RESEARCH PROJECT IN MECHATRONICS ENGINEERING

On the Development of Open-Source, Low-Cost, Waterjet-Powered Robotic Speedboats for Education and Research

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Project Report ME001-2021

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ON THE DEVELOPMENT OF OPEN-SOURCE, LOW-COST, WATERJET-POWERED ROBOTIC SPEEDBOATS FOR EDUCATION AND RESEARCH

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ABSTRACT

Autonomous boats can have a plethora of applications related to sealife and pollution monitoring, search and rescue, border patrol, inspection of internal waterways and the open ocean, among others. Moreover, the design, development, and control of such platforms poses some excellent engineering challenges related to mechanical design, autonomy, robustness, ability to perceive and navigate the highly dynamic and unstructured turbulent water environment, etc. In this paper, we focus on the design, development, and experimental validation of open-source, low-cost, waterjet-power robotic speedboats for education and research. The proposed speedboats are developed based on a modular hull and a waterjet propulsion system that are both 3D printed. The speedboat design is easy to replicate and maintain, and it can accommodate all the sensors needed for autonomous navigation, such as, LiDAR, monocular vision, GPS and more. Water-jets allow the platform to: i) operate in shallow waters, ii) reduce the risk of entanglement, and iii) reduce any risk of injury to users or sealife. The efficiency of the speedboats has been experimentally validated through velocity, thrust, and efficiency testing and real-world deployment. The designs are disseminated in an open source manner and they are accompanied by a speedboat racing competition that involves both dynamic and static events. These resources are expected to be valuable for robotics researchers and for lecturers that want to introduce hands-on assignments in courses related to robotics and autonomous systems.

DECLARATION

Student

I hereby declare that:

1. This report is the result of the final year project work carried out by my project partner (see cover page) and I under the guidance of our supervisor (see cover page) in the 2021 academic year at the Department of Mechanical Engineering, Faculty of Engineering, University of Auckland.
2. This report is not the outcome of work done previously.
3. This report is not the outcome of work done in collaboration, except that with a potential project sponsor (if any) as stated in the text.
4. This report is not the same as another persons report, thesis, conference article or journal paper, or any other publication or unpublished work in any format.

In the case of a continuing project, please state clearly what has been developed during the project and what was available from previous year(s):

Signature:

Date: 15/10/21

Supervisor

I confirm that the project work undertaken by this student in the 2021 academic year is / is not (strikethrough as appropriate) part of a continuing project, components of which have been completed previously. Comments, if any:

Signature:

Date: 15/10/21

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Glossary of Terms

Autonomous Control	The ability to perform under significant uncertainties in an environment and correct system failures without external intervention
Cavitation	A phenomenon where the static pressure of a liquid goes below the liquid's vapour pressure resulting in the formation of small vapor-filled cavities in the liquid
Planing	When a boats weight is mostly supported by hydrodynamic lift, rather than hydro-static lift

Abbreviations

BOM	Bill Of Materials
CAD	Computer Aided Design
DoF	Degrees of Freedom
ESC	Electronic Speed Controller
FDM	Fusion Deposition Modeling
GPS	Global Positioning System
IMU	Inertial Measurement Unit
LiDAR	Light Detection and Ranging

1. Introduction

With the majority of the world consisting of waterways and open ocean it is important that they are well researched, monitored, and protected. Several companies have focused on the development of unmanned marine vehicles that rely on classic or renewable energy sources (e.g., wind powered) and that can monitor the oceans autonomously. This has allowed, among others, tracking of sea life and assessing the impacts of climate change. In New Zealand and the Pacific Ocean in general, autonomous boats are becoming a key part of maritime units that monitor unmarked vessels and ensure marine laws are upheld. These boats can operate 24/7 and can be placed in dangerous situations without endangering human lives. Rivers throughout New Zealand have also been degrading in water quality due to farmland run off and rubbish dumping. The NZ Police and Department of Conservation have attempted to enforce regulations but there are too many waterways for them to look over and monitor. Therefore, having autonomous boats that can independently monitor these rivers is of paramount importance.

Another potential application of autonomous boats and speedboats is searching for survivors and providing lifesaving vests or other inflating devices to people stranded out at sea due to capsized or damaged vessels. Autonomous speedboats will be able to reach the survivors faster as they can be docked at solar powered buoys or lighthouses and can be deployed as soon as a call is received. For such applications to be successfully demonstrated more research needs to be done into such autonomous platforms. When developing autonomous systems, consideration for the system to be safe to operate and to not damage its environment or harm any bystanders is crucial. Therefore in autonomous boats it is common to find the use of various sails for propulsion such as [11], [12]. The safety benefits of these solutions are quickly outweighed by significant disadvantages, such as, the fact that their control is relying on external, environmental conditions. An alternative solution that is safe, yet allows for total control, is a waterjet powered propulsion system that protects the impeller in an appropriate housing, reducing any chance of entanglement. This has been explored by [13] and other commercially available solutions.

An important question is how can we speed up innovation in the field of autonomous boats? A solution that has proven to work in other fields is through competitions. Humans have an innate desire to compare themselves to one another making competitions an effective tool for encouraging students to participate in furthering research and development of systems. Competitions have been traced through all cultures which proves their effectiveness and importance in education [14]. Data presented in [15] has shown that students who took a test before and after participating in RoboFest (an autonomous robotics contest) ended up with higher scores in a STEM assessment afterwards.

In this paper, we focus on the development of open-source, low-cost, waterjet-powered robotic speedboat platforms for both education and research. The proposed platforms are depicted in Fig. 6. The total cost of the platform is $1,300 USD (see Table I). The remainder of this paper is structured as follows: Section II describes related work, Section III presents the designs, Section IV discusses the experimental validation, Section V details the proposed competition, while Section VI concludes the work and discusses some future directions.

2. Related Work

There is a range of autonomous vehicle competitions globally however, very few are low cost and even fewer have open source starting platforms, therefore in most situations the community can't get involved .

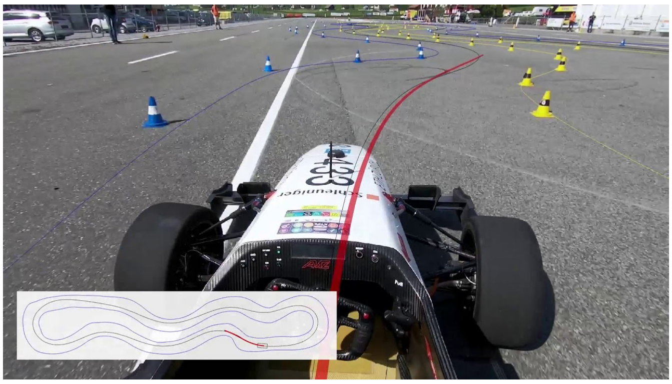

Figure 1 AMZ on board with overlay from navigation system which receives data from an on board LiDAR and stereo cameras [1].

Formula Society of Automotive Engineers (FSAE), is a global competition where university teams are required to design and build a single seat race car and compete in several static and dynamic events [16]. All the dynamic events are performed with one team at a time with no wheel to wheel racing [17]. The events are designed to test all aspects of their designs in a safe environment. Static events are designed for teams to explain their design process and design decisions, judges from industry provide feedback to these teams whiling scoring them on their competence. Competitions in Europe included FSAE autonomous into its competition from 2018 where teams must build an autonomous car on an electric platform. The car has similar restrictions in terms of design to the regular electric cars besides it can't have a human driver and must be SAE level 4 autonomous [1]. This means it must be capable of operating in an emergency or bad weather without any human intervention. In industry this has only recently been achieved, so it is an extensive task that makes it very hard for teams to get to competing level. To make the dynamic events more achievable the courses are set up with yellow cones on the right-hand side and blue cones on the left hand side which gives the car a reference of where it should be, figure 1.

