects, in order to find success, a delicate balance between hardware, electronics and software needs to be achieved. The following section of information will delve into these crucial aspects of mechatronics design, shedding some light on the decisions made by the team and how they impact the overall design of the WAM-V, visible in it's current state, in figure 1.

Fig. 1: Render of the team's WAM-V in it's current format.

A. Power Systems

To power the vessel's main systems, sixteen 100 AH 3.4V Lithium Iron Manganese Phosphate (LiFeMnPO4) cells with a bespoke Battery Management System (BMS) were used. This bank of cells are split up into 2 parallel pairs with 8 cells in each for a nominal voltage of 26.4V. LiFeMnPO4 was chosen due to their durable, safe and reliable operation while in the wide range of operational environments needed.

The BMS, as visualised in figure 2, incorporates custom made voltage and temperature monitoring circuits for each cell, current sensing and a complete active balancing array with internal charging current sensing. The BMS uses multiple high-end micro controllers to collate, filter and transmit the data to the rest systems integrated on the platform.

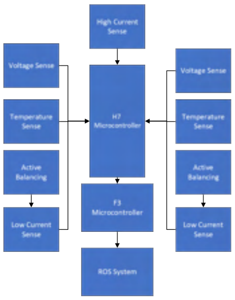

Fig. 2: The power distribution system.

To achieve accurate active balancing, system identification was conducted to calculate the Open Circuit Voltage (OCV) and the total capacity of each cell. This data is also used to estimate a State of Charge (SOC) using a 2 pair RC parallel pair equivalent circuit.

A battery shore monitoring system was created to monitor graphs in real time of temperature, SOC, and cell voltage while the WAM-V is in operation.

B. *Propulsion*

The propulsion solution was designed and developed with the aim to attain full actuation of the WAM-V in all directions. Our current propulsion system includes two Torqeedo Electric Cruise 2.0 RT outboard Motors as the primary thrusters located at the stern of the WAM-V. Each Torqeedo produces a maximum thrust of 115 lbs and operate at a nominal voltage of 24 V. The Torqeedo's on-board computers were removed in previous years and lead to further modifications to the Torqeedo motors. Communication through the RS485 serial standard is configured directly to each motor from high-end micro controllers. A current sensor was redesigned to provide accurate current measurements for thrust approximation.

In addition to the primary motors, two Blue Robotics T500 thrusters were added as secondary lateral or bow thrusters to provide thrust perpendicular to the boat. These can be controlled by sending a pulse width modulation (PWM) signal from micro controllers through the Basic Electronic Speed Controller (ESC) 500 supplied by Blue Robotics to each thruster. These thrusters have raw data available online to easily relate PWM signal to thrust approximations.

The current motor configuration is commonly known as the 'T' Differential Thrust and can be seen in Figure 3.

The Torqeedo motors are attached to each pontoon through an aluminium bar brackets. Two stainless steel brackets and shafts were also designed for the T500 thrusters to be able to manually lower the thrusters into the water. The design goal for mounting the motors to the WAM-V was to be simple, sturdy and transportable [2].

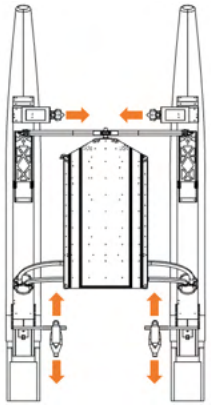

Fig. 3: 'T' Differential Thrust configuration as it appears on the team's vessel.

C. *GNC Case*

The Guidance, Navigation and Control (GNC) case is the central hub for all sensor inputs, actuator outputs, computations, and communications. The case is also responsible for the distribution of power, housing 5V, 12V, and 24V DC-DC converters to power all the required devices. Incoming sensor data from the cameras, LiDAR, GPS, and hydrophones are processed in the GNC case, being fed into one of three intel i7 Next Unit of Computing devices (NUCs). The NUCs execute the primary processing required to fuse sensor information and build a map of the surrounding environment which the vessel can then execute tasks within. The GNC case houses the networking devices used to communicate between all the intel NUCs and the operator control station on shore. The case is situated towards the rear of the WAM-V's platform and is a robust powder coated steel enclosure. A single enclosure is used to minimise the potential for water ingress and simplify the hardware layout on the platform surface. The case includes a modular input/output panel which facilitates the necessary wired connections between the contents of the box and the external hardware.

