Design and Build of a Device to Measure Resistance and Power of Model Submarines in the Submarines in Schools Technology Challenge

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The objective of the Submarines in School Technology Challenge (Subs in Schools) is to stimulate Australian school students to pursue a science, technology, engineering and mathematics (STEM) related career. It has an obvious connection and motivation to grow interest in industries being developed by the SEA1000 Future Submarine Program. One of the principal improvements envisioned to the program is the introduction of more real-world engineering tests into the competition including the measurement of the hull resistance and power. The work reported in this paper aims to enhance student learning experiences through developing a test rig to measure the hull resistance and required power. The instrumentation will be selected based on analytical results and computational simulations to determine the key design elements, e.g. motor requirements and the tension in the towing cables. Having these tests conducted during the competition will facilitate and encourage students engaging in relevant engineering theory to enable them to incorporate resistance and powering aspects more appropriately into their designs.

This paper reflects a work in progress as part of a 2019 undergraduate honours project by the lead author.

INTRODUCTION

Subs in Schools (SiS) was developed by Re-engineering Australia (REA), in association with the Department of Defence and a variety of industry stakeholders, including SAAB Australia and the Australian Submarine Corporation (ASC) [1]. It was established in 2014 as a result of the Australian Government announcing the SEA 1000 Future Submarine Program to replace the Collins class submarines [2]. This is Australia's largest ever Defence procurement and Subs in Schools is intended to develop employability skills in students and interest them in careers in Defence industries to support this program [3].

As presented in Table 1, Subs in Schools offers four project level programs of increasing complexity. This report relates to the most advanced and comprehensive level 4 submarine challenge which allows students to engage with marine engineering and naval architecture theory through experiential learning, including 3D printing, electronics, Computer Aided Design (CAD) and coding. It involves a number of team deliverables, including a project portfolio, a working scale model, a trade booth and a verbal presentation. Students must also engage with industry to seek sponsorship/support, and through this process they learn valuable soft skills such as teamwork, communication and project management [1].

Table 1 – Subs in Schools Project Levels [1]

Level	Suggested School years	Project
1	7-8	Build a mini underwater remotely operated vehicle (ROV) from a kit
2	8-9	Design and build a large underwater ROV
3	9-11	Design an internal accommodation space in CAD
4	10-11	In year 10 construct the REA submarine kit. In year 11 design and build a model submarine either improving the existing design or creating a new design.

The competition requires a practical demonstration comprising trials, where teams operate their submarines to complete surface maneuvering, flotation and ballasting, submerged maneuvering trials and a "timed way-point voyage" [4]. The trials test a number of design aspects including watertight integrity, buoyancy, propulsion and control. Feedback from previous competitions indicates that the model submarines being developed are overpowered, and they do not emulate realistic performance of full size submarines.

A previous UNSW Canberra student, Ryan Cavenagh, attempted to address the overpowering issue [5]. The underlying philosophy was to explore means for limiting the available propulsion power. The strategy was based on developing techniques to measure the resistance of model submarines on the surface, and tools typically used for surface ships were employed. For example, matching of the Froude number (Fr) and modelling in Maxsurf were utilised to determine benchmarking data including resistance and velocity. From this data, two variations of drop tower towing mechansims were designed to measure the resistance: one using multiple pulleys, and the other using a wheel system, as depicted in Figure 1.

Figure 1 – Drop tower Developed by Ryan Cavanagh in 2018 [5]

The drop towers were used to tow the model submarines (an example is described in [6]) on the surface by applying a known tow force by means of a falling mass. The resulting velocity can be measured. This is the reverse of a standard towing tank where resistance is measured for a given velocity. In the competition the team with the highest velocity (hence the lowest resistance) would win that aspect of the competition.

Several limitations with the falling mass design as configured were observed. Firstly, it was only capable of towing on the surface and for a test distance of 6.4m. This limit was a function of available proof of concept materials (drop height, pulley wheel) but having a much longer test length to operate in a standard 25m pool is highly desirable. Secondly, the frame is heavy, it requires significant weights to counterbalance and it needs to be constructed and deconstructed each time it is used, which is not conducive to portability. Thirdly, the velocity is measured manually which introduces uncertainty and offers poor sensitivity or via video which leads to significant data processing.

