Maritime RobotX Challenge

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***Abstract*—The past few years have seen the rise of autonomous systems from research and industry to the public space, with implementation of self-driving cars, such the UBER self-driving trials in Pittsburgh and the publically available Tesla Model S. Now that autonomous systems are emerging into the public domain, there is added pressure and need to develop these systems, and competitions such as the Maritime RobotX play a large role in the maturation of these technologies.**

Maritime Robot X is an international competition which sees world leading universities competing through the development of an autonomous surface vehicle using a standardised platform, the Wave Adaptive Modular Vehicle or WAM-V. The platform is the only standard component, the teams are required to develop various systems to complete the autonomous tasks set out for the competition, where the teams are judged on accuracy and speed.

This year the objective for the UoN Robot X team was to develop a strong platform for future improvement, this was through the learnings of the previous competition, as well as, the new ideas that were conceptualised at the beginning of the year. The Torqeedo propulsion units were re-used, while the linear actuators were replaced with new stepper motors for steering. The computer system was revamped, using four independent computers for the machine vision algorithm, providing much higher speed data updates, with an additional central computer acting as the guidance, navigation and control computer. This central computer was used gather the processed data from the secondary computer network, as well as, the IMU and GPS data and perform the SLAM algorithm. This computer was also responsible for the MPC trajectory planner along with control of the actuators.

Through the system development process, and testing that was undertaken the UoN Robot X ASV is versatile platform for continued autonomous research projects, allowing for different payloads and sensors to be implemented for the different projects.

I. INTRODUCTION

Increased use of unmanned surface vehicles (USV's) in the commercial, scientific and defence sectors, is driving demand for a higher level of autonomy than today's systems can provide. The marine environment presents a number of challenges to implementing reliable automation, especially in the highly dynamic and cluttered, close to shore environment; the littoral zone. When operating close to shore, chances of human machine interaction are greatly increased, requiring systems to handle unpredictable situations in a safe manner. To help drive development in the field of USV autonomy and to encourage students around the world to take up STEM subjects the Maritime RobotX competition was founded.

Maritime RobotX is bi-annual competition first held in 2014 at Marina Bay Singapore and in 2016 held in Oahu, Hawaii, teams must use a common platform, the 16ft WAM-V and develop a fully autonomous system able to complete a number of competition tasks.These competition tasks are designed to mimic real world applications and problems ASV's may face including, navigation, docking, environmental monitoring and obstacle avoidance.

In 2016 the University of Newcastle's WAM-V has been redeveloped to address the lessons learned from the previous competition, this paper documents both the design methodology, design iterations and detailed solutions to the competition challenges.

II. DESIGN STRATEGY

A modular design strategy was chosen for the 2016 RobotX completion, with mechanical, electrical and software systems being broken up into a series of modules that can be easily added or removed from the system; without extensive modifications. A key design constraint for our team this year was limited working hours, having a modular design enables individual system components to be developed and tested in isolation, speeding up development of the system.

Many of the tasks in the competition are able to be solved by vision, both above and below the water. For this reason vision is included in our primary system; the guidance navigation and control payload, which is set-up to perform the following competition tasks:

- Demonstrate navigation and control
- Find totems and avoid obstacles
- Scan the code
- Underwater shape identification
- Find the break

The primary system was given the highest priority with the majority of the teams development time and available budget being used on this system and has been completely redesigned since the previous competition. Where possible robust industrial hardware was used in this system as well as cooling the primary payload box and mounting the entire internal skin on shock and vibration isolators; all contributing

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to increased reliability of the current system, when compared to the previous WAM-V hardware. Although redesigning the existing system came at the cost of increased development time and less time for on water testing, in the long term the increased reliability will allow us to confidently test the boat without issue and allow a greater focus on the secondary systems; the competition payload.

For the 2016 competition the secondary system consists of hardware and software to solve competition tasks which can not be solved using, our primary sensor alone, machine vision. These include:

- Detect and Deliver
- Acoustic pinger based transit

The following sections detail how the each of the sub-subsystems have been implemented.

A. Primary System - Navigation, Guidance and Control

1) Navigation: In order to properly avoid obstacles within the environment, the vehicle must provide estimations for both its pose relative to the global origin, and the locations in space of said obstacles. This problem is commonly referred to as simultaneous localization and mapping (SLAM) [1].

