RE-Engineering Arab World (RAW) – A study for Promoting Maritime Engineering in Schools

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ABSTRACT: Arab world needs more highly skilled technical people who are willing to think and be creative. Traditional classroom techniques are not working. It is time to re-engineer our nation. To inspire and educate a new generation of young people. Thus, it is that the social enterprise, re-engineering Arab world foundation (RAW), is presented. Although, the suggested program will include multidisciplinary engineering activities, in the future, with defined goals, e.g. engaging, inspiring and educating, students, teachers and industry in the Arab world. The first step, introduced in this paper, was focused on promoting maritime engineering technologies in schools through providing teachers and students with a detailed manual of an unmanned under-water vessel (UUV) model. The manual describes all the electrical, mechanical and structural components, steps of manufacturing and areas of innovation. In 2020, the first model will be manufactured and tested by final year under graduate students at the Arab academy for science, technology and maritime transport in collaboration with industrial partners within the maritime domain. In 2021, the developed model will be introduced to teachers and students in secondary schools to be able to participate in a national competition. In addition, a technical support will be provided throughout the construction phase of the UUVs in schools. In 2022, the competition will be extended to the Arab world. An automated towing test device programmed to tow an object through the water at a target velocity for a defined displacement whilst measuring the force on the tow line was developed and results were validated against theoretical formulae. The introduced program in this paper is a step forward to re-engineering the Arab world and would function as a path for introducing new technologies to students. To cement this project long term sustainability, partnerships with industry, Defence and Arab governments is essential.

INTRODUCTION

Reengineering Arab World's (RAW) unmanned under-water vessels (UUVs) Technology Challenge would enable school students to design, build and operate remotely-controlled UUVs to compete in an annual regional competition. The competitors will be permitted to enter an RAW-designed kit-model or alternatively, design their own UUV. However, similar idea of this competition was firstly introduced by Re-Engineering Australia (REA) foundation in Australia, [1], namely, Subs in Schools (SiS) competition, to date, no competitors have successfully manufactured a correctly functioning example of the REA entry-level submarine kit worldwide.

Submarine models invariably suffer from malfunctions associated with water ingression and a general inability to effect reliable depth-control.

The purpose of this work is to provide the RAW foundation a functioning remote UUV kit to compete in the coming regional competition. The inability of the SiS model to perform basic submarine operations, fundamentally undermines its intent and essentially renders it redundant. The overarching limitation on these aspects of the model appear to lie in a general lack of reliable functionality. As such, this study focusses on devising a reliable design of an UUV model to address the deficiencies in the SiS model's watertight integrity and depth-control system. While the parent model reportedly exhibits deficiencies in other areas; such as maneuverability, this project will focus primarily on the design and assessment of an improved pressure-hull and depth-control system. The aim is to determine if a reliable pressure-hull and depth-control system can be designed that is straightforward to manufacture and simple to maintain. The existing model design will be assembled according to the build manual and tested for functionality. Upon identifying the deficiencies and determining the model's reliability, a revised design of the respective systems will be conceived and manufactured. The proved prototype model will be submitted to RAW foundation and hence to schools in the Arab region.

The work was also extended to determine if a portable device could be designed for the Subs in Schools competition to emulate a towing tank facility and accurately measure the resistance and power of the model submarines. By implementing this test into the competition, students will factor these aspects into their submarine design and be exposed to further engineering concepts, enhancing the aim of Subs in Schools. This device has further potential applications, in particular, for use in universities to teach important engineering concepts. To meet these objectives, the project was divided into milestones that are presented in the following sections.

MODEL TEST OF THE PARENT HULL

Fig. 1, shows the SiS parent kit-model which requires several months to build and assemble. The reason deemed to be due to the ambiguous nature of the build manual provided by REA. Thus, one of the aims of this study is to provide early engineering students in schools by a complete road-map of how to design and build an UUV model with clear instructions, revised three-dimensional (3D) drawings of parts that are compatible with 3D printed mounts and detailed but simple electrical drawings.