D. *Supervisory System*

The supervisory system acts as the brain of the platform. It is responsible for being the translator between the Operator Control Station (OCS) and the Robot Operating System (ROS) network on the boat. Distributing messages to and from ROS nodes and ensuring each system has the information that it requires. The supervisory system is also responsible for flagging and acting on any faults detected on the WAM-V. Another aspect of the supervisory system is the mission planning algorithm. The version deployed on the WAM-V takes an input from the OCS specifying what task the platform should be attempting to execute, and with this information, interprets feature positions from the navigation node to develop a mission plan, and pass waypoints to the guidance node. The mission planning suite is also responsible for resource management and will return to base if it cannot execute the designated task for any reason, such as a depleted battery.

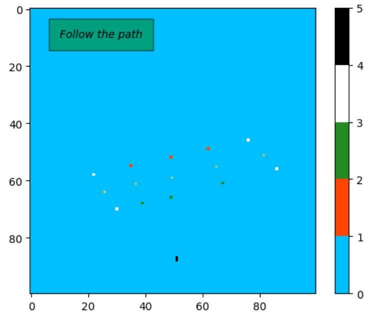

Fig. 4: Graphical representation of the supervisory system.

E. Navigation System

1) GPS: The WAM-V autonomy suite relies on accurate information about the vessel's position in the world, and about how it is moving within the environment. The Advanced Navigation Spatial Dual provides this data through a dual receiver GPS antenna system, combined with an inertial measurement unit with internal gyroscopes, magnetometers, and accelerometers. Of particular interest for the mathematical model for the WAM-V, these integrated sensors provide Global Positioning System (GPS) position, angular orientation, world translational velocity, and angular velocity, as well as other data such as linear acceleration and magnetic field forces. The information is received through a USB connection with the help of the Advanced Navigation Software Development Kit (SDK) built for ROS.

2) LiDAR: The team is using a Hesai Pandar-XT32 Laser Imaging, Detection, and Ranging (LiDAR) device, to obtain range and depth information about objects in the field surrounding the WAM-V. This sensor is a 32-band LiDAR. It operates by emitting beams of light onto objects, where the reflected beams are then detected by an optical sensor to calculate their distance. It uses the time of flight principle (1), to calculate the distance of a target from the LiDAR origin.

$$d = \frac{ct}{2} \tag{1}$$

The team interfaces with this sensor over Ethernet and utilises the available Hesai SDK to obtain position and intensity data for each point in a 360-degree point cloud, a visualisation of which can be seen in figure 5. The LiDAR is mounted on an aluminium extrusion tower on the top plate of the WAM-V to ensure the LiDAR field of view (-16 to +15 degrees) will not be obstructed by other pieces of hardware.

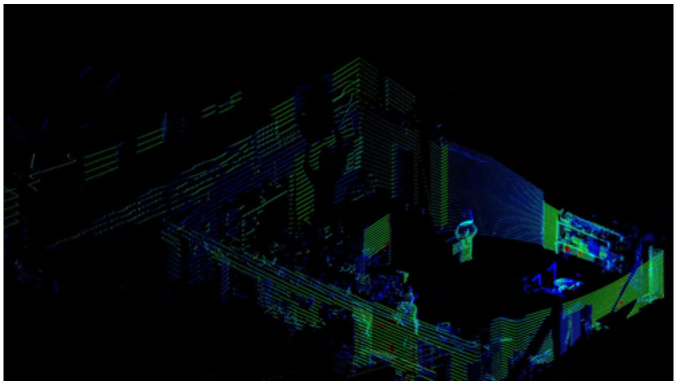

Fig. 5: LiDAR output visualisation of the interior of the team's workshop.