To obtain a good estimate of the environment, a virtual map shall be stored and populated with the information provided by the on board cameras. A probability occupancy grid (POG) has been utilized for this task, which was presented in [2]. This grid form representation has been selected for the RobotX course, due to the following rationale:

1) Obstacles in question are assumed static.
2) The area of the environment is known a priori.
3) Dimensions of detected obstacles can be easily contained within the grid.

We have modified the updating procedure of the POG to allow the 3D information obtained by the cameras to be projected onto a 2D plane. This method always for faster convergence results of the map, thereby allowing us to form more optimal trajectories for the vehicle to follow. The procedure is as follows:

Let the obstacle data returned by the camera centered about the origin C_i by the set $\left\{\mathbf{r}^c_{Q_{ik}/C_i}, \theta_{ik}\right\}$, where $\mathbf{r}^c_{Q_{ik}}$ is the unit sphere coordinates of an obstacle in the environment with centroid P_k, and θ_{ik} is the apparent angular radius of said obstacle, then:

$$\vec{r}_{Qik/C_i} = \frac{\vec{r}_{Pk/C_i}}{\|\vec{r}_{Pk/C_i}\|} \tag{1}$$

therefore:

$$\mathbf{r}^n_{P_k/N} = \mathbf{R}^n_c \left(\frac{r_k}{\sin\theta_{ik}} \cdot \mathbf{r}^c_{Q/C_i} \right) + \mathbf{r}^n_{C_i/N} \tag{2}$$

where $\mathbf{r}^n_{P_k/N}$ is the global obstacle centroid position, and r_k is the radius of obstacle k.

Once the global centroid positions have been found, the existence probability of each grid cell can be updated. This probability shall be incremented for the cell $\mathbf{r}_{G_j/N}$ if:

$$\|\mathbf{r}^n_{P'_k/N} - \mathbf{r}^n_{G_j/N}\| \leq r_k \tag{3}$$

where:

$$\mathbf{r}^n_{P'_k/N} = \text{diag}(1,1,0)\mathbf{r}^n_{P_k/N} \tag{4}$$

The probability shall be decremented if and only if $\mathbf{r}^n_{G_j/N}$ is within the FoV of the camera, and not within the shadow ellipsoids located behind all observed obstacles. These ellipsoids are the sections of the environment that are occluded at the current time step, due to the positions of both the cameras and obstacles. Figure 1 shows this in further detail. The cell $\mathbf{r}^n_{G_j/N}$ shall be within an obstacle shadow if:

$$\mathbf{r}^c_{Q_{ik}/C_i} \cdot \frac{\mathbf{r}^c_{G_j/C_i}}{\|\mathbf{r}^c_{G_j/C_i}\|} \geq \cos\theta_{ik} \tag{5}$$

where $\mathbf{r}^c_{G_j/C_i}$ is the cell position in camera coordinates.

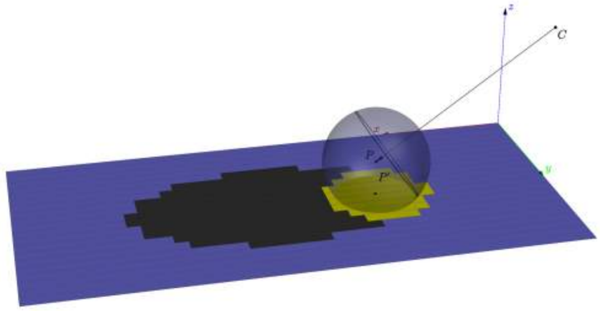

Fig. 1. A buoy with radius r_k and centroid P has been observed for a camera at origin C. The yellow cells indicate where the existence probability is high, and the conic shadow of occlusion is shown in dark grey.

Once the map has been updated, a range vector is formulated to assist in the estimation of the position and orientation of the vessel. This vector shall always possess a range for each bearing angle, where:

$$\rho_k = \begin{cases} \|\mathbf{r}^n_{B/N} - \mathbf{r}^n_{G_j/N}\| & \text{if } p(G_j) \geq T \\ \|FoV_k\| & \text{otherwise} \end{cases} \tag{6}$$

where T is the existence probability threshold and $\|FoV_k\|$ is the maximum range the cameras can perceive in that direction. Figure 2 shows this in further detail.