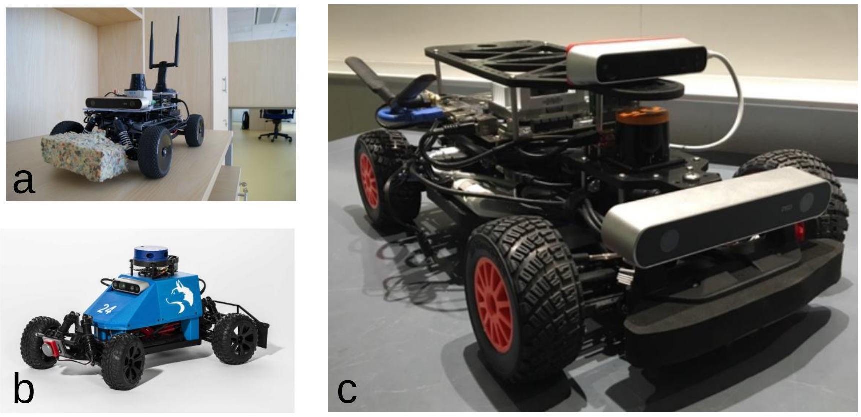

Figure 2 Subfigure a) presents an autonomous platform by f1/10 [2], subfigure b) presents an open source platform for research by Mushr [3], while subfigure c) is a platform built for MIT undergraduate courses [4].

Both Fig. 2b and 2c are both open source platforms that are designed to allow undergraduate students and researchers have a platform for further research. Fig. 2b is half the price of figure 2c due to it being released a few years later where technology prices had dropped due to increased competition. This platform is only $1000 USD which makes it a very accessible.

There are several competitions that are based around scale models to make the competition more accessible. Scale models allow similar dynamics of the system but are much easier to work with due to their reduced size and are seen in figure 2. This leads to smaller actuators and reduced requirements on sensors making the entire system cheaper. Competitions such as F1/10 use a 1:10 scale model of an everyday car making them roughly 300mm long [2]. The reduced size allows for competition tracks to be made indoors that are scaled down from an actual motor-sport track. Teams are required to build their model from a set hardware and sensors which helps level the playing field between teams. The tasks include completing the course in the fastest time on and open track.

Wheel to wheel racing is also seen with [18] where they propose one on one racing with their 1:43 scale model cars. With the ability to control the cars from an external camera and computing power. This competition would be purely based on software and algorithm design since the hardware and sensors is one setup that all competitors use.

Simulation competitions have a unique advantage where it can be easily and effectively modelled after games to make it more interesting and producing more "admirable videos" [19]. To increase the realism of the competitions they are built on top of physics engines that have been made to model the physics of reality. These environments allow for extensive testing and have no limitations to what competition events can be. A number of competitions have been built on TORCS where teams are required to design the algorithms to complete the set race track [20] [21]. The Simulated Car Racing Championship is a competition where competitors can design their system and test it on the test tracks provided. Once they are satisfied with their design it can be entered into a race. The race is not run in real time as all the designs are loaded in, then run once the outcome has been computed [20].

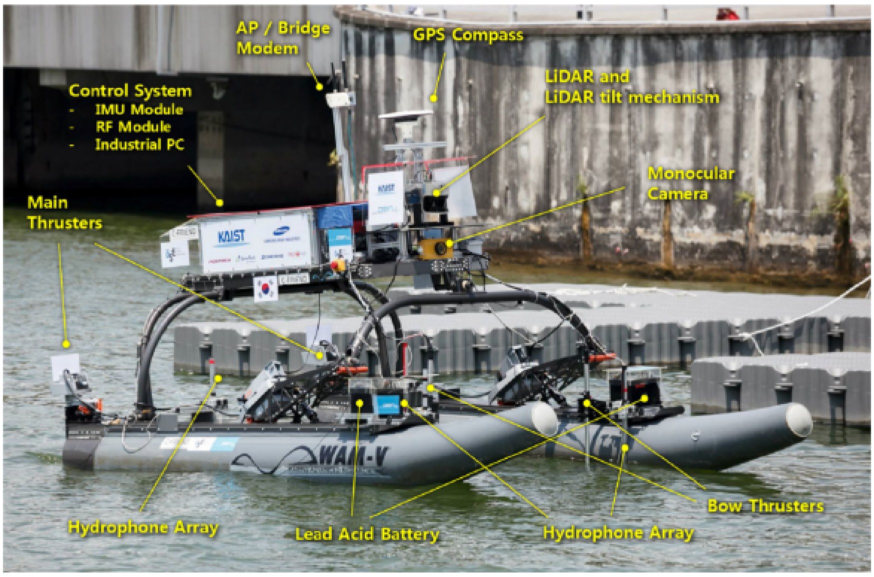

Figure 3 The provided platform for the RobotX competition with additional components added by the competing team such as a LiDAR, camera and batteries [5].

Regarding boat competitions, a strategy used by the RobotX competition is that all teams are required to use a set platform that is supplied by the organisers for the competition seen in figure 3. This ensures that all contestants will have consistent hardware and will only be limited by their sensing and perception (software) capabilities. The supplied monohull boat platform is roughly 5 m long and 2.5 m wide which requires a boat trailer to move it around and to take it to the testing site [5]. Moreover, the cost of additional components is well over $5,000 USD.

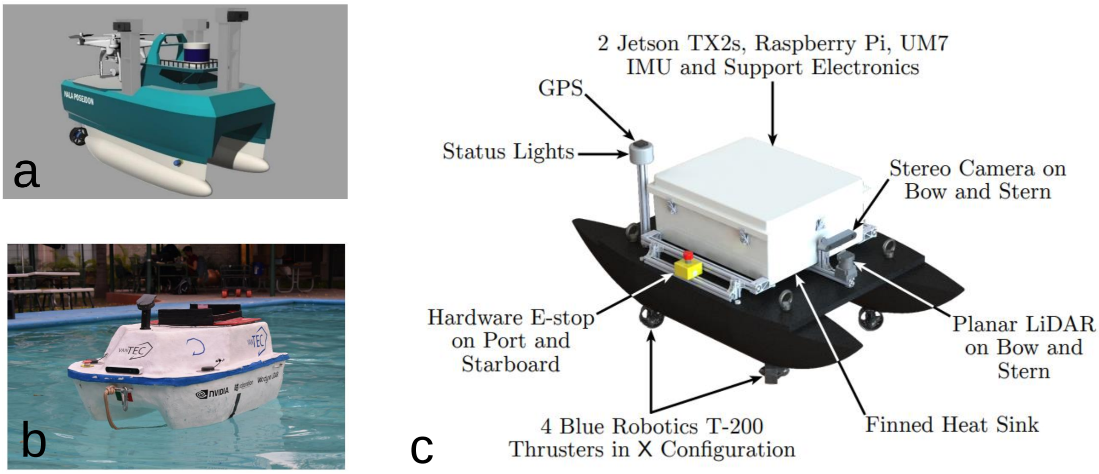

Figure 4 Multiple RoboBoat platforms are shown with subfigure a) being a CAD model of their proposed platform [6], subfigure b) is a completed platform by Barunastra ITS [7], while subfigure c) is a basic platform that highlights the use of off the shelf components [8].