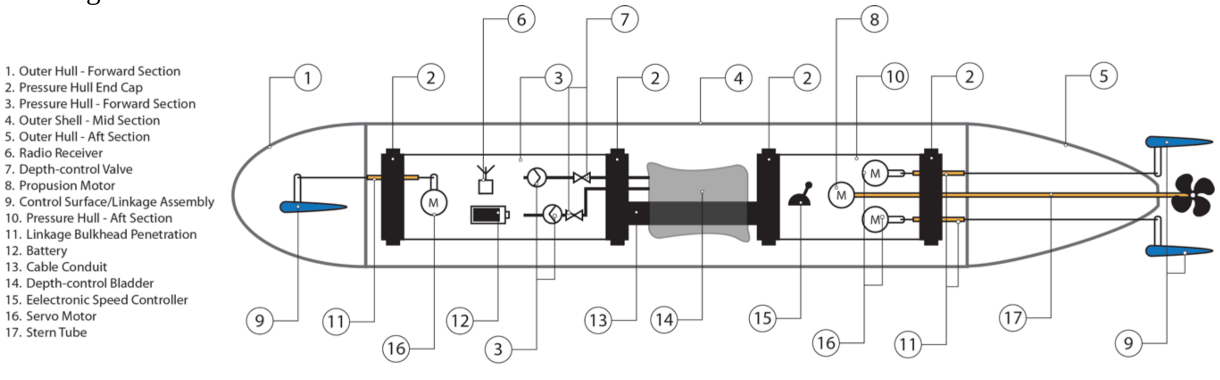

Figure 1: : Schematic diagram of SiS parent kit-model with a length overall of 0.98 m and a beam of 0.1 m.

Figure 2: Completed SiS kit-model connected to an antenna

The current Subs in Schools kit-model is primarily composed of simple 3D printed components, PVC piping and standard remote-controlled vehicle hardware, as shown in Fig. 1. In addition, the model includes, e.g. a transparent double-sectioned watertight cylinder enclosed by o-ringed end caps and joined by a watertight cable conduit. This part is known as the "pressure-hull" and houses all electronic components. The assembly is mounted within an outer shell constructed from a section of PVC pipe. The outer shell is capped with the nose cone which houses the bow plane assembly. At the stern, sits the tail cone which houses the propeller, stern tube, rudder and elevator assemblies. The conning tower is mounted on the outer shell and houses the main battery switch and the cable to antennae float.

The depth-control, ballast system, is activated by means of a pump and bladder system. The bladder is located amidships within the void located between the forward and aft pressure-hull sections. To descend, air is transferred from the bladder via a dedicated pump and solenoid valve to the pressure-hull. As the bag deflates, water is able to occupy the void and the vessel's overall density increases. The vessel subsequently becomes negatively buoyant and consequently submerges. To return back to the surface, the procedure is reversed by means of a separate dedicated pump-valve system.

A series of experiments were conducted using the 25 m swimming pool in the Australian Defence Force Academy and the SiS model, as shown in Fig. 2. The preliminary tests showed that the pressure-hull suffered from significant water ingress even at shallow depths. This is a considerable problem as it prevents the model from being properly tested. Until a solution to the problem can be found, the model is restricted to surface experiments in order to prevent damage to the sensitive electronic components. In addition, the depth-control system failed to operate correctly. The time taken to fully submerge the vessel was considerable and the model failed to surface with a satisfactory trim attitude.

Interestingly, these two problems appear to be coupled. As predicted in the later literature, pressure-hull ingression appears to be isolated to the bulkhead penetrations; specifically, the bellow seals that fit over the control linkages. It was hypothesised that design of the depth-control system may be the primary source of this defect. Because the depth-control system displaces air from the pressure-hull in order to surface, the pressure-hull enters a state of vacuum as the submarine ascends. The design of the bellows seals is such that they are insufficient to support this negative pressure and, combined with the positive external pressure forcing water in, are failing.

The embarked water subsequently increases the overall weight of the vessel beyond the buoyant capability of the hull, and leaves it partially stranded at depth. At this stage, the stern tube and pressure-hull end cap seals appear to be functioning correctly. However, with the inherent vacuum effect in the current depth-control system, reinforcing the linkage seals may successively induce failure in these systems. The time taken to fully submerge to a depth of 200mm was approximately five minutes.