3) Hydrophones: The ability to detect and categorise a high-frequency pulse delivered by an underwater beacon is a key requirement in the first competition task. The team has integrated an array of four Aquarian Audio AS-1 hydrophones onto the WAM-V to achieve this. The hydrophones are mounted as far apart as possible to facilitate the extraction of phase information required for subsurface target localisation, testing of which can be seen in figure 6. The two front hydrophones are mounted inside the bow thruster mounts, and the rear two are mounted in their own rotating assembly to enable easy transport and deployment.

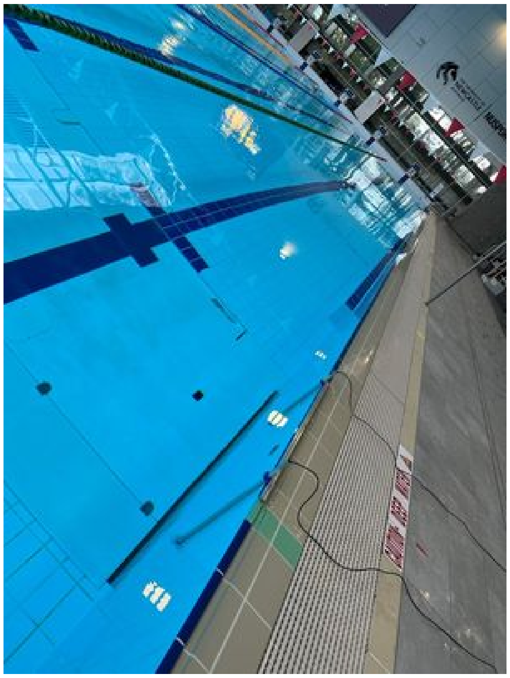

Fig. 6: One set of 2 hydrophones, collecting data at the pool.

4) Navigation Software: The navigation system has the role of informing the team of the position of the vessel, as well as what the surrounding environment looks like. It integrates the available sensors, in this case a LiDAR and GPS/Inertial Measurement Unit (IMU), and uses the incoming data from these measurements to estimate the state of the WAM-V and the world around it. An Unscented Kalman Filter (UKF), demonstrated in algorithms 1 and 2, is used to manage the measurement updates and merge these with the mathematical process model that explains how the WAM-V should move.

The UKF works by representing measurements and the state of the vessel as Gaussian probability distributions with varying mean and covariance. It has three main steps: first, obtain the measurements, then integrate these measurements to update the probability of the state using conditional probability, and last, predict the next state of the vessel. The fundamental process happening inside the UKF is called an unscented transform. Here, sigma points are formed around the mean of the input, and these are pushed through their respective non-linear function. The mean of the covariance of each of these sigma point outputs is taken and turned into the resultant probability distribution. The navigation system, with the help of the UKF, can then pass on estimates of state and landmark positions in the world to the other systems for use in their algorithms.

Algorithm 1 Unscented Transform [3]

```
$N \leftarrow$ Number of States
$\boldsymbol{P} \leftarrow$ Covariance Matrix
$\mathcal{X} \leftarrow$ Matrix of $2N+1$ Sigma Vectors
$W \leftarrow$ Weights Associated with Sigma Vectors, Add to 1
$\lambda, \alpha, \beta \leftarrow$ Scaling Parameters

$\mathcal{X}_0 = \mu$ of $x$
$\mathcal{X}_i = \mu + \sqrt{(N+\lambda)\boldsymbol{P}_{\boldsymbol{x}}}_i, \qquad i = 1, ..., N$
$\mathcal{X}_i = \mu - \sqrt{(N+\lambda)\boldsymbol{P}_{\boldsymbol{x}}}_i, \qquad i = N+1, ..., 2N$
$W_0^m = \lambda/(N+\lambda)$
$W_0^c = \lambda/(N+\lambda) + (1 - \alpha^2 + \beta)$
$W_i^m = W_i^c = 1/2(N+\lambda), \qquad i = 1, ..., 2N$
```