RoboBoat a similar autonomous boat competition that has taken a more open approach as teams must propose solutions that respect the imposed length, weight and power constraints [22]. These custom built vessels are still expensive, costing at least $3,000 USD to build a competitive platform are seen in figure 6. The only low-cost platform that could be used for such competitions, is the micro Unmanned Surface Vehicle (USV) platform that was proposed in [9] seen in figure 5. This platform has been designed to operate in indoor laboratory environments. It is built using 3D printed and off-the-shelf electronic components, it is very small (23 cm long), inexpensive (costs 320 USD per unit for 10 vessels), and an excellent platform for algorithm validation in an indoor environment.

Figure 5 A 3D printed USV platform designed for indoor swarm research [9].

Unfortunately, to the best of our knowledge, in the field of autonomous boats there is no open-source platform with a cost <1,000 USD that can offer multiple engineering challenges related to mechanical design, autonomy, perception, and control like the Mushr platform does in the field of car racing platforms [3] seen in figure 2b.

3. Design

The designed platform and test bed are shown in Fig. 6 with the flaws of the test bed hull explained. The proposed platform is then broken down into four main subsystems: i) the hull, ii) the propulsion system, iii) the power-train electronics compartment, and iv) the sensing and processing components compartment.

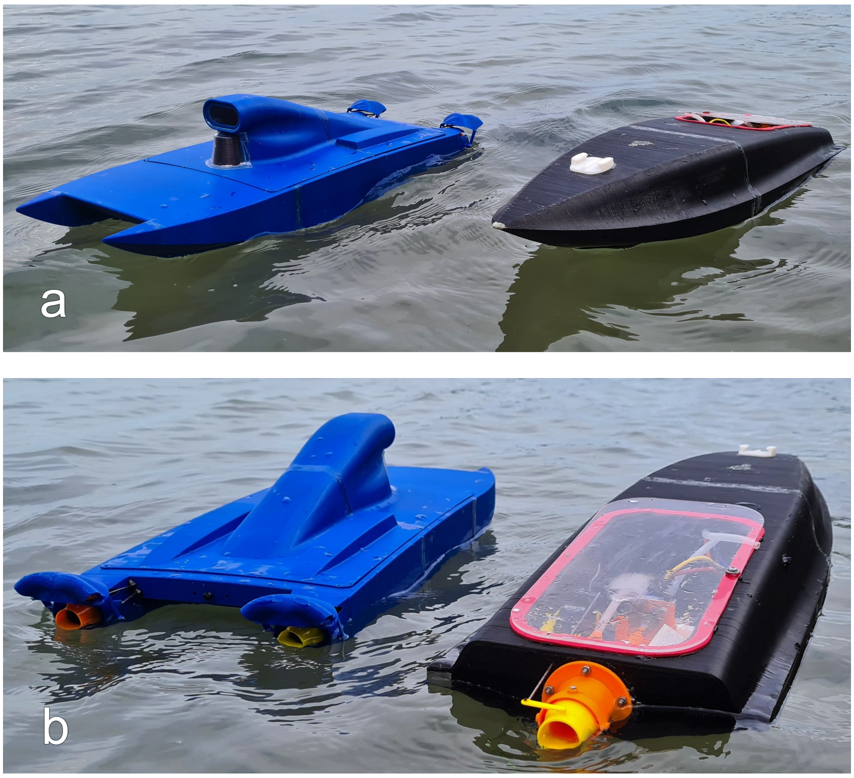

Figure 6 The proposed open-source, low-cost, waterjet-powered robotic speedboats are presented. Subfigure (a) presents the front view and subfigure (b) the rear view of the robotic speedboat platforms that have been developed for this work. The black speedboat is a monohull version that has been designed and developed for testing of the waterjet module. The blue speedboat is the final catamaran version that is equipped with two waterjets.

3.1 Hull

Hull design is crucial as it is the housing of the electronics and is responsible for the protection of all the electronics and provide stability and planing capabilities for the propulsion system. Planing is needed to reduce the wet surface of the hull which reduces the overall drag, this increases the speed of the boat increasing the efficiency of the jet. In terms of possible hulls, there are three options being monohull, catamaran and trimaran. As stated by their names each one results in an increase in total hulls that are joined by bridges.

3.1.1 Monohull

It was the easiest to design and implement as it was only one hull and therefore only required one jet propulsion system figure 7. The boat was capable of rolling as the vectoring nozzle rotated which reduced the turn radius of the boat making it very maneuverable. However due to its roll it produces an unsteady surface for the camera and LiDAR which results in unusable footage and LiDAR data. Therefore it was used to validate that a 3D printed hull would be durable, buoyant and waterproof enough. It also allowed for testing of propulsion systems on open water in dynamic testing rather than just stationary.

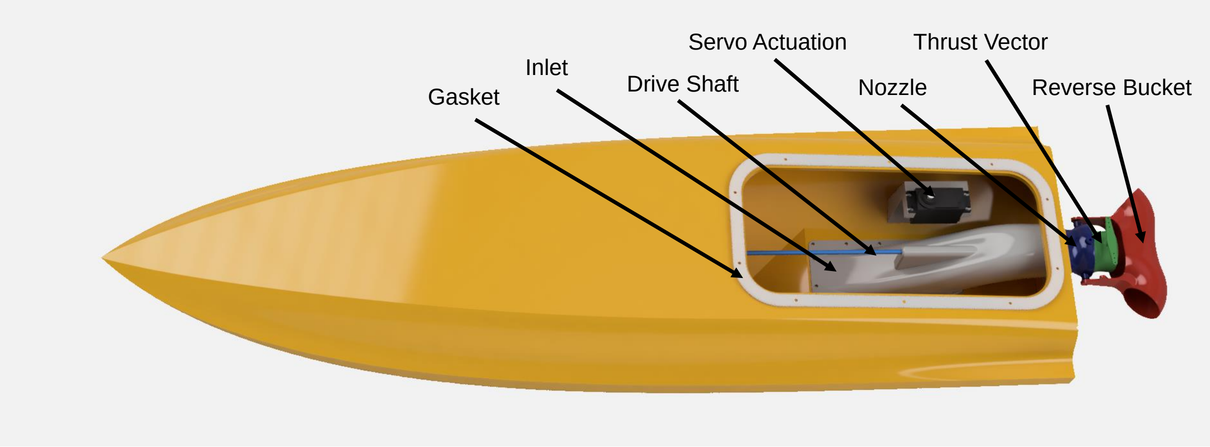

Figure 7 The test bed was a monohull robotic speedboat which was used to test initial designs of the waterjet system such as the steering actuation of the thrust vector and inlet and nozzle geometry.

3.1.2 Catamaran

This design is seen in Fig. 8 is the catamaran and consists of two hulls that are joined together by the central bridge. The major advantage of this is that when the boat performs a turning maneuver there is very little roll due to its stable base compared to a monohull. It also allows for more innovative forms of propulsion systems to be used that can increase overall maneuverability of the boat. On this boat a dual jet propulsion system was selected that allowed the boat to rotate through differential thrust and thrust vectoring which is explained further in the propulsion system.