RELIABILITY ANALYSIS

A key factor influencing further functional testing of an under-water vessel is the pressure-hull's watertight integrity. This section will be limited to determining the reliability of the various components that potentially contribute to failure of pressure-hull' watertight integrity. In order to analyse the reliability of these components, the method of exponential analysis will be applied in conjunction with Fault-Tree Analysis (FTA) and Failure Mode Effect Analysis (FMEA) techniques [2]. The exponential analysis method is employed primarily for failures that occur randomly as a result of fatigue or overload. It should be noted that for this analysis, it was necessary to estimate several key parameters as the circumstances of the experiments did not permit to conduct repeatability study.

The pressure-hull assembly is composed of several components that could influence its ability to maintain watertight integrity. These components and their functional relationship with respect to failure, are presented in Fig. 3. By analysing the resulting data, it was observed that the reliability of the pressure-hull was dominated by the reliability of the linkage seals and stern tube seals. This suggests that by improving the reliability of these components, the functionality of the pressure-hull will be significantly improved.

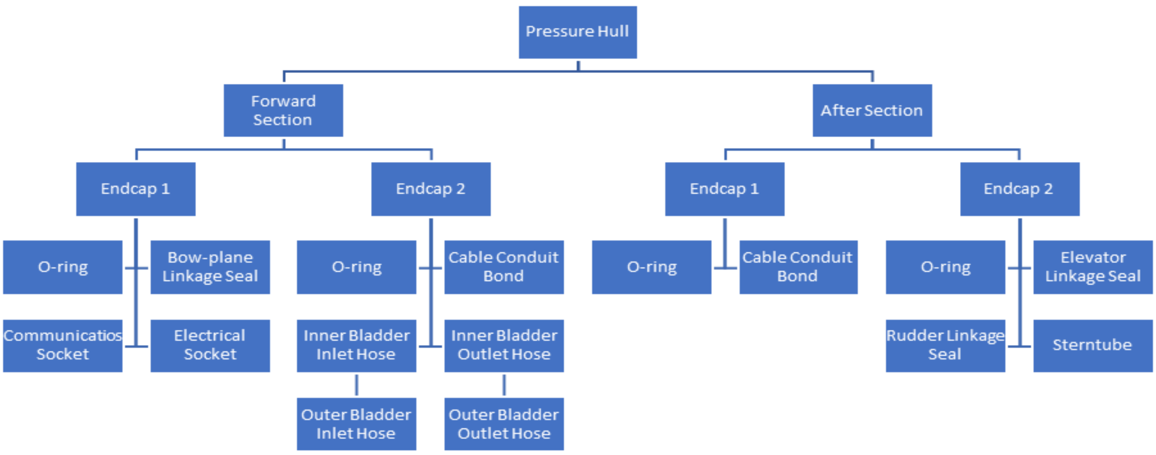

Figure 3: Functional component layout: SiS kit model pressure hull

DESIGN OF THE UUV MODEL

Based on the results from preliminary experiments, relevant literature and the intent of the UVV competition, several requirements were formulated for the new design.

The UUV model assembly must consist of the following mandatory components and/or features, presented in Table 1. The submarine assembly may also consist of the following optional components and/or feature, presented in Table 2. In addition, Table 3 summarises the main particulars governing the UUV models and general regulations of the competition.

Table 1: Mandatory Componenets.

A body (which includes a virtual cargo)	Bow cap	Stern cap
On/Off Switch	Fin / Sail	Propeller

Table 2: Optional features:

Trailing antenna/aerial	Trailing Satellite Receiver	Internal systems as necessary
Speed control mechanism	Fore control mechanisms	Using adhesives for joining components

Table 3: Showing the competition general regulations:

Item	Requirement	Grade
Safe construction	All components operate smoothly	20 Pts.
Design, Manufacture & Construction	CAD/CAM Designs	20 pts.
Propeller	Enclosed by a guard/ cover	20 Pts.
Finishing and Assembly	Be finished to a high standard	20 Pts.
General Dimensions	Length overall ≤ 1000 mm Beam ≤ 300 mm Overall Height ≤ 300 mm Virtual Cargo (Pay Load) ≥ 500 mm in length and 80 mm in width Sail ≤ L 100 mm x B 30 mm x H 50 mm	20 Pts.