There are three primary techniques for measuring resistance on a submarine. These include physical scale modelling using a towing tank or wind tunnel and applying a modified surface vessel resistance method; using CFD modelling to predict resistance; and, using analytical approximation techniques. To design a device capable of simultaneously measuring total resistance and speed to the Subs in Schools program and to enhance students learning experiences, analytical solutions were compared with CFD results to make sure that the towing tank device components are adequate and capable of measuring the hull resistance accurately.

METHODOLOGY

Depicted in Figure 2 is a basic overview of the methodology used to design an alternate system/device for SiS. The first phase was to estimate the resistance to obtain an approximate value that the system must be able to both tow and measure. For example, electronic components have specified operating limits and analysis is required to ensure each component integrates within the system appropriately. The second phase is to verify that the approximation results are accurate by comparing them to numerical results using CFD simulations. This is to provide a level of certainty. The third phase is to design and build the system/device, and the fourth phase is to test the model and compare the experimental data with the computed results.

Analytical Method

There is a direct relationship between resistance and propulsion. For example, theoretical power is the power needed to overcome the resistance of a naked hull at a defined speed i.e. $Power = force\ \times velocity$. Thus, if the resistance at a constant velocity is known, then the theoretical power required to overcome that resistance can be determined. Resistance is a measure of the horizontal component of opposing force on a vessel as it traverses through water. The primary components of resistance on a submerged submarine are skin friction and hydrostatic pressure [7].

To calculate the resistance on the REA model submarine, an analytical method was employed using a recommended procedure in chapter 4 of reference [7]. The analytical results are compared with corresponding CFD results in the coming section.

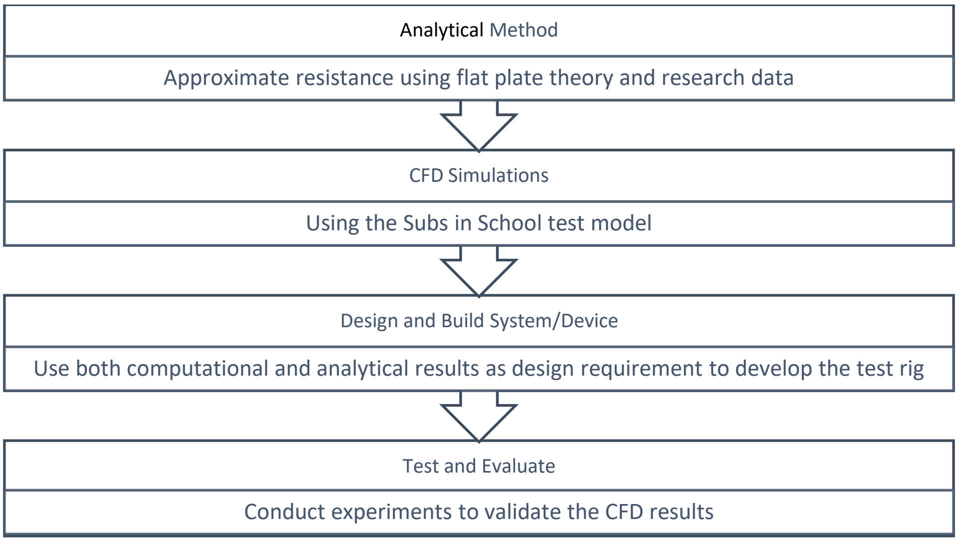

Figure 2 – Summary of the methodology

Numerical Method

Over the past decade, CFD has been developing significantly. As such, CFD is now a powerful tool that can accurately predict total resistance components of a submarine model moving in 1 Degree of Freedom undersea. To build a simple towing device facility, CFD is employed to predict the corresponding drag force at a range of operational speeds. Although Fr is irrelevant in submerged towing tank testing, it may be used to calculate a realistic towing speed. The selected speed range was primarily chosen based on Froude scaling of full-scale submarines, e.g. HMAS Collins. This submarine has an unclassified submerged speed v of 20 kn (10.29m/s)) and a length L of 77.4m [7]. Thus, it was decided to run simulations at a range of water inlet velocities from 1 to 2.5 m/s in 0.5 m/s increments, e.g. Fr scaling.

