UoN RobotX 2018 Technical Paper

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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 as the UBER self-driving trials in Pittsburgh and the publicly available Tesla Model S. The recent accidents involving autonomous vehicles further enforce the added pressure and need to develop safe autonomous systems, and competitions such as the Maritime RobotX play a large role in the maturation of these technologies and the development of safe autonomous solutions for the public.**

The Maritime Robot X Challenge 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 RobotX team was to develop a strong platform for future improvement, this was through the learnings of the previous competitions, as well as, the new ideas that were conceptualised at the beginning of the year. The Torqeedo propulsion units were re-used, while the steering system returned to a linear actuator design. The computer system maintained independent computers for the machine vision processing and the central computer remained acting as the guidance, navigation and control computer. The central computer is also used for datalogging of the IMU, GPS and LiDAR, and perform the SLAM algorithm. This computer was also responsible for the MPC trajectory planner along with control of the actuators.

The UoN RobotX ASV is a versatile platform for continued autonomous research projects and the modular design of the WAM-V payload tray allows for different payloads and sensors to be implemented in the future.

I. Introduction

The Maritime RobotX Challenge is a bi-annual competition, held in 2014 at Marina Bay Singapore, and Oahu Hawaii in 2016 and 2018. Teams must use a common platform, the 16ft WAM-V, to develop a fully autonomous system capable of completing several competition tasks. These competition tasks are designed to mimic real world applications and problems a USV may face, including navigation, docking, environmental monitoring, and obstacle avoidance.

In 2018 the University of Newcastle's WAM-V (see Figure 1) has been redeveloped to address the lessons learned from the previous competitions. This paper documents the design methodology, design iterations, and detailed solutions to the competition challenges.

Figure 1: UoN WAM-V 2018 Design.

II. Design Strategy

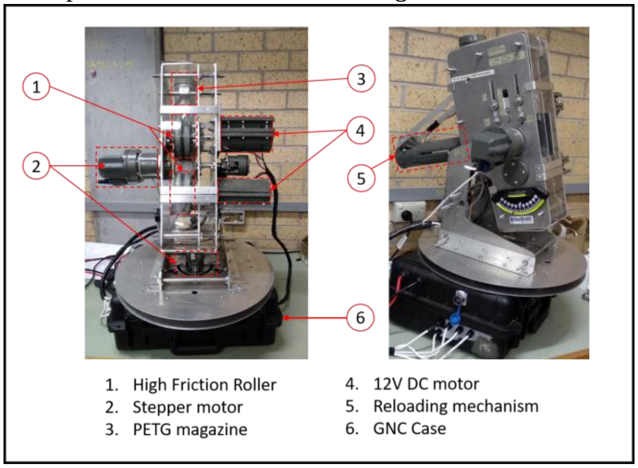
A modular design strategy was chosen for the 2018 RobotX competition, with mechanical, electrical, and software systems being broken up into a series of modules that can be easily added or removed; without the need for extensive modifications. Having a modular design enables individual system components to be developed and tested in isolation, thereby speeding up the development process of the entire system.

The majority of competition tasks require at a minimum machine vision and LiDAR. The LiDAR, Dual Heading GPS and Payload Delivery System were new additions. Due to such additions, the team is expected to achieve to following competition tasks: demonstrate navigation and control, find totems, avoid obstacles, perform payload delivery, and scan the code.

Mechanical and Electrical hardware design and implementation pushed late into 2018, significantly impacting software development and hence resulting in minimal on water testing. The mechanical and electrical design and implementation focussed on producing robust and reliable solutions.

A. Mechanical

Mechanical designs were required to have quick assemble and dissemble times. The WAM-V payload tray was redesigned, primarily to reduce the increasing number of holes per iteration of sensor mounting.



B. Electrical

The electrical system redesign strategy was to allow for the quick removal of cables if the GNC case was required for bench testing or WAM-V disassembly.

III. Vehicle Design

A. Mechanical

1) Payload Delivery System

The Payload Delivery System (PDS) consists of a single barrel two degree of freedom mechanical ball launcher. Critical design requirements identified to achieve the detect and deliver task were reliability and initial ball control.