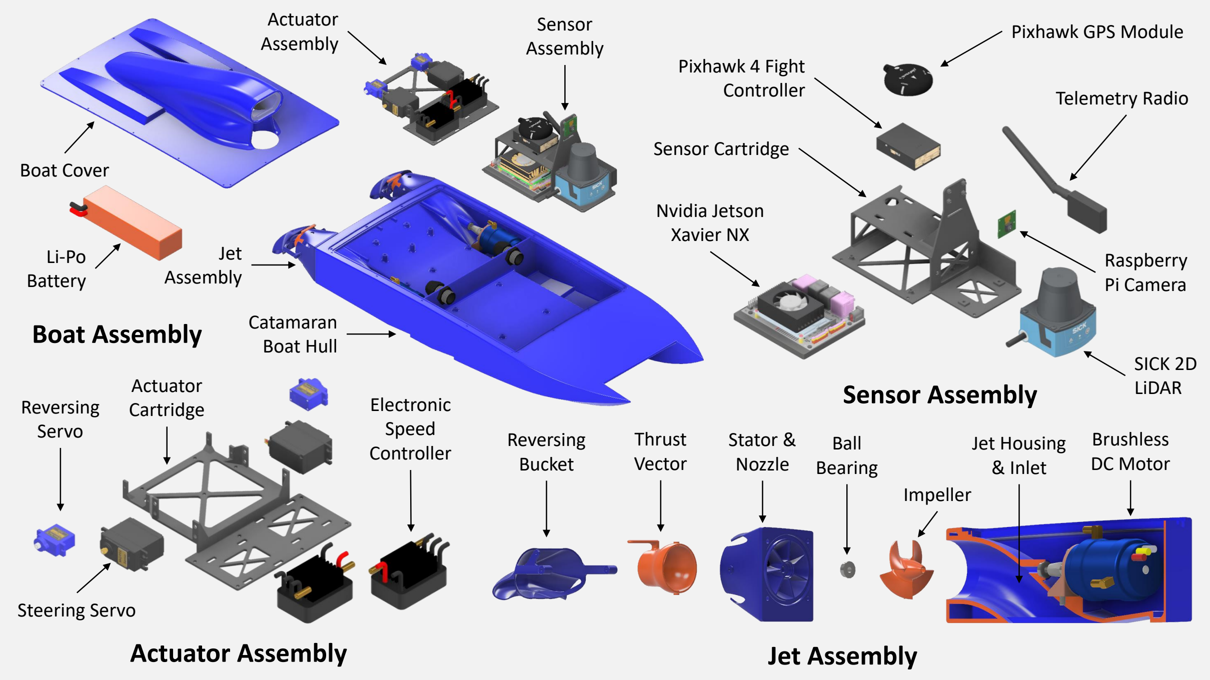

Figure 8 Exploded view of the proposed catamaran robotic speedboat which the system broken down into smaller sub systems such as actuator and jet assembly.

In terms of component placement there are two main sections with waterproof equipment in the rear compartment alongside the motors and ESC that are water cooled along with the actuation servos for the propulsion. The front section is the dry area that contains all the components that can't get wet at all. This includes the batteries that are placed in the fronts of the hulls on opposite sides to maintain stability. The LiDAR and camera are placed at the front for increased visibility and the flight controller and micro-controller are placed centrally.

In terms of the form of the hulls seen on the catamaran they are designed with two main criteria in mind; speed and stability. To increase the overall boat speed the hull efficiency is considered which involves decreasing wetted surface area and wave making [23]. To do both of these moving from a displacement hull (monohull) to a planing hull both these components are reduced. Its even more prominent with a hydro filing hull but due to their complexity they are not explored. In regard to stability this is determined by the size and weight distribution of the boat. Increasing length and width would increase overall stability but at the cost to maneuverability. To determine these dimensions it was mostly due to the limitations of available 3D printers. This caused the maximum width of the catamaran to be 250mm with the overall length roughly 600mm. To get this length multiple segments had to be printed and attached to one another.

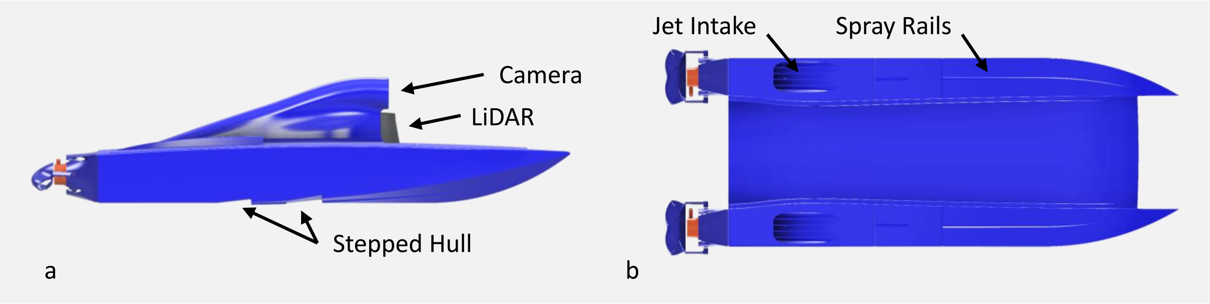

Figure 9 The proposed catamaran hull is shown in multiple views. Subfigure a) side view with stepped hull features visible while subfigure b) is the bottom view with jet intake and spray rails depicted.

In figure 9 extra design features can be seen such as the stepped hull which helps the hull begin to plane while reducing wetted surface area and maintaining stability. The spray rails are used to add additional buoyancy to the hull but also divert water away from the sides of the boat to allow for improved efficency at higher speeds.

3.1.3 Fabrication

The hull needs to be manufactured in a way that is easily repeatable by the competing teams and is low cost so more money can be put towards the electronics and vision components. Therefore 3D printing was explored as it is currently the most common manufacturing machine between all Universities and researchers. There is a range of 3D printing methods available and print bed sizes. At Auckland University the leading printer is the Prusa I3 Mk2. This is an FDM printer which uses the cheapest print material PLA which is actually strong enough for this design and is waterproof without any extra treatment. The constraints of the printer bed size are 250 mm x 210 mm x 210 mm 3D printer bed so the hull was split into multiple sections 10 that could be printed independently and assembled afterwards using five minute epoxy. As seen above the jet inlet was printed as part of the hull which meant that the design is fixed but due to the limited size of the hull, a modular option wasn't possible.

An alternative option is composite manufacturing which offers superior strength, rigidity, and waterproofing which is why it is very common with full size hull construction. Usualy it is a combination of fibres with a resin matrix to allow for high tensile strength but still maintaining strength ion compression and torsion. In order to build a hull using this process it is much more complicated that just 3D printing it. It would required specific moulds to be made by either CNC work on a wooden block or 3D printing them but this can cause