The numerical simulations were executed using the Reynolds Averaged Navier Stokes (RANS) solver Fluent. The code resolves the incompressible RANS equation in integral form utilising the finite volume method. The motions of the model were restricted in all degrees of freedom, i.e. applying an inlet flow at a given velocity with the body remaining stationary using the traditional fixed grid method. The simulations were performed using 10 nodes of the high-performance computing cluster (consisting of 322 cores), at the National Computational Infrastructure, Canberra, Australia.

Illustrated in Figure 3 is the REA model submarine geometry. The main particulars of the model are as follows: length L/D = 1/0.11, the forward and aft control surface have a chord of 0.061 m. The sail has a chord of 0.25 m and span to 0.104 m from the body centerline.

A slow growth rate was selected for grid generation to ensure smooth transition between neighbouring structured cells, as illustrated in Figure 4 (a). The grid was generated with at least seven density levels in order to capture pressure distribution around the submarine model. The finite volume meshing method was implemented for all simulations to solve the differential equations for a viscous 3D monophase flow represented by RANS equations in which the effect of turbulence is solved using two equation Shear Stress Transport (SST) k-ω eddy viscosity model. To resolve the near wall turbulence quantities all y+ wall treatment was selected that attempts to combine the high y+ wall treatment for coarse grids and low y+ treatment for fine grids, where y+ is a non-dimensional wall distance.

The computational domain is shown in Figure 4(b). The boundary conditions used were velocity inlet at the right-handed side of the domain, pressure outlet at the left-handed side of the computational domain, non-slip wall at the hull surface of the model and slip-wall at the domain wall, while the plane that bisects the submarine model vertically was treated as a symmetry plane, as shown in Figure 4(b).