This range vector is then utilized within an Unscented Kalman Filter (UKF) [3], which is used to estimate the state of the vessel using process and measurement models described below. A UKF has been selected as we have assumed a discrete-time nonlinear state-space model with additive Gaussian noise:

$$\mathbf{x}_{k+1} = f(\mathbf{x}_k) + \mathbf{w}_k, \tag{7}$$

$$\mathbf{y}_k = h(\mathbf{x}_k) + \mathbf{v}_k, \tag{8}$$

where the current state is $\mathbf{x}_k$, the process noise $\mathbf{w}_k \sim \mathcal{N}(\mathbf{0}, \mathbf{Q}_k)$ and the measurement noise $\mathbf{v}_k \sim \mathcal{N}(\mathbf{0}, \mathbf{R}_k)$.

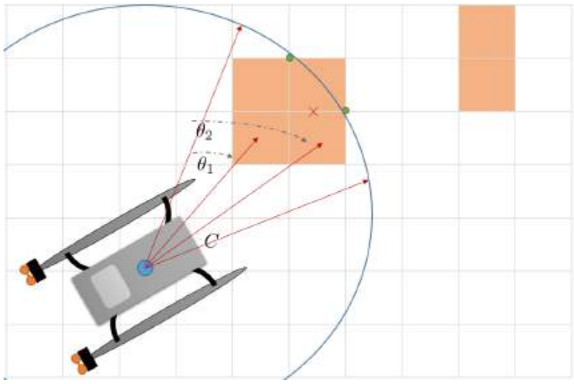

Fig. 2. Obtaining the Range Vector from the POG Map. For each bearing angle, the range from the vessel to a grid cell with a probability value above a selected threshold is obtained. If no cell is above the threshold, the maximum FoV range is recorded instead.

2) *Guidance:* The D guidance algorithm implemented in the 2014 competition, proved to be successful so remains unchanged for this competition. The grid based system consisted of two key steps:

- Obstacle Clustering
- Path Planning

Detected obsticles that are too close to eachother for the boat to pass through are grouped together, shown below in Figure 3.

3) *Control:* Trajectory tracking control of the WAM-V is performed using nonlinear model predictive control (MPC). MPC functions by defining a cost function, based upon the response predicted using the systems model from the current state, which represents undesired behaviour and is minimised at each control interval whilst ensuring system constraints are not violated. For the WAM-V a nonlinear vessel model has been formed which relates the actuator commands, consisting of independent control for each of the two thrusters and their respective angles, to the vessel states; defined as positions in the local earth fixed reference frame and body fixed velocities.

At each control interval a prediction of the vessel response over the chosen horizon is formed using an sequence of control values. The deviation of this response from the desired trajectory, and changes in actuator usage, forms the cost to be minimised by varying the predicted control values to use whilst ensuring that any constraints are not violated. As the vessel model is nonlinear this minimisation is performed iteratively using sequentially quadratic programming (SQP) which can handle the slew rate and amplitude constraints placed upon the actuators. The first values in the sequence of control values obtained from this optimisation forms the actuator commands to use on the vessel, this whole process is then repeated at each control interval to calculate the new actuator commands to be used.

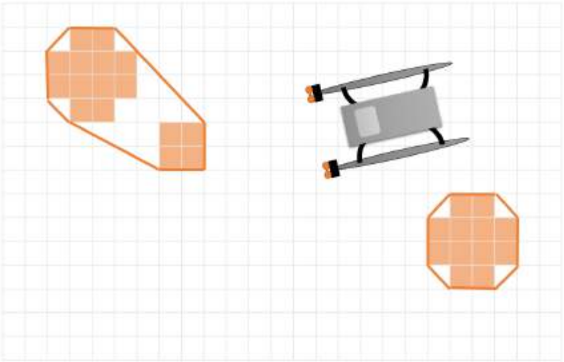

Fig. 3. When objects are too close together to be navigable, the guidance system clusters them into one obstacle.

The resultant MPC system has been tested in real time simulations to be an flexible and effective control system with the nonlinear predictive nature achieving good performance under an wide range of scenarios such as actuator failures; offering a level of robustness to the overall system.