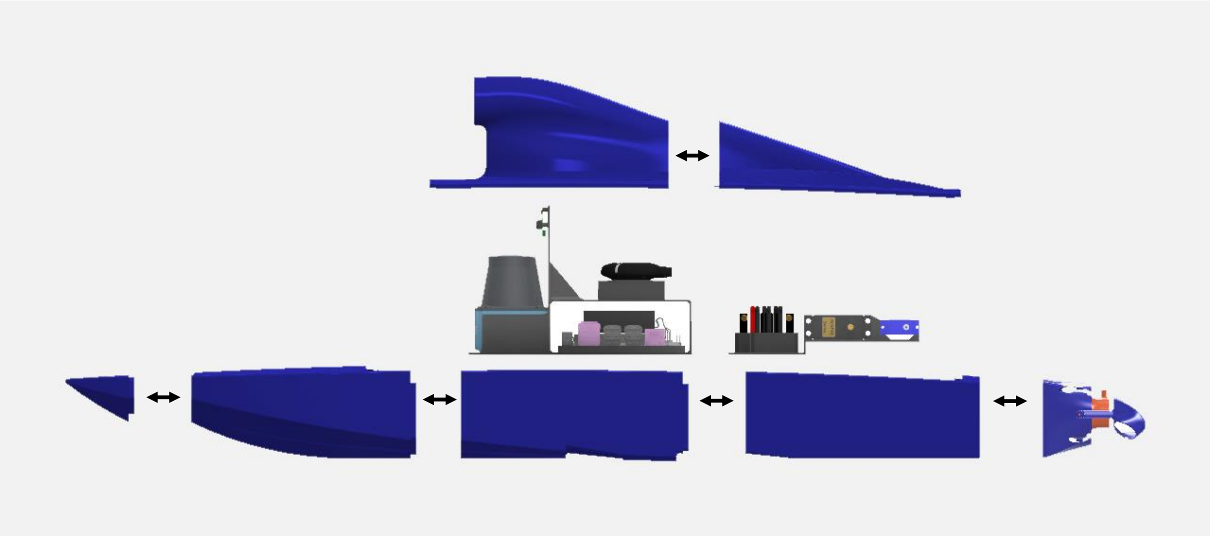

Figure 10 The platform's hull is printed in 6 core sections that fit independently on a standard bed size of a FDM printer such as the Prusa Mk2 I3.

problems such as poor surface finish [24]. After this they would still need to be laid up with the fibres and resin and then vacuum sealed to insure an even mixture then heated to cure the resin.

3.2 Propulsion

Propellers are the most commonly used propulsion systems on unmanned surface vehicles. This is due to the simplicity of their design and implementation, however, they offer no protection to their surroundings. A simple duct can be added to protect the blade tips while offering some protection to users, but it doesn't reduce the chances of entanglement. Therefore it was decided that waterjets would be the ideal solution as they are inherently safe, allow for operation in shallow waters, reduce the risk of entanglement with ocean algae, are more efficient than propellers, and provide a range of design optimisation options. The design is based off an axial flow pump following a standard pump curve. As seen in Fig. 8 it is made up of a number of features these being the inlet passage, impeller, nozzle, and thrust vectoring components. Additional features are added such as an o-ring to reduce pressure loss and bearings to reduce friction. Within these there are more features that can be modified to vary pump performance to suit the user or task requirements.

3.2.1 Inlet Passage

The inlet length and inlet angle have been optimised Fig. 11 to reduce the overall inlet swirl and wall cavitation based on findings of [25]. This was done by having an inlet angle of 30-35 degrees which still leaves room for mounting a range of motor sizes. After the inlet angle, enough length is needed to house an impeller to ensure a very close fit to improve pressure differences. At the base of the inlet, a slight curvature prevents flow separation which further increases hydraulic performance [25]. The diameter of the inlet was restricted to 40 mm as if it gets smaller than this efficiency will drop significantly due to the fixed hub size and increased overall friction on the flow.

3.2.2 Impeller

The impeller has a number of key features, these being the number of blades, blade pitch, hub diameter, and the overall length. These measurements are best determined from

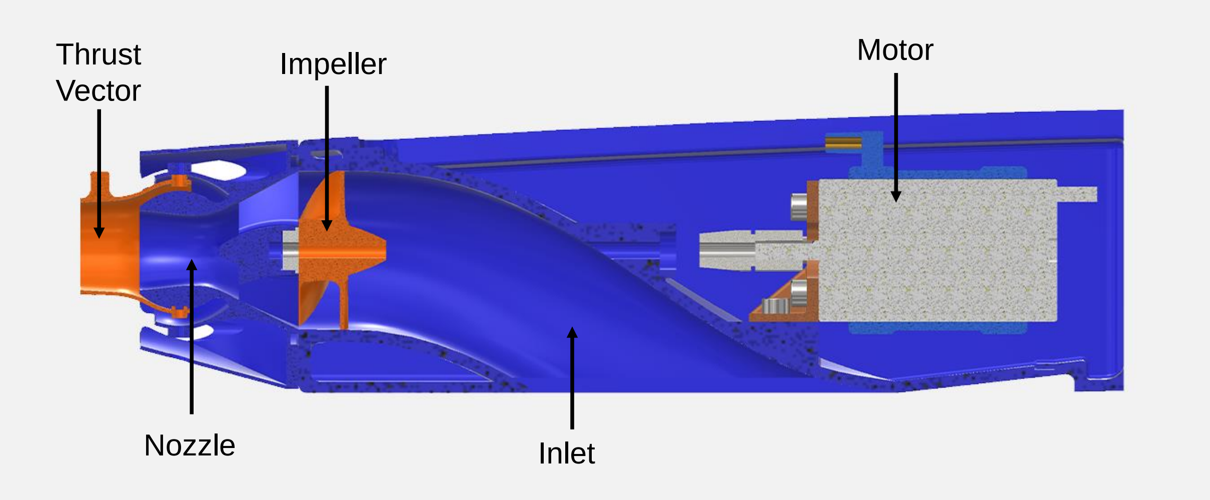

Figure 11 A cross-sectional view of the jet assembly which shows the geometry of the inlet along with the reduction in area seen at the nozzle exit.

experimental testing due to their performance being very dependant on the other features of the waterjet system. Therefore the design was made with the ability to easily change these features and test them. The impeller is printed with a D-slot that fits onto the key of the shaft. The equation for waterjet thrust (T) is given by

$$T = \rho Q(v_j - v_m), \tag{1}$$

where ρ is related to the density of water (1000kg/m^3), Q is the flow rate of the waterjet, v_m is the inlet velocity, and v_j is the waterjet exit velocity. The inlet velocity is given by $v_\mathrm{m} = 4Q/(\pi {D_\mathrm{m}}^2)$ and the exit velocity is given by $v_\mathrm{j} = 4Q/(\pi {D_\mathrm{j}}^2)$, where D_i is the impeller diameter and Dj the nozzle exit diameter. The jet ratio a [26], is given by

$$a = \left(\frac{D_m}{D_j}\right)^2, \tag{2}$$

while combining Eq. 1 and Eq. 2, we get

$$T = \rho Q v_m (a - 1) \tag{3}$$

which connects changes made to the impeller and nozzle design to their impact on thrust. Increasing the number of blades reduces the amount of flow separation on the blades, which increases the amount of torque transmitted to the flow therefore, increasing thrust. Efficiency also improves due to more of the flow being in contact with a blade which reduces turbulence in the flow [27]. However, after a point, efficiency decreases as friction of the blade surface increases to the point where it outweighs the benefits previously mentioned [28]. Increasing the size of hub diameters increases pump efficiency at lower mass flow rates by the majority of the work done on the flow being centripetal. It is also increases the inter-row meridional velocity, which leads to more axial flow downstream [28]. With a smaller hub diameter it is more efficient at higher flow rates, increasing the throat area which reduces the frictional losses. With changes to pitch the flow rate of the system increases, but it requires more torque from the motor, and therefore greater current draw. If not balanced correctly, it leads to a decrease in efficiency, so the ideal pitch is found from testing with the specific motor and nozzle design.