Algorithm 2 Updates after the Unscented Transform [3]

```
$\bar{\boldsymbol{y}} \approx \sum_{i=0}^{2N} W_i^m \mathcal{Y}_i$
$\boldsymbol{P}_{\boldsymbol{y}} \approx \sum_{i=0}^{2N} W_i^c (\mathcal{Y}_i - \bar{\boldsymbol{y}})(\mathcal{Y}_i - \bar{\boldsymbol{y}})^T$
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F. Vision System

1) Camera Mounting: Mounted to the vessel are three Blackfly S USB3, 1.3 Megapixel, 170FPS cameras. One of these cameras is equipped with a 60° horizontal field of view (FOV) lens, facing outwards from the bow of the vessel. The other two cameras are equipped with 190° FOV lenses, positioned on the port and starboard sides of the lenses, covering the flank of the primary camera, as seen in figure 7. Optimally, a fourth, additional, camera would be positioned at the rear of the vessel in order to maintain a complete 360 degree view. This however was unattainable due to the issues present in obtaining the necessary hardware.

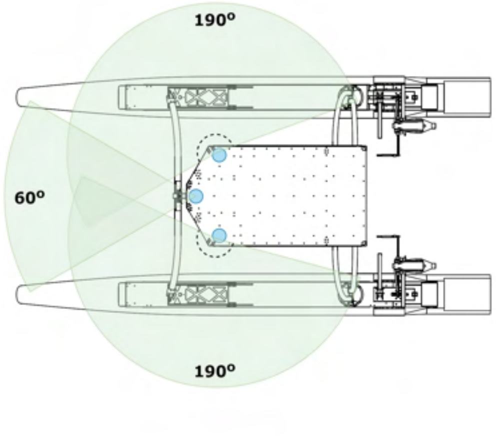

Fig. 7: Camera configuration on the team's vessel, visualising it's approximate field of view.

2) Vision Software: The goal of the vision system is to use the input from the vessel's attached camera systems in order to identify and help locate different objects in the world, providing crucial knowledge to the system which will allow it to complete many of the competition tasks.

The vision model utilises a CNN model known as YOLOv5 [4] (You Only Look Once), an extremely well optimised model used within many machine vision applications. The model has been trained on a collection of images and has been continually expanded upon as time has gone on, with approximately 3000 images making up the current training dataset.

In the current configuration, images are read in from each camera at a fixed frequency and processed on a NVIDIA Jetson Nano. Each image is run through the detection model and the location of the proceeding bounding boxes for each object are recorded. The image is then split into 10 segments as seen in figure 8, with the segment each detected object appears in also being recorded. The purpose of this process is to provide as much information as possible to the Navigation system in order for the LiDAR to locate the detected objects and generate accurate range measurements, allowing for a map of important landmarks to be generated and for a path to be calculated.

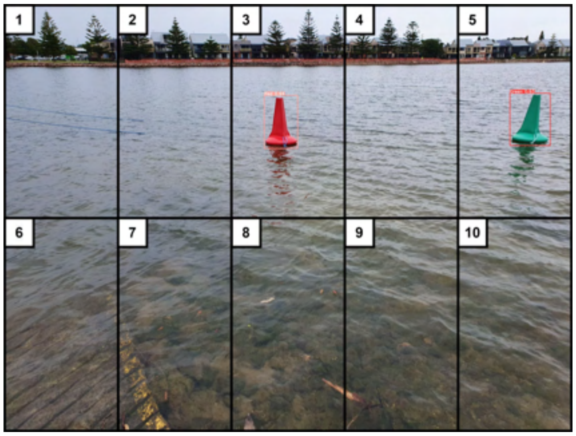

Fig. 8: A representation of how the vision system processes an incoming image, assigning each detected object to a specific image segment (Image not taken from onboard camera for purpose of clarity).

G. Guidance