B. Secondary System - Competition Payload

1) *Hydroacoustic Localisation:* One method to solve the source localisation problem is using a linear hydrophone array with a sum and delay beamformer. Also known as conventional beamforming, is a form of spacial filtering. Being it gathers information from a desired signal or location while attenuating the undesired. This is achieved by inserting av timeshift into signals received at the transducers and then adding the artificially shifted signals together. The time shifts are chosen based on the assumed wave front model (ie planar or hyperbolic). If the inserted timeshift matches that of the actual timeshift the signals should add coherently, producing a larger lobe on the beam time series pattern.

$$b(t) = \sum_{n=0}^{n-1} w_n x_n(t + \tau_n) \tag{9}$$

Where;

- τ_{n-1} ; is the inserted time shift

- W_{n-1} ; is the weighting or 'shader' coefficient
- x_n (Chan N-1) ; is the signal seen by the hydrophones

To prepare the noise corrupted signals received from the hydrophones a pre-amplifier circuit has been utilised, comprising of instrument amp to read the signal coming in from the high impedance passive hydrophones and a bandpass filter to attenuate signals of unwanted frequencies.

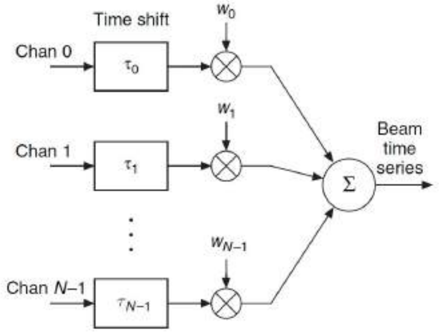

Fig. 4. Conventional or delay and sum beamformer.[4]

The hydroacoustic localisation system uses a dedicated National Instruments CompactRIO processor module with an FPGA chassis and ADC that is configured as shown in Figure 5. The data from the hydrophone array is sampled at 500kHz and all signal processing is located on the CompactRIO while beacon localisation is performed on the Kontron system.

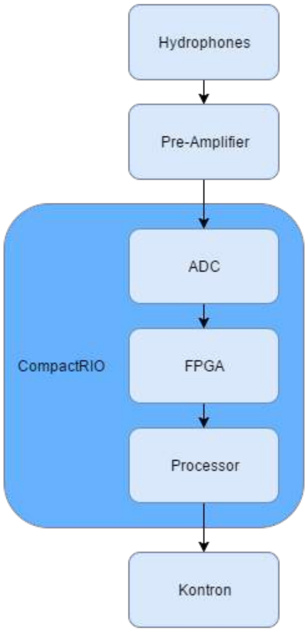

Fig. 5. The hydroacoustic localisation system.

2) Payload delivery: The payload delivery system consists of a four barrel air cannon mounted on top of the the secondary system pelican case. No PVC pipe was available to match the diameter of the payload used in the competition so a sabot was developed, which is pictured below in Figure 6

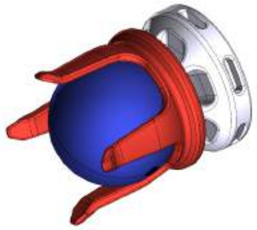

Fig. 6. Sabot, to carry fit competition payload in PVC pipe.

III. VEHICLE DESIGN

The modular design strategy for the UONs Maritime Robot X platform was chosen to support an evolutionary, yet economical approach to the design of all the systems on the platform. This meant that all sub-systems were designed out of smaller components, allowing for future iterations to use some components, and replace others without the need for complete redesigns of the sub system.

To leverage the lessons learned from the previous competition team meetings were held early in the year and all the previous sub-systems and new requirements were discussed. This meant that opinions and needs of the various engineering groups could be heard, and a target could be set for the overall system.

A. Mechanical

The mechanical design is typically the most costly and timely to iterate on. Due to the time and cost constraints set for the team the physical iterations of mechanical designs are limited or non-existent. To combat this 3D CAD was used extensively to iterate and review designs so that designs would meet requirements the first go wherever possible.

B. Motor Pods

An example where designs could not be physically iterated was the propulsion pod, due to the cost and time to manufacture. Requirements for the pods were to mount to the back of the WAM-V, contain integral batteries, as well as, mounts for the propulsion/steering. Mounting the pod to the WAM-V became a point of contention, as there were plans to design a suspension system so that thrust could be transmitted efficiently and wave action could be suppressed however there was insufficient time to develop such a system. This gave birth to the final modular design, where the flotation (and battery storage) is independent to the mounting arrangement, so future design iterations can implement a new suspension/mounting system while utilising the same flotation and battery storage.