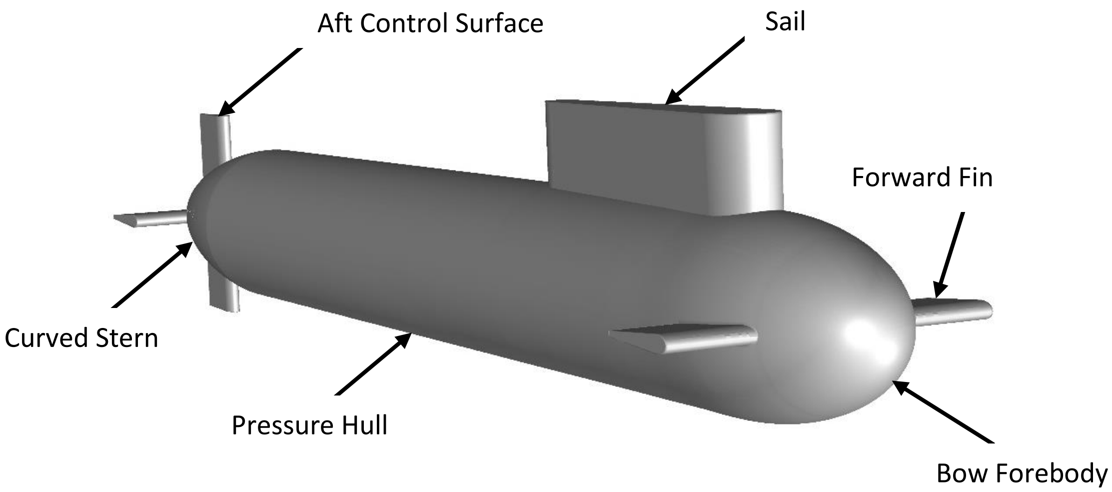

Figure 3 – The CAD REA model submarine

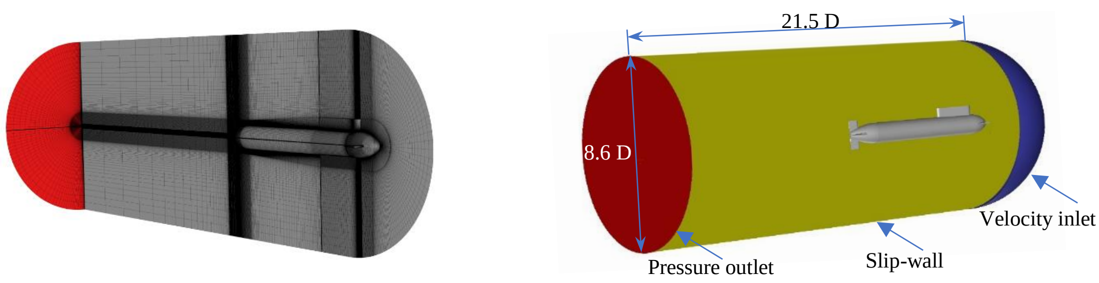

Figure 4 – (a) the generated fine grid and (b) the boundary conditions and the numerical SiS model submarine

The applied physical model in all simulations uses the Eulerian multiphase segregated iterative method to solve the conservation equations for mass, momentum and energy (RANS equations). This model solves the flow equations for the velocity components and pressure in an un-coupled manner. First, the linearised components of the momentum equations are the prevailing pressure and mass fluxes through the control volume faces (inner-iterations), followed by a Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) to resolve the pressure-velocity coupling, while the linkage between the momentum and continuity equations is achieved through predictor and corrector stages.

Grid Independence Study

To study the sensitivity of computed results against the used sizes of cells to discretise the domain and the 3D geometry of the submarine hull model, grid-density independence studies were conducted, as shown in Table 2. Provided is a summary of the independence grid studies and associated uncertainties against the measured data. The second column presents the grid size and the third column compares between the results utilising three applied grid densities (first column). The total number of generated cells varies from around 6 million, 12 million and 14 million cells for coarse, medium and fine fixed grids, respectively.

Table 2 – Summary of Numerical Independence Study

Grid level	Grid Size (millions)	Drag force difference to fine grid (%)
Coarse	6	1.7
Medium	12	0.6
Fine	14	-

Results presented in Table 2 shows that the uncertainty error bounds did not enhance significantly despite required higher computational cost. Thus, it was decided to use the medium sized grids for the presented results on the basis of the slight change in timing of drag force magnitudes with respect to the applied coarse stationary grid, as presented in Table 2. The time-step varies in order to satisfy a chosen steady state solution.

Results and Discussion

Presented in Figure 5 is an image of the pressure distributions around the submarine hull, with a demonstrated stagnation pressure at the bow and the fins facing the flow direction. The pressure distribution is of importance during the design stage of the REA model as it provides users with the locations that are under higher stress levels on the hull. These locations are with higher risk of failure, e.g. the stern fins. Insights on the flow behavior around the submarine model and areas of improvement to reduce drag force on the hull and to achieve higher speeds can be obtained by studying Figure 6.

Good agreement is illustrated in Figure 7 between the analytical and the computed results with a deviation of less than 5% between both results. This comparison could provide the designer of the towing device with important information for efficient facility design, e.g. regarding the load cell’s range.