The PDS consists of three integrated modules: launching, aiming, and control. The launching module consists of two rollers, each powered by DC motors (12V), a reloading mechanism actuated by two servo motors (7.5V), and a 3D printed PETG magazine. The two high friction counter rotating rollers (Item 1 of Figure 2) propel the racquetballs at 20m/s after being fed into the grip of the rollers by the reloader mechanism (Item 5 of Figure 2). This arrangement permits multiple balls to be launched at a maximum range of 30m, with up to 8m of ball trajectory experiencing negligible drop.

The rollers are arranged vertically rather than horizontally to increase the reliability of the reloader passing the payload into the roller grip. The vertical arrangement takes advantage of the magnus effect (backspin) which counters the effect of gravity in flight by imparting a lift force; the magnus effect contributes to the almost linear 8m trajectory reducing the complexity of the targeting algorithm.

The yaw and pitch Degree of Freedoms (DOF) are actuated using geared stepper motors; stepper motors were selected for their position accuracy. The PDS tilt pan frame is mounted to a medium sized pelican case which doubles as the PDC control box; the control box houses an Arduino with custom shield, power relay and motor drivers. The PDS is a standalone module which requires only power and target location from the main system.

The PDS mounting position was selected to maximise the field of fire. The PDS position effected the mounting position and height requirements of the Antenna module as the lowest beam of the LiDAR would detect the PDS.

Figure 2: Major components Payload delivery system.

2) Modular Rail System

The Modular Rail System (MRS) was designed using System 30, Slot 6, T-Slot aluminium extrusion; the T-Slot aluminium extrusion in Figure 3 allows standard M6 nyloc nuts to be inserted into the channel reducing cost and lead times for speciality fasteners. The MRS design was driven by the necessity to attach and secure new hardware without drilling additional holes in the WAM-V payload tray.

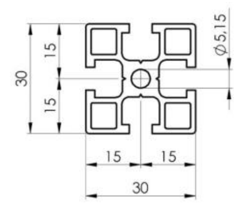


Figure 3: System 30, T-Slot Aluminium extrusion profile allows standard fasteners to be used when assembling and attaching to the Modular Rail System.

The MRS became the design base which drove the attachment design for the Antenna Mast, Ubiquiti WIFI Antenna, Hydrophone Mast, and Radiator Reservoir; Figure 4 demonstrates the Antenna Mast mounted to the MRS.

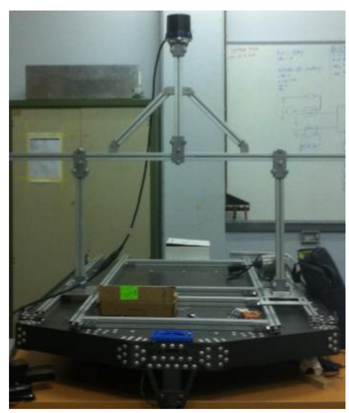


Figure 4: The Antenna Mast mounted to the Modular Rail System allowing adjustment to position without drilling new mounting holes in the WAM-V payload tray.

The MRS cross rails restrain the PDS and the Guidance Navigation Control (GNC) case in position on the WAM-V payload tray; the GNC case is secured in the centre of the WAM-V payload tray.

3) Floatation pod redesign

The 2016 competition entry suffered from large drag forces when underway, caused by a void between the pontoons and battery pods as shown in Figure 5. Flotation pod inserts were designed, verified in CFD simulation, fabricated and installed in the void between the WAM-V and the floatation pods. The inserts were made of polyurethane foam reinforced with fiberglass chopped strand mat. The pod inserts effectiveness was obvious by the level pitch when underway during water testing.

Figure 5: Floatation pod design used in the 2016 competition. A large void is present between the rear of the WAM-V pontoon and the floatation pod which produced large drag forces when underway.

4) Actuators

The Torqeedo electric outboard motors used in the previous competitions have proven to be an effective and reliable system. However, the stepper-motor based steering system used in 2016 experienced operational issues. Thus, this year we returned to a linear actuator based system (see Figure 6) similar to that of 2014. This new steering system enables a thrust azimuth of +59° / -65°. See Appendix—A for a detailed drawing.