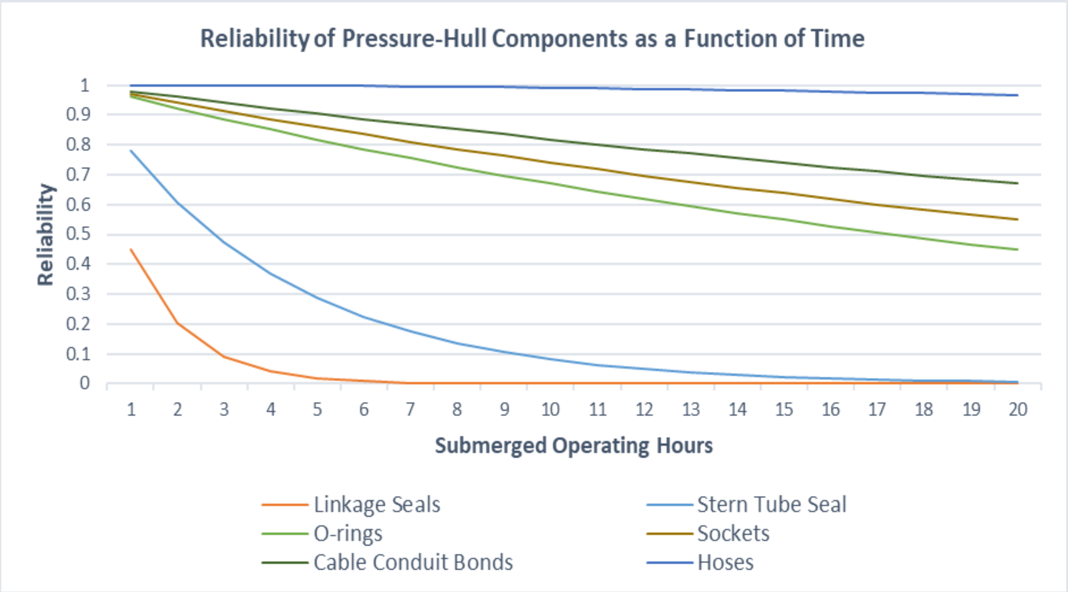

Figure 4: Reliability of Pressure-hull Components as a Function of Time

Although, the new design attempts to draw on Burcher and Rydill's philosophy of simplicity in the pressure-carrying envelope [3] by minimizing the amount of pressure interfaces; while simultaneously improving the process of manufacturing and subsequent disassembly/assembly. A duel ballast tank system was adopted due to the prevalence of the configuration represented in the literature [3-5]. The general arrangement and new components were designed with special consideration given to ease of manufacturing, maintainability and robustness. The new design was intended to be capable of being integrated with the existing outer shell components and attempted to minimize substitutions for fundamental parts in the current kit where possible. The overall general arrangement of the redesign is depicted in Figure 5.

To aid with maintenance and robustness, a series of new structural components were also conceived. The redesign included a forward and aft self-aligning quick release coupling assembly. The forward and aft ballast tanks could be separated from the main pressure-hull by means of a bayonet fitting included in the collars. The collars also included a void space for fitting electrical connectors with a slot where wires could penetrate and be loomed along the inside of the outer shell. To assist with maintenance, a removable machinery chassis was designed to allow all hardware to be mounted correctly in the pressure hull. This device facilitated quick removal of all parts and elevated the sensitive electronic components from the base of the hull; away from water accumulation in the event of a leak. The addition of the aft ballast tank to the rear of the pressure hull, necessitated extension of the existing propeller shaft.