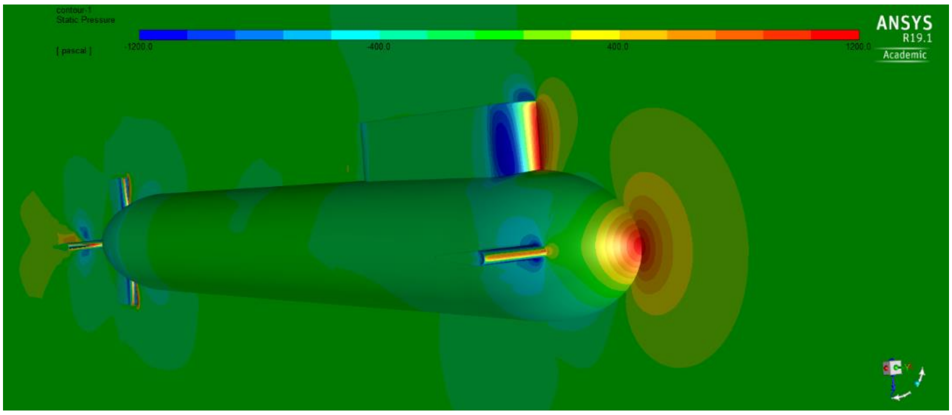

Figure 5 – Pressure contours around the submarine model

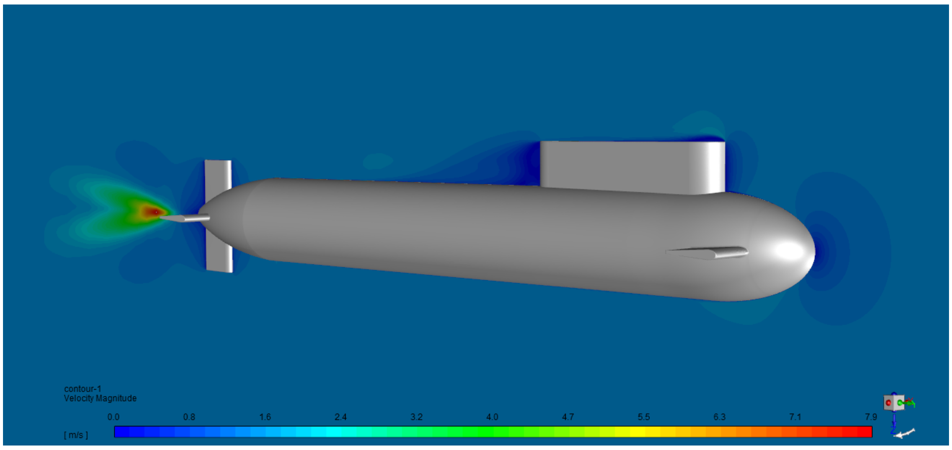

Figure 6 – Velocity flow behavior around the submarine model

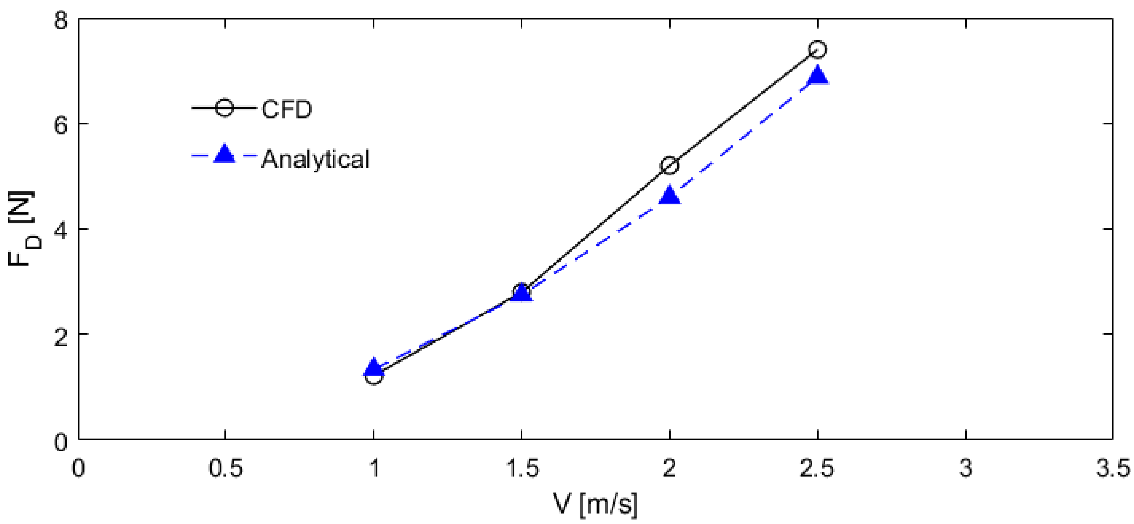

Figure 7 – Comparison of the total drag force CFD results against the analytical results

SYSTEM REQUIREMENTS

Analysis of the analytical and computed resistance results was undertaken to select the design specifications for the new experimental system/device. This involved first approximating the resistance on a built REA model submarine by using approximation theory. This yielded an approximate resistance value of 7 N at a maximum velocity of $2.5\,ms^{-1}$, providing a baseline level of resistance for which the device must be able to overcome.