The Torqeedo on-board computer was removed and a custom made current transducer circuit was installed in it’s place, enabling accurate current measurements to assist in thrust estimation. The design was more mechanically involved than electronically as it must preserve the enclosures IP rating (see Figure 7 and Figure 8).

5) Antenna Mast

The Antenna Mast was designed to mount the dual GPS antennas and M8 LiDAR. The design allows the GPS antennas to be spaced equidistant from the INS, and as far apart as possible, which is desired, whilst staying within the envelope of the WAM-V. The mast also allows the lowest beam of the LiDAR to clear the height of the payload delivery system, resulting in no sensor occlusion zones.

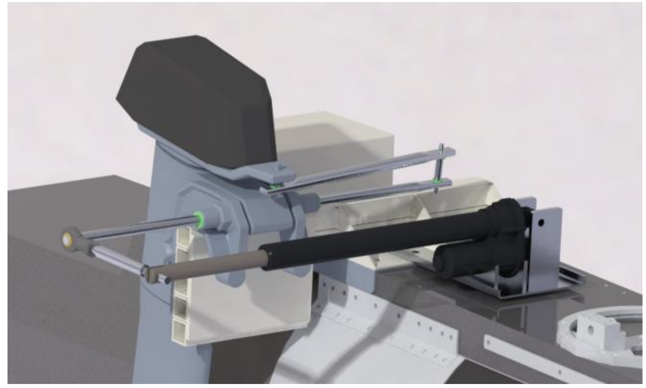


Figure 6 Linear-Actuator Based Steering System

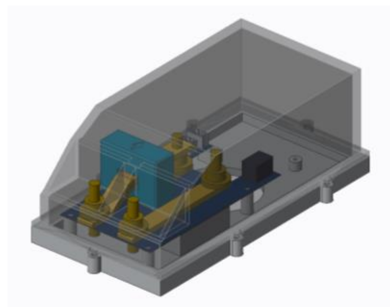


Figure 7 Thrust Current Transducer Design

Figure 8 Thrust Current Transducer Implementation

B. Electrical

1) Power Distribution

The central Power distribution box was replaced with two smaller power distribution boxes located adjacent to the motors. Each power distribution box contains the Torqeedo power E-stop isolation contactor, isolation switch, and a current transducer part of the battery management system.

2) Global Positioning System

The 2016 team had problems obtaining usable heading estimate using their GPS and IMU system, to overcome this issue a dual antenna INS, the Spatial Dual GPS from Advanced Navigation, was purchased.

The Spatial Dual can provide accurate position, velocity, acceleration and orientation data due to its combination of GNSS receiver, IMU sensor and the inbuilt sensor fusion algorithm.

3) LiDAR

The 2016 competition identified shortfalls in the teams SLAM software. LiDAR systems have successfully been used in autonomous vehicles and by other RobotX teams to provide accurate object detection and range information for the SLAM problem.

The Quanergy System M8 LiDAR is an 8 beam 360° field of view range sensor. The LiDAR completes a full scan at a rate of 10Hz, returning 400k points per second. The LiDAR is positioned at the top of Antenna Mast to avoid scanning the payload tray and attachments.

4) Emergency Stop System and Remote Control

For 2018 we sought a wireless emergency stop system with improved range, as this was an issue with our previous system, we selected the Humanistic Robotics Inc vehicle safety controller (VSC) model VSC-006 as it provides remote control functionality in addition to standard E-stop functionality. The E-stop will activate if connection to remote control, wireless E-stop, or signal board is lost.

5) Signal Conditioning and Interfacing Board

A custom circuit board was designed and fabricated to interface with actuators, multiple sensors, the safety control system, and remote-control system (see *Figure 9*). The primary motivation for the custom board was to provide accurate timestamping of sensor data as is required by both the control and navigation algorithms.

The circuit board acts as a shield that an STM32-H7 Nucleo board can plug directly into. The STM32-H7 series was selected due to both its performance and interfacing capabilities. In fact, our system requires all three onboard ADC units, 7 of the 8 available UART interfaces, the DAC unit, and the RJ45 Ethernet port.