3.2.3 Nozzle

The design of the nozzle has two key features, the guide vane design and the reduction in area from the impeller to the outlet Fig. 12. The guide vanes (stator) have the purpose of converting rotational flow to axial so as to improve the performance of the waterjet and increase flow rate. Guide vanes can vary in length and number. The number of vanes is best determined by the number of impeller blades as the two can have adverse affects such as resonance [29]. In terms of reduction area, the greater the reduction the greater the change in velocity and pressure and therefore the increase in thrust. However, motor limitations lead to the flow rate and efficiency decreasing therefore there is a balance between impeller pitch and nozzle reduction [26]. All features can be modified and attached to the inlet with four simple bolts that attach to the inserts of the hull, as shown in Fig. 8.

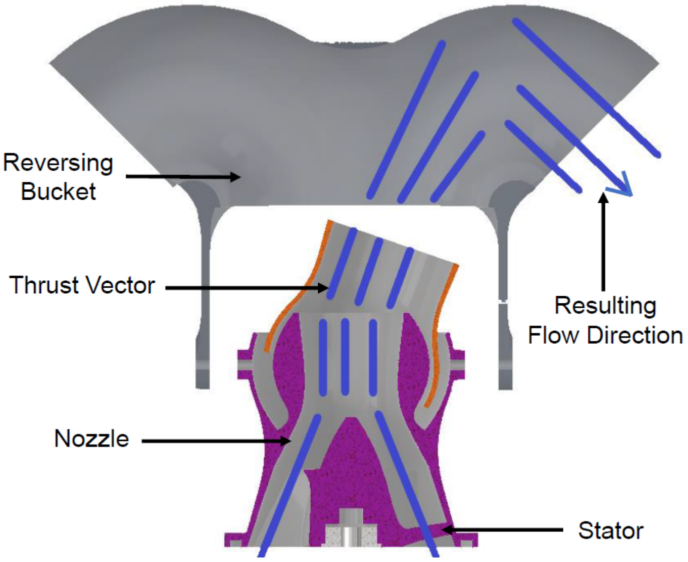

Figure 12 A cross-sectional view of the thrust vectoring system when the reversing bucket is lowered.

3.2.4 Thrust Vectoring

Waterjets provide a force in line with the inlet which allows the hull to be propelled forwards, however, for it to turn the thrust needs to be vectored. This is done using the thrust vector shown in Fig. 12 with a rotating section that is controlled by a servo. It has 60 degrees of rotation, with 30 degrees in each direction, allowing the hull to rotate. Waterjets aren't capable of running in reverse, therefore a reversing bucket was designed. This redirects the thrust so as to allow the platform to reverse but also steer with the bucket redirecting flows at a 45 degree angle. It also forces the water down at a 45 degree angle to prevent the buckets pulling the boat down.

3.3 Control and Sensing Hardware

The hardware for the platform are all the components required for autonomous control. These include a LiDAR and monocular camera for vision, a GPS and an IUM for pose estimation. Using the combined data in a specialised processing unit motion planning can be determined with the desired control being sent to the flight controller. This controller then distributes the control outputs to the electronic speed controllers, servos and then to the motors seen in figure 13. Everything is powered through lithium polymer batteries in this case 3S however if more thrust is desired 4S or 6S can be used.

Specific Hardware Selection

$$RPM = Kv * V_{Battery} \tag{4}$$

The motor was selected using equation 1 which determines the RPM of the motor at different Kv ratings and Battery voltages. To ensure the propulsion system would not have

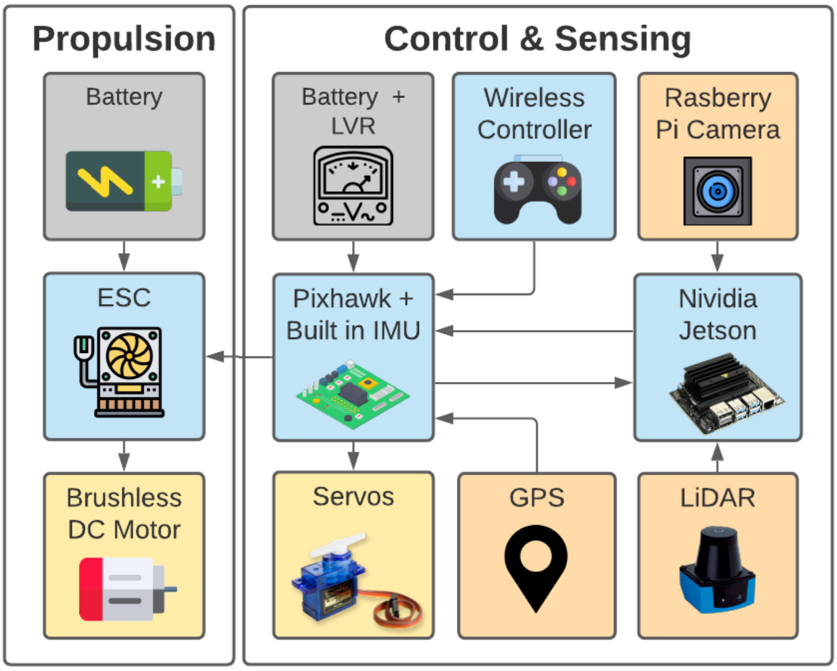

Figure 13 A block diagram that shows the connection between the different platform components such as the Pixhawk flight controller takes control inputs and outputs to the ESC.

issues, such as cavitation around the impeller due to high RPM a lower Kv motor was optimal. This also meant the battery didn't need to have any more than four LiPo cells.

$$BatteryLife = \frac{Capacity_{Ah}}{I_m} \tag{5}$$

I_{m} is the motor current draw in amps. Battery life is important to increase testing time of the propulsion system but it's just as important to keep the weight of the battery down and size. Weight and size are both important factors with designing the stability of the ASV.

$$CRate = \frac{I_m}{I_b} \tag{6}$$

The motors are rated to 94A max current draw, the max of the battery is v_{b}. It is crucial that the C rating of the battery is greater than the max possible from the motors to prevent catastrophic failure of the battery.

The ESC's were selected after the motors and therefore 120A options were selected as they would easily control the selected motors and larger ones if they were wanted during future research.

3.4 Costs of Components

The costs of all components are presented in Table 1. The Jetson Xavier NX and Sick LiDAR were not included due to cheaper alternatives that serve the same purpose with similar ability. The motors and ESC do not need to be as powerful with less than 50% of their power being used.

Table 1 The platform components and their costs in USD.