The design requirements for the device were then established. The primary design requirements include:

- The device must be able to measure both resistance and power of model submarines;
- It must be lightweight and portable to meet airline check-in luggage requirements;
- It must be powered and controlled by electronics and be a self-contained unit i.e. no external power source or counterweights;
- Critical components must be water resistant; and
- Must be user friendly i.e. requiring very little setup and effort on behalf of the user.

CONCEPT DESIGN

Based on the design requirements a concept study was conducted to determine the most suitable concept on which to conduct further study. The concept chosen was a portable device that incorporates a DC motor driven fishing reel and a load cell. To measure resistance, the device will have a main towing component at one end of the pool and another guide rope retaining unit at the other end of the pool. Model submarines will be trimmed to a depth of 0.5m through a calibration lap of the pool then a towing harness will be attached to the nose cone. Another guide harness will be attached near the tail and this harness will be connected to two ropes/lines that run the length of the pool.

The maximum velocity value was used to determine the torque and RPM requirements for a DC motor to couple to a tailored fishing reel. This was achieved by approximating the net mass of the model submarine and using this mass, the approximated force and velocity in dynamics analysis. This yielded a minimum torque of 1.23Nm and a minimum motor RPM of 186, and a DC motor was purchased based on this analysis. The change in velocity due to the spooling effect of the reel was also analysed, and it was determined that there was only a 4.2% change in velocity over a 25m pool course and this was deemed acceptable. The DC motor chosen has a built-in rotary encoder to measure the angular velocity, and this will be used to code the motor to wind the fishing reel at the characteristic velocity.

The fishing line between the reel and model submarine passes over a grooved bearing that is mounted atop a load cell that will be coded to record a peak and average resistance reading for the duration the model submarine is at a constant velocity. A conceptual representation of the system is shown in Figure 8. The proposed device/system components are listed and depicted in Figure 9.

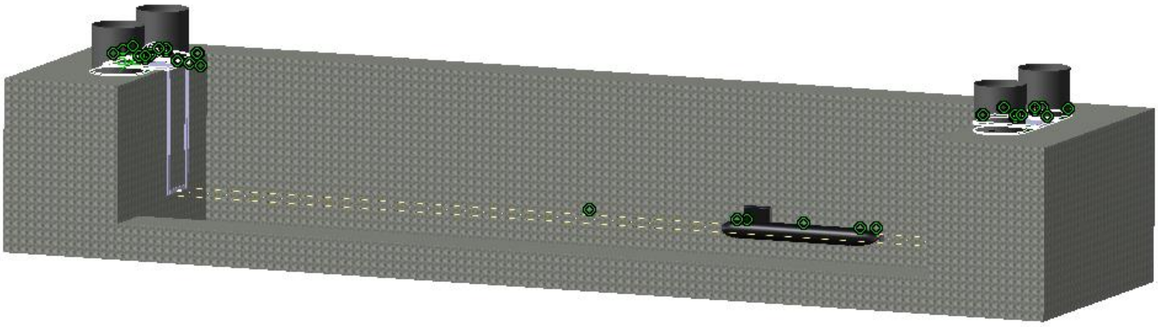

Figure 8 – Conceptual Representation of Model Tow Configuration

Number	Component
1	Aluminium frame and telescopic legs (variable depth adjustment)
2	Grooved roller bearings
3	Bearing to Load cell mount
4	90 degree folding brackets for legs
5	Collapsible buckets (for anchoring sub-system)
6	Motor to Reel coupling
7	Gear DC motor with encoder
8	Arduino Uno
9	12V Li-ion battery
10	Fishing Reel
11	Removable bucket mounts (rubber base for anchoring sub-system)
12	Arduino shield for resistance and power readouts
13	10kg rated load cell and driver