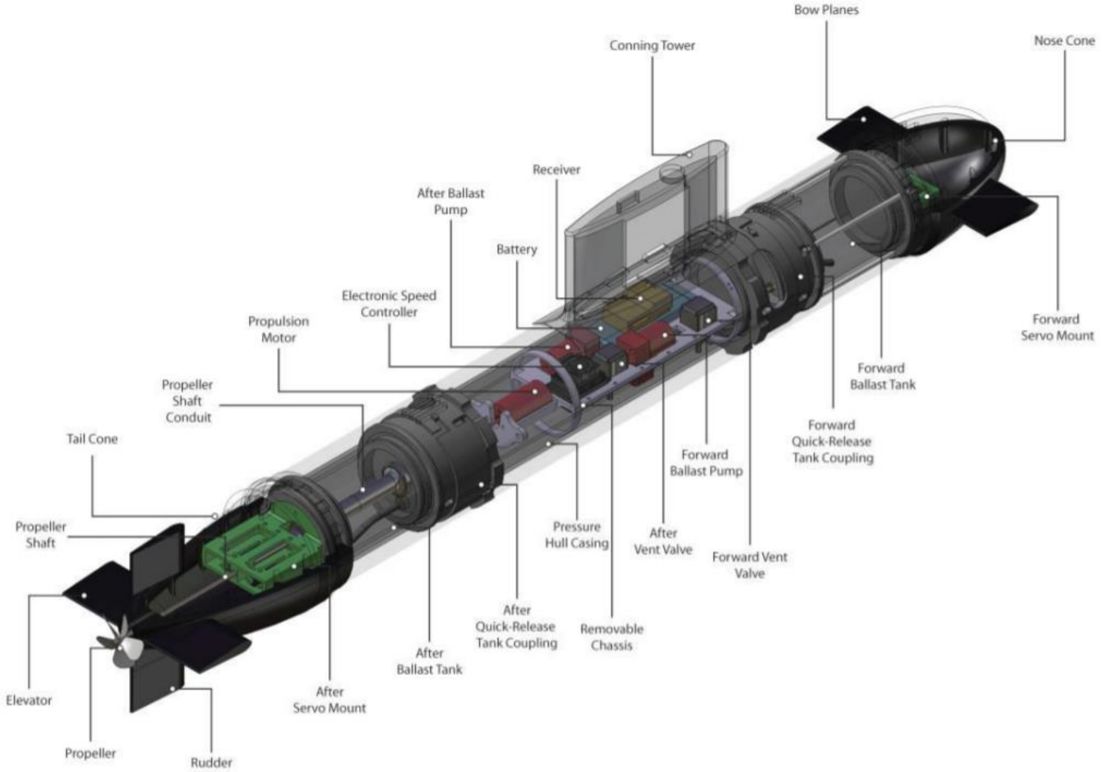

Figure 5: The developed UVV model, including the new design of the pressure hull and depth-control systems.

To aid in disassembly, this was achieved by appending a tail shaft with an additional shaft coupler to the end of the existing shaft. The conning tower was totally redesigned with functionality as a focus. Lower scuppers were added to assist with drainage during surfacing operations and an access panel was introduced to allow effortless connection/disconnection of the main battery switch. Adhesive bonding was avoided wherever possible to allow for total disassembly of the boat when necessary. As a result, the boat was able to be totally disassembled to the component level with the exception of the pressure hull quick release couplings, which were bonded to the pressure hull casing with high-strength adhesive hull quick release couplings, which were bonded to the pressure hull casing with high-strength adhesive.

TOWING TEST FACILITY

The towing test facility was designed to tow an UUV at a constant velocity whilst measuring the force on the tow line. By implementing this test into the competition, students will factor these aspects into their UUV design and be exposed to further engineering concepts. This device has further potential applications, in particular, for use in universities to teach important engineering concepts.

As such, the design of the towing test facility considers the end user available budget and level of education. Figure 6 depicts a CAD model of the concept design conducting a resistance test on a model UUV. On the left-hand side of the pool sits the main towing unit which is weighed down by buckets filled with pool water. Through the length of the pool runs the line which is connected to the nose cone of the UUV. The towing apparatus is a reel driven by a geared DC motor with encoder feedback for control of velocity and to measure displacement through the pool.

Fig. 6 shows the line passes over a pulley mounted on top of a load cell. As the model submarine is towed at a constant velocity, the load cell continuously takes readings to measure the force on the line. The reel's inbuilt drag system is employed when the system is used to test the installed propulsive power of the model submarine.