The guidance system is responsible for generating a state trajectory which can meet the mission requirements communicated by the supervisory system and can be feasibly achieved by the control system. The guidance solution takes both the binary occupancy grid map and the mission planning data as inputs, generated by the navigation and supervisory systems, respectively. This data is used to generate a collision-free trajectory from the current pose to the mission goal via the D* Lite path planning algorithm, which is a dynamic variation of the widely implemented A* algorithm. Each obstacle is inflated by a fixed radius to ensure the WAM-V remains a conservative distance away from objects on the course, which is visualised in Figure 9.

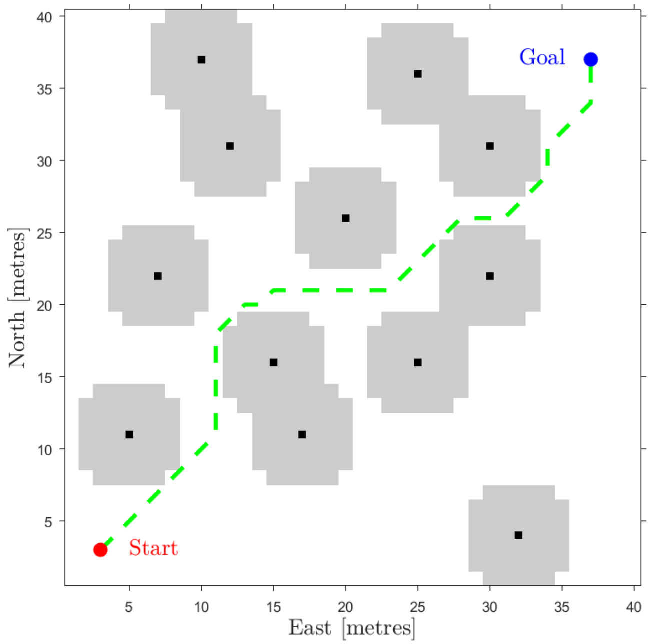

Fig. 9: D* Lite algorithm simulation with inflated obstacles.

Key way points are then extracted from the algorithm's path result and fed into a quadratic programming routine which fits optimally smooth cubic splines to the path. The quadratic programming spline generation ensures the reference trajectory is smooth and continuous, as pictured in the top-down trajectory plotted in Figure 10, and as such can be reasonably tracked by the control system. This process is run in real time and continually updates the path during active missions based on changes in the map environment.

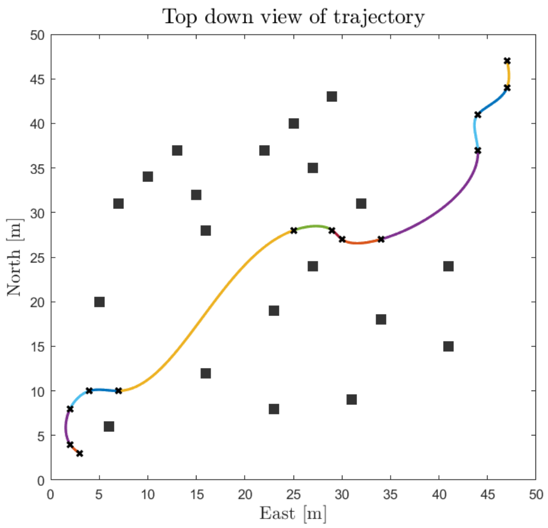

Fig. 10: Trajectory produced by the quadratic programming optimisation routine.

H. Control

The control solutions desire is to accurately and efficiently navigate the unmanned surface vessel (USV) along a desired path. To accomplish this, two control schemes were developed for trajectory tracking and station keeping tasks. The trajectory tracking controller uses two separate feedback control loops to maintain body fixed velocity and earth fixed heading of the boat. Both control loops use proportional integral derivative (PID) with static gains and an anti-integral windup to perform effective tracking of the USV.

The station keeping controller uses three separate PID control loops to effectively maintain the pose of the USV. Through the thrust configuration on the boat, the USV can maintain the heading and position on the water with external currents and wind imposing disturbances on the system. The three separate control loops track the local earth fixed x and y positions along with the earth fixed heading and by using the thruster configuration an appropriate thrust output can be determined.

The current position, heading and velocity is received from navigation along with the desired position, heading and velocity for the planned path from guidance to correctly determine the given errors for the PID control loops. Both controllers were tested within simulations to confirm their feasibility. Figure 11 highlights the simulated results from the trajectory tracking controller which has been implemented on the WAM-V.