Referr to Figure 10 for the multiple systems to which the board interfaces with, including sensors not in the figure such as steering actuators, position sensor, steering actuators current sensor, and Torqeedo current sensor. The board has been designed with expansion in mind, enabling additional LiDAR (or other NMEA 0183 listeners) to be connected, should future years desire.

As described in the communications section below the LCM framework is used for communication. As such the firmware running on the STM32-H7 broadcasts all incoming and outgoing data/signals as LCM messages. This greatly simplified debugging, testing, integration and data logging.

6) Computer Hardware

The Kontron main computer was replaced with an intel NUC i7 for increased performance and consistency of Hardware; the intel NUC i7 was also selected for redundancy as any of the four other intel NUC i7 used for machine vision can replace the main computer in the case of hardware failure.

C. Software

1) Guidance

The Guidance System uses a D*lite algorithm [1] for the path planner and a cubic Bezier spline algorithm as both the smoother and Trajectory converter.

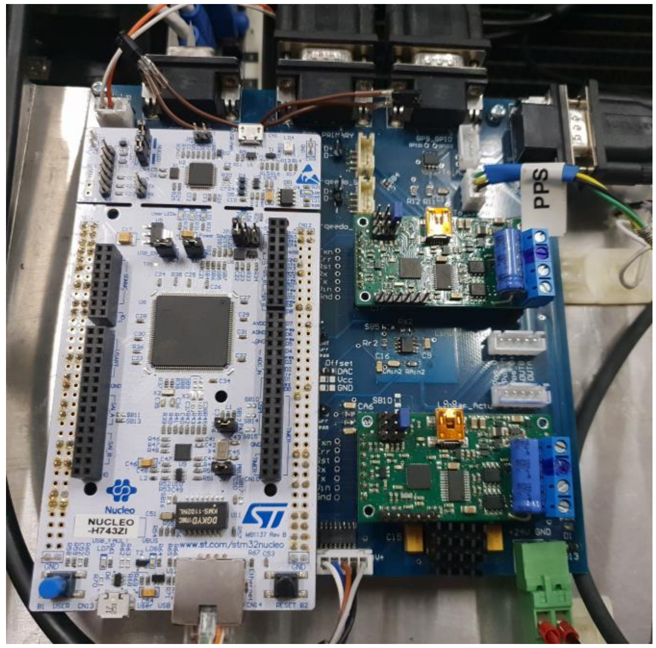


Figure 9 Signal Conditioning and Interfacing Board

The path planner uses the standard D* lite algorithm. At initialisation of D*lite, a binary occupancy map is requested from the Navigation System over LCM. When expanding each cell, D*lite first checks if the cell is occupied in the occupancy map and is only expanded if the cell is unoccupied; this replaces checking the movement cost of obstacles in the standard D*lite algorithm.