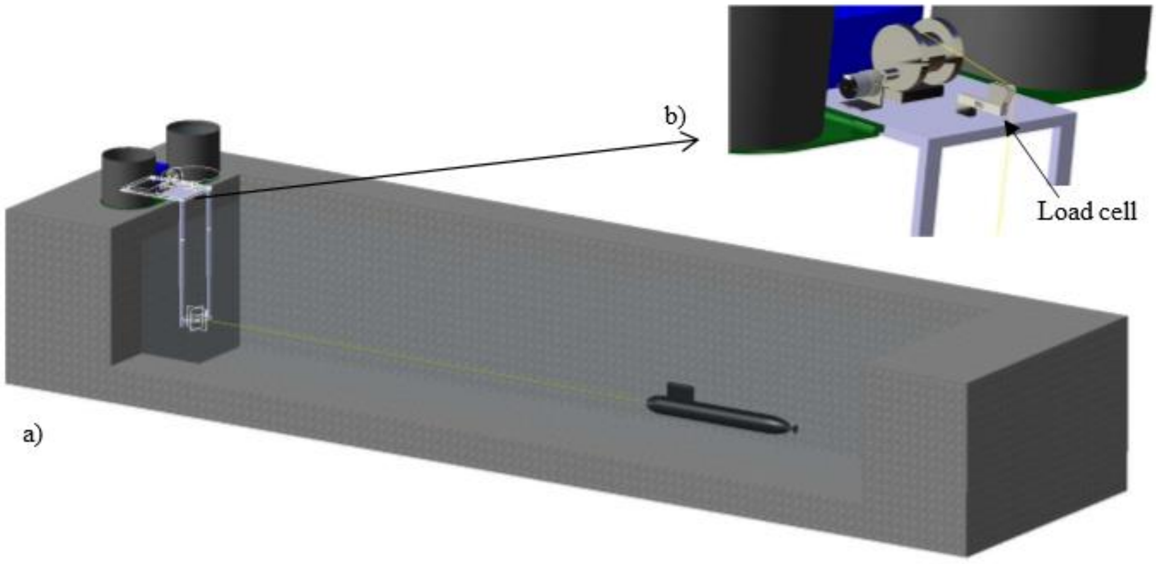

Figure 6: Showing a) CAD concept drawing and b) close up of towing unit.