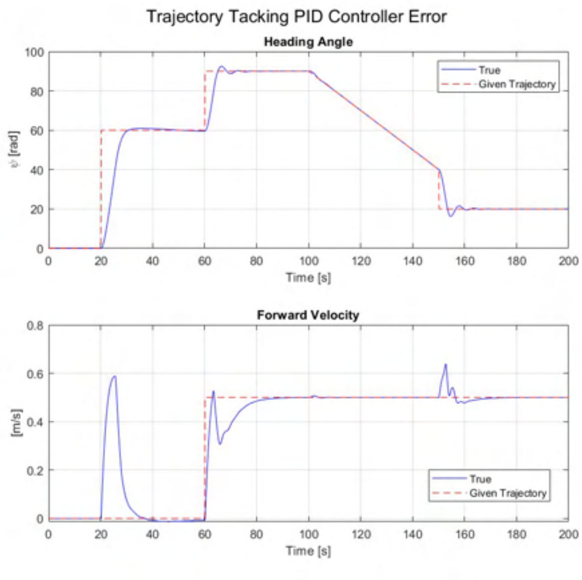

Fig. 11: Trajectory error produced during simulation of PID controller.

I. Operator Control Station

In order to communicate with the vessel from the shore, an Operator Control Station was developed. This device houses a Raspberry Pi 4 attached to a Light Emitting Diode (LED)

panel which allows for clean interfacing to and from the vessel via a user interface shown in figure 12. The bridge between the OCS and the WAM-V itself is created using a pair of Ubiquity Rocket 5AC Lite base stations linked together in point-to-point mode, essentially acting as an invisible Ethernet cable.
The OCS serves 3 main purposes:

- To relay and display important information to the team such as GPS outputs, useful plots and even more useful error messages.
- To inform the vessel of whether it should be behaving in manual or automatic configuration and to facilitate this through either manual input commands from an attached PS4 controller or through competition task and waypoint inputs which dictate the behaviour of the onboard autonomy systems.
- To provide remote E-Stop functionality, allowing the team to cut power to the motors from the shore.

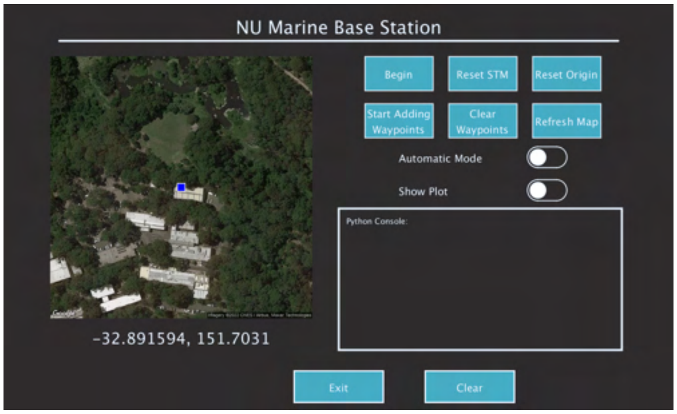

Fig. 12: Version 1 of the team's OCS user interface.

J. Safety System

In order to comply with competition regulation [1], as well as to uphold the highest degree of safety, a designated safety system has been developed, as visualised in figure 13. Attached to the vessel are 4 E-Stop switches that are connected to a shared relay. If one of these buttons is pressed, a further relay is tripped, blocking power flow to the motors and adjusting the status light atop the boat accordingly. Furthermore, connected to E-Stop relay is an STM32H7 micro controller, this board is configured to receive in serial data from the OCS on the shore through a link created between a pair of RFD900x devices. Within the OCS housing, a separate STM32F303 is set up to read in a signal from a fifth E-Stop button, mounted to the housing. If this button is pressed, a signal is sent across the serial link in under a second, triggering the relay and mimicking the effect of pressing a button mounted to the vessel itself.

In addition to this functionality, a consistent frequency "heartbeat" message is sent across the serial link. If this message is not received by the vessel for any reason, power is also cut to the motors, maintaining safe operation of the vessel.

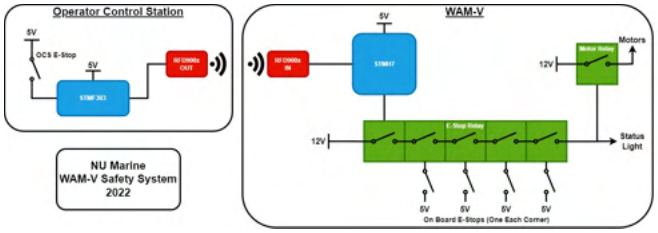