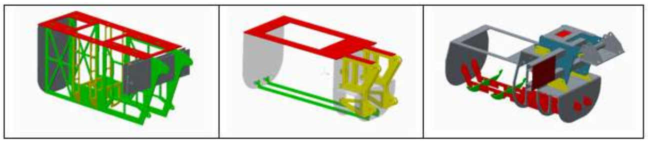

Fig. 7. Design iterations of flotation pods from left to right. Note, centre design was abandoned by final design (and not completed).

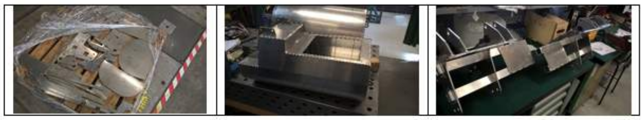

Fig. 8. Motor pods. Left: Laser cut plates. Middle: Flotation pod. Right: Mounting arrangement.

1) Actuators: The Torqeedo electric outboard motors used in the previous competition (pictured below in Figure 9) have proven to be an effective and reliable system. However, the linear actuators used to provide steering were too slow, and their mounting prevented the Torqeedo motors from being tilted up, the new design specifications required faster actuation and an improved mounting system.

To achieve the speed and control requirements high torque geared stepper motors were selected, along with suitable drivers. Due to their proximity to the water they needed a waterproof housings/mounts. These housings were designed with 3D CAD such that they could be 3D printed by some of the team members 3D printers. This allowed for physical design iterations to be made, tested and modified until a suitable design was reached.

2) Electronics Enclosures: The electrical systems were divided into three main components which included the power distribution, the competition specific payload, as well as, the guidance, navigation and control (GNC) module. This was decided so that the system could be easily modified or adapted to suit other projects, where the competition payload can be easily unplugged, removed and swapped out for a different sensor payload. This also means the GNC module can be removed and installed on other platforms.

The three systems are contained in their own pelican case which is strapped down to the payload tray. The required inputs and outputs are accessed via waterproof bulk head connectors or cable which have been penetrated with cable glands for waterproofing. The GNC module also incorporates shock and vibration damping, to reduce the noise effects on the inertial measurement unit.

3) Camera Housings: The previous camera enclosures met the original design requirements, which were to protect the cameras from the elements, and provide sufficient field of view for the 192 degree lenses. However, during the competition it was found that the Perspex tubes that allowed for the large field of view created artefacts in the vision data due to the internal reflections. This prompted the second

Fig. 9. Actuator housing and mounting 3D print iterations.

Fig. 10. Torqeedo electric outboard motor, used in both the 2014 and 2016 RobotX competitions.

Fig. 11. Actuator assembly. Left: Stuffing box. Middle: actuator on Torqeedo. Right: Homing switches for calibrations.

Fig. 12. Computer hardware housed in a Storm iM2950 waterproof case.

Fig. 13. Power Distribution housed in a waterproof case.

design revision, which was to utilise Perspex tubes with a tilt assembly, an internal shield to prevent reflections and a new mounting arrangement.

One reason for the Perspex was to allow for the polarising film to be installed without the distortion that would occur with a spherical dome as a cover. The new design became much larger than the original due to the extra length specified to allow the cameras to be mounted higher, in addition to the tilt assembly. During a design review, it was suggested to remove the lens and install the polarising film straight to the CMOS sensor and re-install the lens, making the polarising film integral to the camera.

This became the ideal solution as it would permit the use of a dome camera housing that would make the whole assembly more compact. The polarising film was tested on one of the old cameras, and it worked, so the final design iteration of the camera enclosure includes a plastic dome cover, and aluminium housing with integral mounting.

Fig. 14. Design iterations of the cameras housing with the final design on the right.

C. Electrical

The WAM-V's electrical system consists of two main subsystems power distribution and computer hardware, each housed in there own waterproof cases, the following sections detail the design of the two subsystems.