Part	Quantity	Cost (USD)
Powertrain		
BLDC motor 3660 3180 kv	2	\$197.38
ESC 120 A [30]	2	\$211.58
LiPo 3S 80C 5000 mAh [31]	2	\$150.00
Drive shaft coupling	2	\$25.56
Flange ball bearing [32]	4	\$7.10
Servo stall torque 3 kg	2	\$26.20
Servo stall torque 1.6 kg	2	\$8.01
Electronics		
Jetson Nano [33]	1	\$135.69
Pixhawk 4 mini + GPS module [34]	1	\$201.00
Telemetry Radio [35]	1	\$40.61
Planar LiDAR	1	~\$250
Rasberry Pi camera v2 [36]	1	\$44.61
Miscellaneous		
PLA 3D printing filament 1 kg	2	\$40.00
Cable gland	2	\$6.16
Threaded inserts (100)	1	\$21.47
Total \$1321.83		

4. Experiments

4.1 Waterjet Testing

A single waterjet setup identical to that on the boat was run with varying impeller designs and nozzle sizes at a fixed throttle input. This means that the theoretical RPM is the same due to the same PWM signal being sent to the motor, however the actual RPM varies due to the varying torque required. All measurements were taken from static testing therefore when the boat is moving the values will vary due to inlet velocity ratios. The important parts to consider from testing is the efficiency and thrust which is based on the current draw and the force measurements recorded using a load cell. As shown in Fig. 14 with simple changes such as number of blades, blade pitch, nozzle diameter and hub size the results vary significantly. Analysing subfigure 14a it is clear that the best result was a 4 blade, 40 mm pitch impeller with a 30 mm nozzle diameter which produced 4.5 kg of thrust at an efficiency of 38%. Looking at subfigure 14b this impeller and nozzle combo performs very poorly which highlights the trade off between thrust and waterjet velocity. In terms of boat performance the trade off results in a balance between acceleration and top speed. A combination that offers a good balance is the 3 blade, 40 mm pitch impeller with a 25 mm nozzle. Further optimisation can be done to produce more efficient waterjets with a better balance of thrust and jet exit velocities.

4.2 Proposed Platform Testing

Catamaran testing was done in relatively rough water with waves of up to 150mm high Fig. 15. Due to the boat being loaded to full capacity it was unable to get past half throttle where it was only just starting to plane. This is due to the boat pitching to much and becoming unstable as it drops off the waves as seen in figure 16. In future the design should have an additional section to extend the length of the boat from 600mm to 800mm

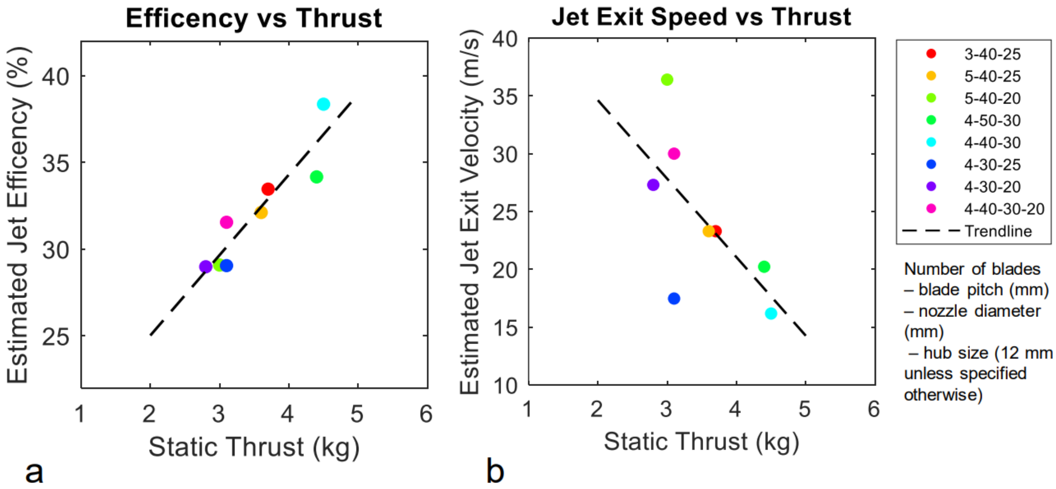

Figure 14 Subfigure a) presents jet efficiency against thrust, whereas subfigure b) presents jet exit speed against thrust.

to better distribute the weight and reduce the pitch allowing for increased vehicle speed.

Figure 15 Proposed platform testing of the catamaran at the Onehunga Bay Reserve, Auckland, New Zealand.

Each jet had its own motor and ESC which was water-cooled using a waterline from the jet exit that used the pressure of the jet to pump the water through the cooling jackets. Due to the tight enclosure there was very little heat dissipation through convection, therefore additional cooling lines could be used to further improve the water cooling. From operation of the jets it was found using differential thrust was optimal at slow speeds and it can be used it conjunction with thrust vectoring. At high speeds differential thrusts causes the boat to be very unstable and begin to roll. Therefore only thrust vectoring should be used at higher speeds. The jet stream was mostly submerged which meant there was significance resistance on the flow preventing greater acceleration and higher top speeds. A larger wake is needed to improve their performance.

5. Competition

To increase research and development in autonomous water-crafts a competition is proposed that uses the low cost, open source autonomous catamaran platform. This will allow the majority of those in the community to get involved, including undergraduate students and

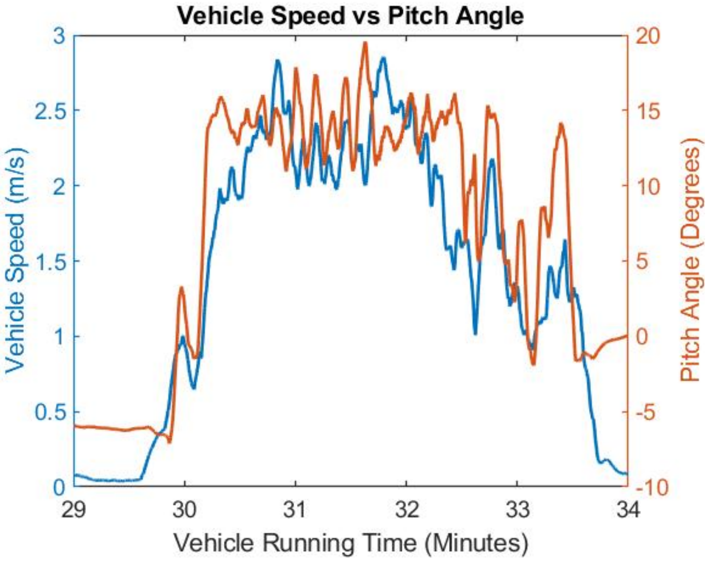

Figure 16 On-board data from IMU and GPS to demonstrate the relationship between the pitch and speed of the platform.

researchers.