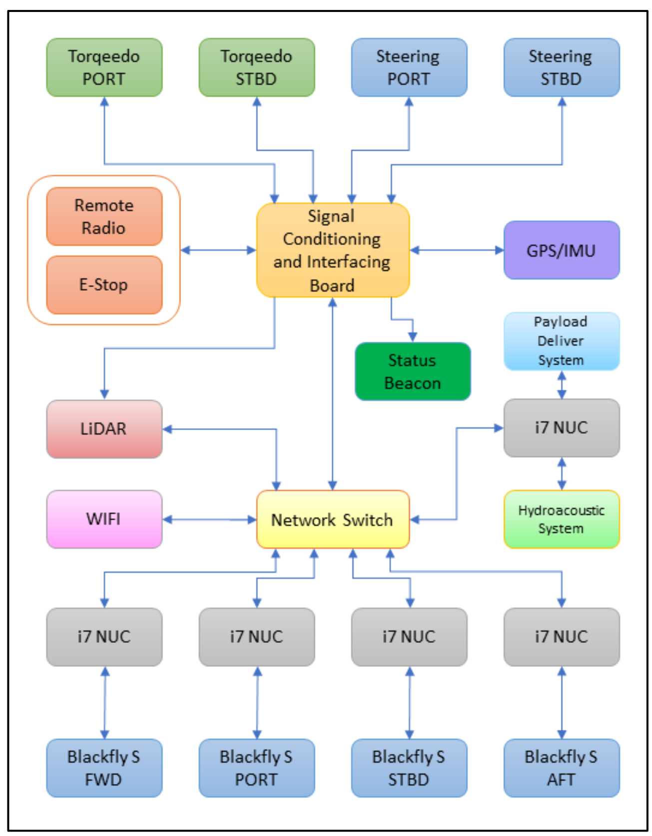


Figure 10 Computer System Block Diagram

The D* Lite algorithm was originally selected for the replanning functionality. However, the initial search is not computationally expensive on an Intel core i7 NUC therefore instead of using the replanning parts of D* lite, the initial search is rerun.

D* Lite produces a path through the occupancy map without obstacles represented as points. Producing a spline using linear interpolation does not produce a smooth path or continuous velocity profile when converted to a trajectory therefore a higher order polynomial is required. A cubic polynomial is the minimum order which can produce a continuous first and second derivative; the second derivative being the acceleration; the acceleration is continuous however the profile produced is linear.

Bezier splines are produced by stitching together Bezier curves. A nth order Bezier curve requires n+1 control points. Applying the D*lite points directly as Bezier curve control points produces a path which does not pass through each point on the path D*lite identified without obstacles. Forcing the spline to pass through each point requires calculating the Bezier curve control points where the first and nth control points are the path points.

The cubic Bezier curve was selected as the system of equations to calculate the 2-(n-1) control points produce a tridiagonal matrix which can be solve efficiently with the Thomas algorithm; higher order Bezier curves can produce smoother acceleration and velocity profiles at the cost of increasing complexity. The first and second derivatives are set equal for points 2-(n-1) ensuring smooth continuous velocities and accelerations.

2) Navigation

The Spatial dual GPS provides inbuilt data fusion and filtering algorithm for position, orientation, velocity and acceleration. The navigation system uses the LiDAR and machine vision to produce a Probability Occupancy Grid. Localisation is calculated using the GPSs dual heading for orientation and for position.

3) Perception

The machine vision system uses convolutional neural networks (CNNs), with the aid of TensorFlow. The machine vision is required to identify, detect, and classify the various buoys, channel markers, and colored shape signs.

CNNs were chosen due to the recent popularity and success of TensorFlow in aiding the design and evaluation of neural networks. They also offer a reliable method of classification, especially on simple colors and geometries like what we will encounter in the competition. Two different modes of computer vision will be used: one fast, for when reliable information is passed to the computer vision system from the lidar, and one slow, where the CNNs will be simultaneously identifying and classifying the target objects that appear the in images.

The slower classification and detection mode utilizes pre-trained models from the TensorFlow object detection API that are re-purposed for detecting and classifying the objects we want. The architecture uses the Faster-RCNN [2] combined with the Inception network design to achieve both detection and classification. This will output a bounding box that predicts the location and highest-class probability within it above a certain threshold as seen in Figure 11. CNNs are computationally expensive but work well for objects at closer distances; CNNs are not as reliable when detecting objects at longer distances.

A calibrated camera model was developed to accurately create a pixel to vector lookup table. On detection of an object, CNN converts the pixel location into a direction vector and broadcasts the vector over LCM.

The pixel to vector look up table is generated by a calibration routine. A VICON motion capture system was used to detect the position and orientation of the camera and a black and white checkerboard in camera body co-ordinates; the black and white checkerboard provides known distances when viewed through the camera. Pixel locations of the checkerboard corners represent the identical location given from the VICON system therefore a direction vector can be calculated for the lookup table; Figure 12 shows an image of the checkerboard captured with the machine vision camera during calibration.