1) Computer Hardware: The computer hardware is mainly contained within the guidance, navigation and control payload and consists of a main computer; a Kontron miTX-E38 which runs the control, SLAM and guidance algorithms. Four Intel NUC i7's are used to process images, and output information on what has been detected as well as range and bearing to obstacles, utilising a computer per camera allows the software team to save time by not managing and assigning priority to each individual camera. A system block diagram can be seen below in Figure 15. Having five powerful computers in a confined space, requires a cooling system in order to dissipate heat and keep the system running efficiently. To achieve adequate cooling a high

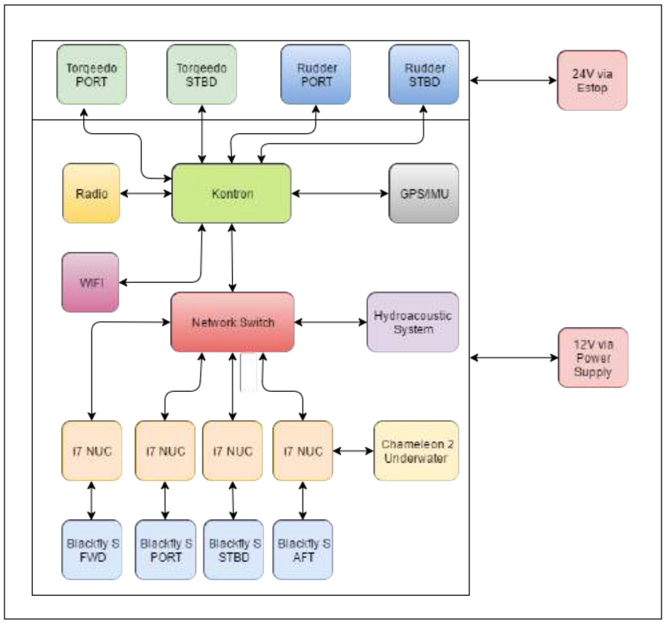

Fig. 15. Computer system block diagram.

performance computer radiator has been added to the box, with three high flow fans drawing air from the top of the box directing flow through the radiator. Water is then pumped in a closed loop system to below the water line, to another radiator.

In the last competition the team used a number of small IP68 cases in order to house computer hardware, this proved both difficult to conduct quick system tests in the lab and to work on the hardware, the Storm cases used this time (see Figure 16) offer an elegant solution to the problem and allow our computer hardware to maintained with ease.

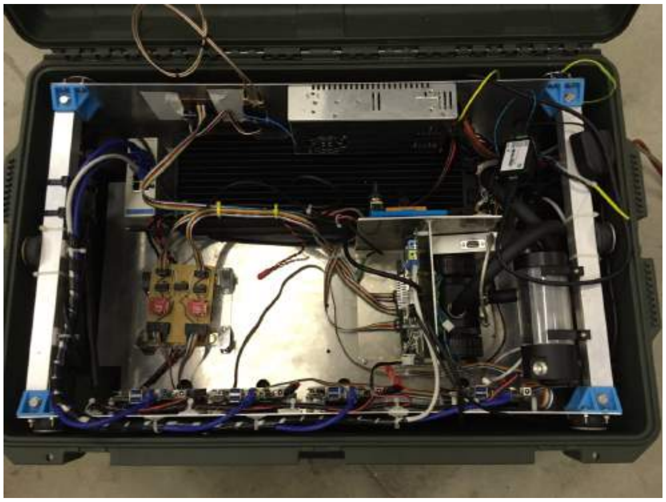

Fig. 16. Mounting configuration for computer hardware.

2) Power Distribution: The power distribution box's main function is to allow electrical isolation of the actuators, whilst allowing the computer hardware to remain active; enabling the possibility of recovering faults. A block diagram of the system can be seen below in Figure 17.

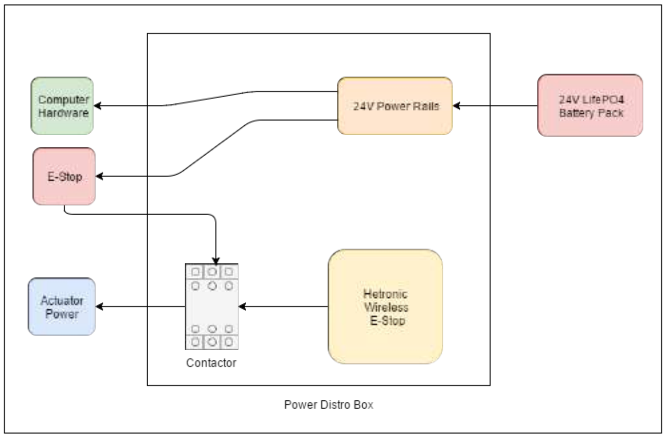

Fig. 17. Power distribution system overview.

A 24V DC contactor is controlled via the Hetronic wireless E-stop system, allowing the system to stopped at any time if control of the WAM-V is lost. The power distribution box and wireless e-stop remote are pictured below in Figure 18.