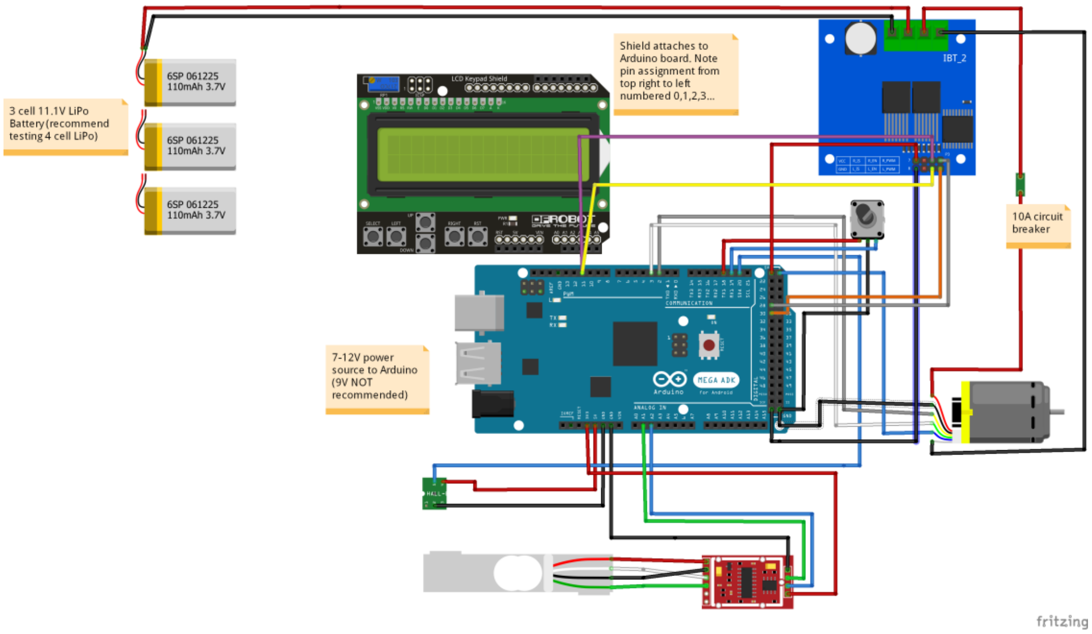

Figure 7: Wiring diagram for electronics

This was achieved by setting the amount of force required to unspool the line from the reel and measuring the time taken for the submarine to unspool a defined length of line from the spool under its own power. This length of line is determined by a hall effect sensor mounted near the reel's spool which has four permanent magnets fixed evenly around the circumference. This records the revolutions of the spool and uses the reel's gear ratio and line retrieved per handle revolution to measure the displacement.

To select the components for the towing unit, an experiment was conducted to determine the linear displacement of line retrieved per revolution of the reel's handle. This was found to be 645 mm, and with a gear ratio of 3.6:1, this equates to each revolution of the spool retrieving 179.2 mm of line. The approximated resistance of 4.6 N, the design velocity of 2 m/s and the reel's gear ratio were then used to conduct dynamic analysis to estimate the required specifications for the DC motor and load cell.

Significant work went into electronics and software design. As depicted in Fig. 7, the main electrical components consist of an Arduino board with a Liquid Crystal Display (LCD) keypad shield for a user interface, DC gear motor, a motor driver, load cell and load cell amplifier, hall effect sensor and a rotary encoder. The system was designed for standalone use without an external computer connected, and several firmware functions had to be developed that could operate via a user interface.

EXPERIMENTAL TESTS AND RESULTS

A series of experiments were conducted to test the code, to prove the design concept and determine if the device could take force and velocity readings that were consistent and repeatable, as shown in Fig. 8. To validate the results using empirical formulae two 90 mm diameter by 5mm length discs were 3D printed from PLA with one including a central 2mm hole to which line was secured. One disc was secured to a 421 mm length of 90 mm diameter PVC pipe, and the other disc had a series of 13 mm holes drilled centrally. The cylinder was placed in a tank of water and a piece of foam was added centrally and adjusted until the cylinder was neutrally buoyant at 0.5 m depth with nil trim. The foam was then secured at this location and the rear disc was secured to the other end of the cylinder. The Reynolds number (Re) was calculated by measuring the temperature of the pool, looking up the value for kinematic viscosity at this temperature and using the fresh water density, as discussed in Annex I. Based on this Re value, the drag coefficients and relationships for the predicted drag force were obtained based on an empirical formula [7], for further details refer to Annex I. Fig. 9 illustrates the calculated results and measured data from conducting a series of experimental tests by utilising the cylinder model that was towed at a range of constant speeds from 1.31 to 1.36 m/s in 0.2 m/s increments.