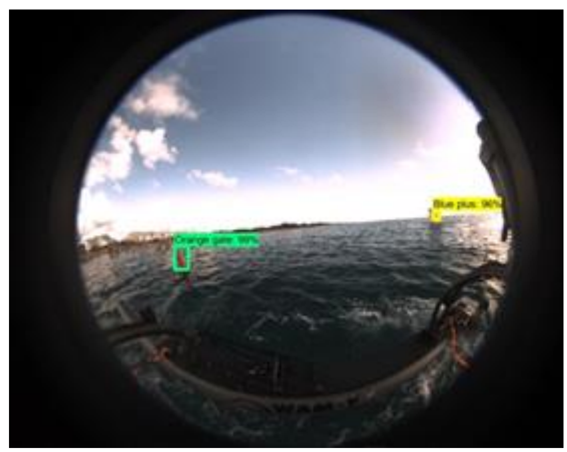


Figure 11: Object identification using a convolutional neural network where the bounding box and probability is shown.

The CNN fast mode uses a vector to an obstacle identified by the LiDAR to reduce the region of the image to classify. The CNN processes the reduced region as an object classifier. A massively augmented dataset was used to train the network to be robust to things like changes in lighting conditions and changes in orientation of the objects.

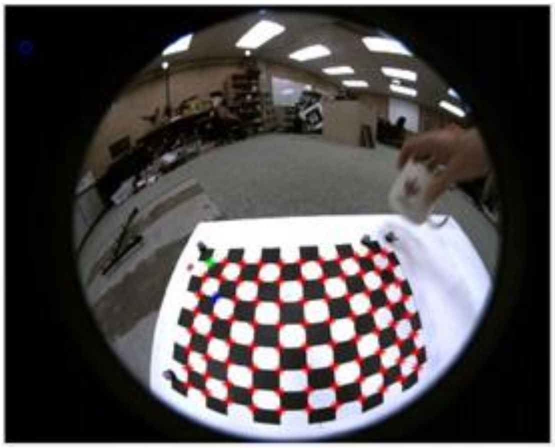


Figure 12: Camera calibration using VICON motion capture equipment.

4) 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 angle, to the vessel states; defined as positions in the local earth fixed reference frame and body fixed velocities.

5) Communications

The NUCLEAR communications software was replaced with the Lightweight Communications Marshalling (LCM). LCM is a reliable, open source, and proven solution having been used in other autonomous vehicles. LCM also provides the capability to playback recorded LCM messages over the network for offline system testing.

IV. Experimental Results

This section highlights some of the issues identified and fixed on the WAM-V.

A. Field Testing

1) Floatation pods

The floatation pod design caused large drag forces due to the cavity between the WAM-V pontoon and the floatation pod during the 2016 competition as per Figure 2. The floatation pod insert design effectively reduced the drag forces during water testing resulting in a more level pitch when underway.

Figure 13: Large turbulence caused by inefficient floatation pod design.

The floatation pods house the WAM-V batteries which used a hard rubber seal to prevent water ingress through the lid. When vacuum tested, the floatation pod would not hold a vacuum therefore the rubber seal was replaced with a silicon seal; subsequent vacuum testing was successful and no water ingress was sighted after water testing.

2) Signal Conditioning and Interfacing Board

Testing of the Signal conditioning and interfacing board identified the RS485 transceivers on the board and the Torqeedo RS485 transceivers are prone to failure from faults (open circuit, short circuit) on signal lines; Six RS485 transceivers in total failed and were replaced with fault protected RS485 transceivers.

The thruster current transducer circuit induced significant noise on the Torquedo RS485 communications. The issue was solved by using a common earth reference for both the RS485 and current transducer circuit.

V. Conclusion

The UoN RobotX WAM-V has been redeveloped using lessons learned from previous competitions. The redevelopment was performed by the UoN RobotX team with the intent of developing a strong platform for future team members to build upon. The 2018 team focused on accurate signal and data processing, and improved steering actuation.

VI. References

[1] S. Koenig and M. Likhachev, “D* Lite,” *Association for the Advancement of Artificial Intelligence,* pp. 476-483, 2002.

[2] S. . Ren, K. . He, R. B. Girshick and J. . Sun, “Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks,” *IEEE Transactions on Pattern Analysis and Machine Intelligence,* vol. 39, no. 6, pp. 1137-1149, 2017.

VII. APPENDIX—A