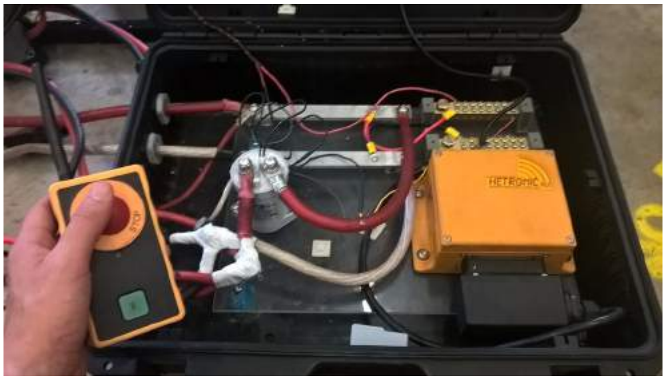

Fig. 18. Power distribution box and remote E-stop controller.

D. Software

The software architecture is NUCLEAR, developed at the University of Newcastle. Nuclear is a novel open source system to pass messages between different systems, allowing all our software to run on independent modules.

IV. EXPERIMENTAL RESULTS

1) Image Processing: To recognise objects in images captured by the cameras, neural networks were used. These were implemented using Tensorflow, using its Python API.

Initially, the main goal was to detect dark round buoys in video data obtained from a past competition. An input image is broken up into grid cells. Cells in certain positions were marked as filtered. This was done to prevent processing cells that were never of interest, such as those blocked by parts of the WAM-V, seen in Figure 19.

Then, from the unfiltered cells, more cells are generated. These cells covered the region of the image, with certain horizontal and vertical step sizes. This was done multiple times, with different cell and step sizes, illustrated in Figure 20.

Each generated cell is then passed through a convolutional neural network, which attempted to guess whether the cell contained a buoy. Predictions that exceeded a certain confidence were retained. Processing was done to remove cells that had a high enough degree of overlap with others, see Figure 21.

Each image took roughly 0.5 seconds to process. One method of speeding this up was to use a simpler network to detect cells that contained only water. Such cells would then not need to be processed using the slower convolutional

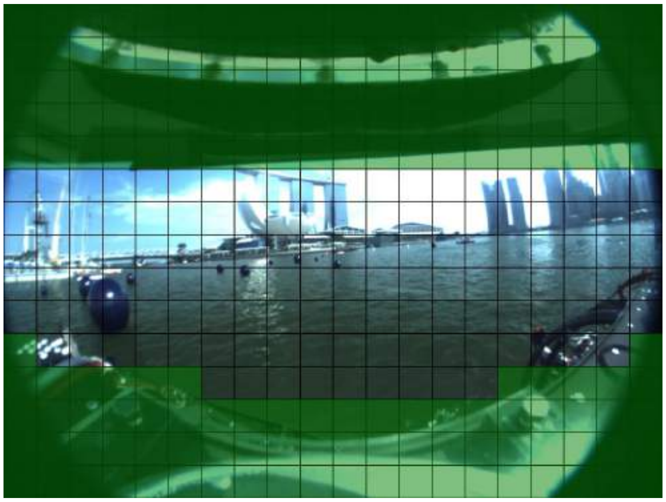

Fig. 19. Cells that contain the WAM-V are filtered and not processed, shown in green.

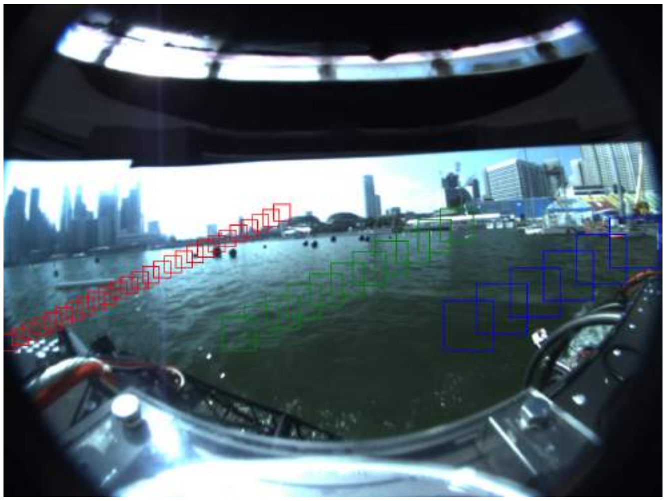

Fig. 20. Cell generation in unfiltered regions.