Fig. 13: A graphical representation of the vessel's safety system as it appears on shore and on the vessel itself.

IV. EXPERIMENTAL RESULTS/TESTING

Testing is a crucial part of any engineering project and as such, throughout the year, the team has endeavoured to validate functionality of the vessel's systems both in simulation and in real world environments.

1) Simulation Testing Analysis: In order to reliably test certain functionality of the vessel, the team set up a simulation within MATLAB as seen in figure 14. This simulation utilised MATLAB toolboxes such as the LiDAR Toolbox in order to simulate the functionality of the team's hardware. Building this simulation also helped the team develop the mathematical model of the vessel's dynamics which serve as the foundation for the GNC systems.

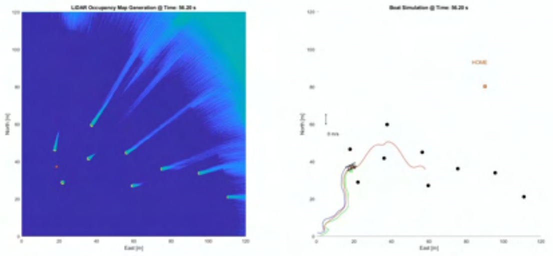

Fig. 14: Screenshot from one of the team's MATLAB simulations of the vessel.

2) Live Testing Analysis: Whilst testing in simulation is simple and convenient, many things can only be learned by taking the vessel out on the water in real world conditions. As of the writing of this paper, the WAM-V has been put on the water a total of three times throughout the year, one of these occasions being displayed in figure 15. These tests took place at the local waterways in Carrington, New South Wales, Australia. The main objective of these tests was to validate the functionality of devices such as the on board GPS and communications systems. Test days like these were also a prime time to collect data on the boat which could be used to perform system identification, improving the mathematical model of the vessel developed through simulation testing.

In conjunction with testing on the water, the team also performed a number of "Carpark Tests", in which the WAM-V was driven around the campus car parks on the back of

Fig. 15: A shot of the team's WAM-V in action during a test day in Carrington.

a trailer. These types of tests proved extremely beneficial throughout the year due to their ability to rapidly test and validate changes without consuming all of the time required to get the vessel out on the water.

V. ACKNOWLEDGEMENTS

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- Varley Group,
- Ampcontrol,
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- Robotic Systems,
- SAFEgroup Automation,
- Janus Electric,
- Newcastle High-Tensile Bolt Co,
- Murray Consulting Solutions,
- Thales Group.

The team would also like to acknowledge the NU Teams organisation as a whole for providing a fun, safe and collaborative workspace throughout the year.

VI. REFERENCES

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