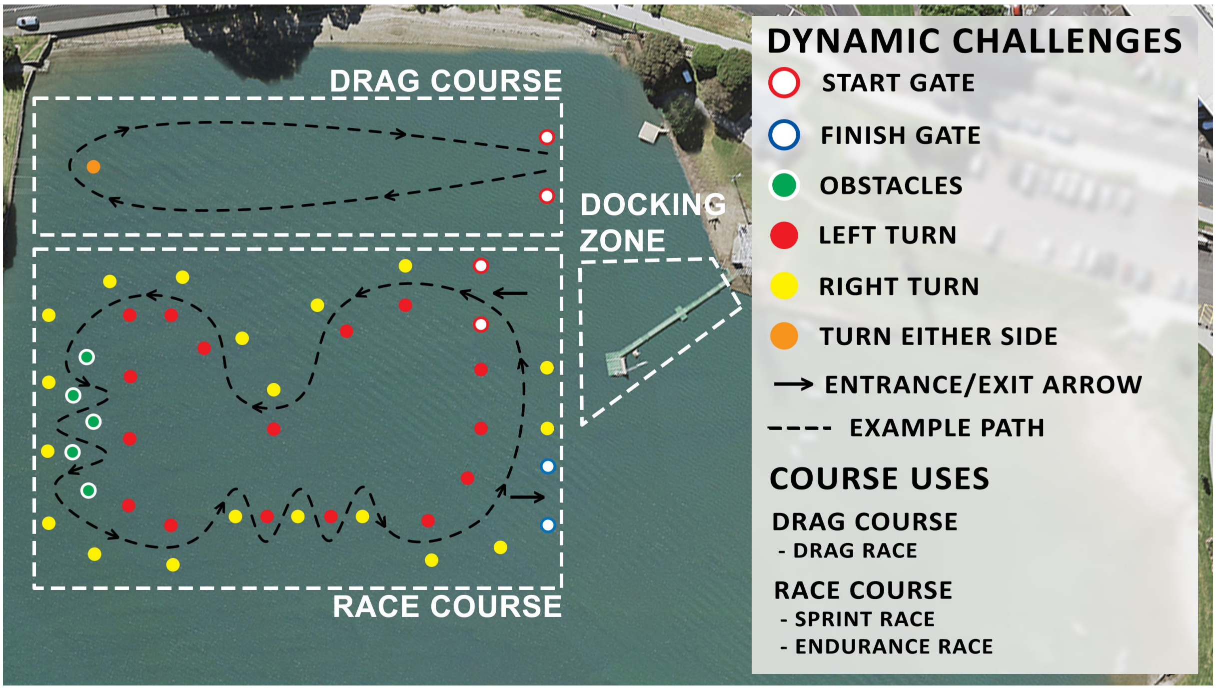

Figure 17 A possible layout for the dynamic challenges at Onehunga Bay Reserve, Auckland, New Zealand [10].

The competition should be exciting to watch and participate in therefore the challenges have been focused on being high pace and pushing the boundaries of what people think is possible. There are three dynamic challenges, these being a drag race, sprint race and endurance. Static challenges are also included where teams can provide validated research in the form of a report to back their design. All teams will have the option to use the supplied base platform to help them in their platform endeavours.

5.1 Dynamic Challenges

Drag Race: This will require the platform to accelerate to a buoy that is placed within 50 meters of the starting point, perform either a clockwise or counterclockwise turn around the buoy and then traverse back to the starting point. The goal of this challenge is to test the propulsion system, hull design and maneuverability with the autonomous side having to quickly distinguish the way points.

Sprint Race: The sprint race will be a set course with yellow buoys marking the right hand side of the route and red buoys on the left. Green buoys can be placed throughout the course as obstacles to increase the complexity for the autonomous systems. The platform will have to complete one lap of the course with the time being used to score the competitors. Any deviation from the course or contact with the buoys will result in a time penalty.

Endurance: Endurance is the same course layout as the sprint race but will require the platform to complete up to 10 laps of the sprint race course. This will allow the autonomous systems to optimise their path planning which should result in reduced lap times. This race will test the reliability of the platform systems and consistency, in other prominent competitions this has proven to be the most challenging task with most competitors systems failing due to reliability issues.

The power usage throughout this event will be recorded to measure the efficiency of the propulsion system. This will be used to balance the scales between those with high powered propulsion systems and those that focused on efficiency. Scoring will be a combination of overall time and the efficiency of the platform system. Any incidents or deviations from the course will result in time penalties.

Potential Venue locations: The dynamic events will ideally be hosted in a still waterway such as a pond, lake or human made pool complex. This will reduce the complexity of the platform system as there is the reduced risk of the platform capsizing and vision systems struggling to determine buoys. As the competition evolves participating in rivers and harbours will be encouraged as it adds the dynamic of waves and unexpected obstacles such as shallow water and rocks.

Vector Wero Whitewater Park is a potential venue located in Auckland that could boost exposure of the competition while providing a technical course layout. It is purpose built for rafting and kayaking which provides the artificial river environment. Alongside this it has hanging markings used for slalom kayaking that can be used as specific challenges along the route.

5.2 Static Challenges

Due to the complexity of the dynamic events, static events are crucial to encourage strong design frameworks and reward teams that tried more novel solutions even if the implementation failed. The key event will be a design report that teams will have to submit before the competition outlying each subsystem of their platform and their research to get to this point. These will be reviewed with teams that have shown novel ideas and thoroughly designed systems receiving more points.

5.3 Rules

With platform's being Autonomous safety is critical to ensure those running the event and supporting platform's out on the water are not put in harms way.

Key rules include:

- The platform must be completely electrically powered, no fuel powered vehicles allowed due to potential damage to the water ways in the case of an accident.
- Motor power and battery capacity will be limited to ensure those that can afford more expensive components do not have an unfair advantage.
- Water proof rating similar to that of IP68 need to be demonstrated before the platform can enter the water to prevent damage to electronics.
- Propulsion systems are limited to those of water jets where the impeller is housed by an inlet that has grates to prevent any form of injury with those that come in contact with the platform.
- overall size of the boat will be limited to less than a meter in length and half a meter wide along with its weight being limited to less than 10kg. This is to ensure the platform can safely navigate the course and be easily rescued/removed if needed.

5.4 Scoring

Table 2 Allocated points for each challenge and scoring method

Challenge	Points	Scoring Method
Static Challenges		
Design Report (DR)	15	Judging
Cost Challenge (CC)	10	Vehicle Cost
Dynamic Challenges		
Drag Challenge (DC)	15	Time
Sprint Challenge (SC)	25	Time
Endurance Challenge (EC)	35	Time
Total	100	

To score the results the individual challenges (S_{CH}) need to be scored which is done using Eq. 7 (S_{CH}). This is formed from the teams score from the challenge (S), the result of the wining team (T_s) and the maximum allocated points for the challenge (Max_{CH}) as seen in Table 2. Once all the individual challenges are calculated, the overall score (S_{Total}) is found using Eq. 8 which is just the sum of all challenges.be seen in Eq. 7, where the final score associated with a challenge is calculated.

$$S_{CH} = \frac{S}{T_s} \times Max_{CH} \tag{7}$$

$$S_{Total} = S_{DR} + S_{CC} + S_{DC} + S_{SC} + S_{EC} \tag{8}$$

More details about the competition, as well as the robotic speedboat designs, code, and an HD version of the accompanying video containing the experimental validation, can be found at:

https://www.newdexterity.org/autoboat

6. Conclusions & Future Work

This paper focused on the development of an open-source, low-cost, waterjet-powered robotic speedboats for education and research. The final result was a working monohull test platform, autonomous catamaran platform, an optimised waterjet design and a autonomous speedboat competition. The monohull test platform could be used to dynamically test the waterjet system along with steering and reversing actuators but it could never be used as an actual autonomous platform due to it's inherent body roll. The catamaran platform was 3D printed on standard FDM print bed size that was strong and waterproof while being very cheap and easy to reproduce. With the use of laser cut gaskets and rubber o-rings the internal compartments were made watertight however, it was much more difficult than initially intended. This was due to initially printing the inlet separately to the hull which meant the high inlet pressures caused leaking through the seals at the interface with the hull. The final waterjet system was tested with a range of nozzles and impeller variations to find a an optimal balance between jet exit velocities and thrust while improving efficiency. Further optimisations can still be made through simulations and geometry improvements. Lastly the proposed competition will hopefully help in creating a community that will test different platforms and compare the advancements achieved over the years. The events themselves will evolve with the designs to encourage new innovations and competition between teams.

Future work will focus on creating more platforms such as a trimaran hull design which takes the stability of a catamaran combined with the single jet propulsion system of the monohull. Therefore, resulting in a stable yet simpler design that will cost less due to a reduction in the hardware needed for propulsion. Fluid dynamic models should be created and validated of the waterjets to allow for increased optimisation while reducing the need to print a large number of impellers and nozzles. The competition itself needs to be trial run with a select group of teams to refine the challenges and rules.

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