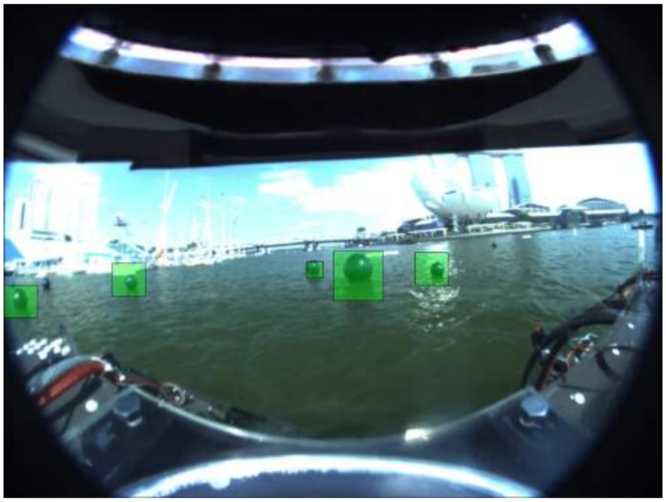

Fig. 21. Predicted cells which contain buoys.

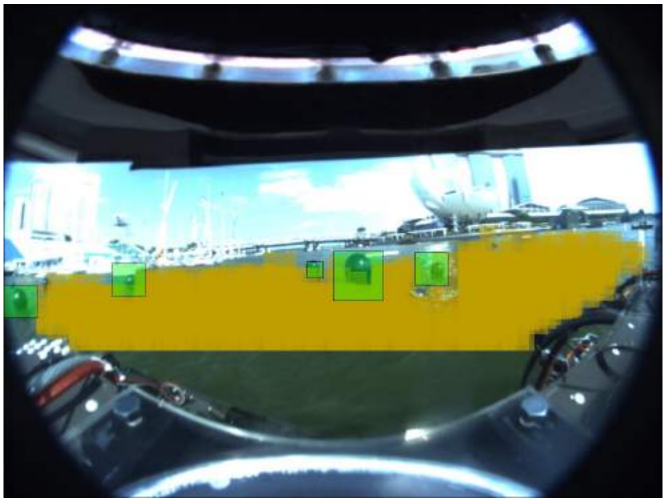

Fig. 22. Beige region represents regions in which water detected, so no further processing is done on these cells.

network.

In the above image, yellow indicates cells that were detected as only containing water. Another optimisation would be to generate fewer large cells at positions far from the WAM-V, and fewer small cells at positions close to the WAM-V. It was intended that the network would be extended to detect other objects, such as the rod-like buoys, the dock markers, etc.

2) Field Testing: During field testing a number of problems were encountered that were not present in the bench testing in the lab. These problems were present in the propulsion system, including the Torqeedos, the rudder actuators, and radio communication with the ground station. The problems were difficult to trouble shoot, because they were sporadic, sometimes one motor did not work and sometimes the other motor wouldnt work with no other changes. To correct these issues components were systematically changed or swapped with limited benefit.

The issue ended up being caused by the difference in the bench testing to the field testing. When in the lab the system was powered by a power supply unit, which meant the Kontron and Actuator power were switched on simultaneously. In field the Kontron was always switched on first, with the actuator power being turned on after with the E-stop system activation. This was causing the Torqeedo communications system to time out, and was correct by powering Actuator system prior to activating the Kontron. Another issue was reliability of the telemetry radio link with the ground station, this was found to be caused by the serial to USB converters. The USB converters were changed with a RS232 converter to take advantage of the RS232 headers on the Kontron board.

V. CONCLUSION

Using the lessons learned in the previous competition further development of the UONs RobotX WAM-V platform was performed by the participating students, with the emphasis on developing a solid platform for continued autonomous surface vehicle research projects. The key aspects were implementing a robust guidance, navigation and control system along with improved system actuation to allow for better control authority.

These successful design and implementation of the new GNC and actuators has meant that future teams will be able to concentrate on advanced behaviour of the ASV and improve the sensor systems where ever possible, with only minor planned modifications to the actuators. The modular design also allows for the same GNC system to be implemented on other research platforms.

Continued development on autonomous system research will allow for increasingly complex missions to be achieved faster and more reliably by these autonomous platforms, and ultimately allow for human error to be factored out.

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