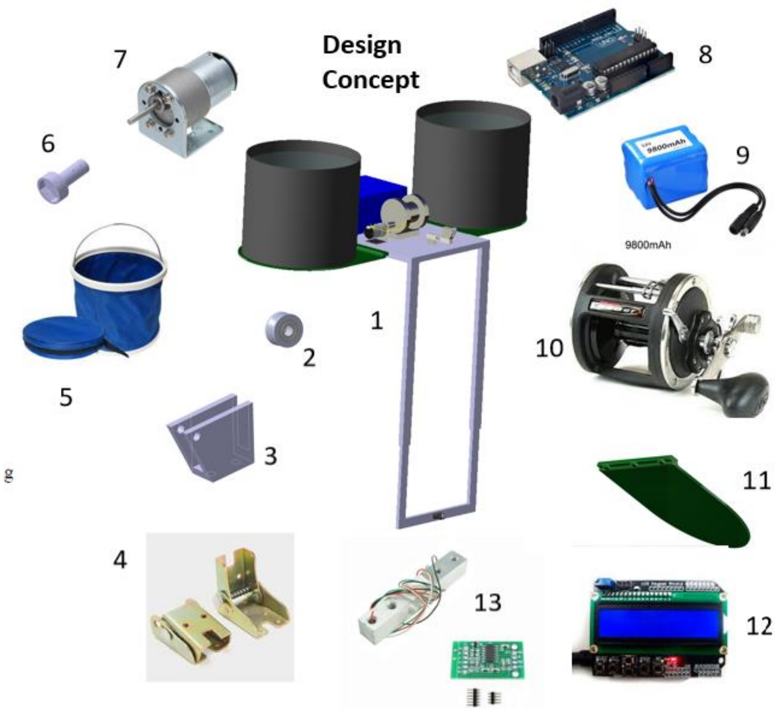

Figure 9 – Proposed Model Towing System Components

To measure power, the inbuilt drag system on the fishing reel will be set to a value that all model submarines within the competition are capable of overcoming. This will be achieved by pulling on the fishing line whilst reading the force measured on the load cell and adjusting the drag system until it begins unwinding line at the desired force value. The submarine will be connected via a harness designed to keep the line away from the propeller and the submarine will be ordered to proceed at full speed ahead. The time taken for the submarine to traverse through a given displacement will be recorded in order to measure the maximum power output. An additional "bollard pull" test could be conducted by turning off the drag system and measuring the maximum thrust of the model submarines at zero speed ahead.

FURTHER WORK

Work to build and test the device is scheduled to commence in the third quarter of 2019 and results will be presented at the conference.

Once the device is built, experiments will be conducted to validate that the device is able to accurately measure resistance and power. This will be achieved by first towing the respective harnesses through the water and measuring the resistance. Experiments will then be conducted using the model submarine, for example a parametric study of resistance while varying velocity. The model will be towed at the characteristic velocity and the harness resistance value will be deducted from the gross resistance value to give the net resistance on the submarine. This value will be compared to analytical and CFD approximation results to determine the accuracy and levels of uncertainty with the device.

CONCLUSION

A review of theory and a previous thesis have yielded foundation theory and system design requirements necessary to achieve the aim of this project. A planned methodology has been established, design work and procurement are in progress and construction of the concept design is scheduled to commence in July 2019. CFD results were in good agreement with analytical results, and CFD was able to predict the pressure contours and the velocity distributions around the 3D submarine model.

This design project aligns well with Australia's strategic interest to stimulate interest in its youth to pursue STEM and submarine related careers.

Acknowledging the work is ongoing, as an undergraduate thesis, it is anticipated that complete detailed results will be available when the paper is presented and updates will be available from the authors.

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