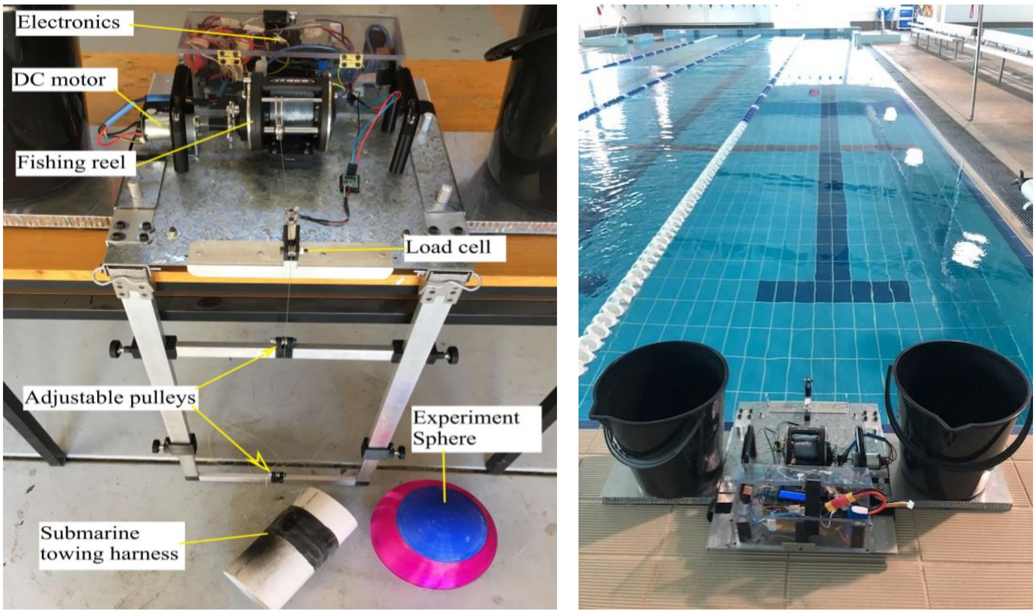

Figure 8: Showing (a) components of the resistance and power testing apparatus, and (b) the test rig setup poolside.

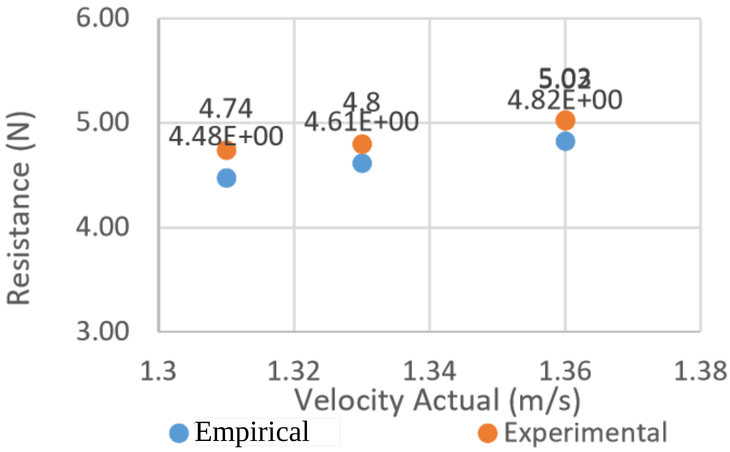

Figure 9: Showing the empirical results of resistance magnitudes and the measured data with a deviation of < 5%.

DISCUSSION

The objective of this work was to design a portable device for the Subs in Schools competition to emulate a towing tank facility and accurately measure the resistance and power of the model submarines. Preliminary testing data for the resistance and power testing apparatus were promising. The target velocity of 1.5 m/s was not achieved as the PID values are yet to be tuned, resulting in the system not being able to achieve and maintain the required set point value. Nonetheless, the theoretical resistance at the experimental actual velocity values were calculated and compared against the experimental results. The towing device consistently gave readings that were on average 4.6 % above theoretical. When the same target velocity of 1.36 m/s was achieved, the experimental readings were within 0.01 N of each other. The difference between theoretical and experimental results are attributed to friction in the lower pulley, resistance on the line through the water and the change in velocity due to the spooling effect. With further testing there is scope to be able to determine a friction factor that may be deducted from the output readings via the code to improve the accuracy.

Prior to the cylinder experiment, a single attempt was made to tow the model UUV through the pool. The UUV's electronics were turned on for the test to enable the operator to make adjustments to the control surfaces to set them at zero angle of attack. During the 25 m resistance test an electrical issue cycled the servo motors that drive the control surfaces, which steered the UUV model out of control. Due to time constraints the UUV model tests were abandoned, including an experiment to validate the 'power test' function. This initial attempt to tow the UUV indicated that the towing test facility can only be used on model UUVs that are fully functional, so that the operator can make adjustments to the control surfaces to ensure that a course to mid ships is maintained during testing.

Preliminary experimental results prompted a design review which highlighted that noise in the load cell readings caused the average resistance value to be inaccurate. Filtering the readings through the use of the statistical median or low pass filter shows potential for the device to offer a capability that is unparalleled on this scale.

Important applications for the towing test facility have been identified. The device could be used by students in marine engineering to measure the drag force on various geometric shapes in a pool, and then compare the results to theory. It could also be used in a naval architecture laboratory to measure the resistance and power of model ship designs.

This means that any maritime university in the world with access to a pool could use the designed towing test facility to facilitate student learning of important key engineering concepts. It may also be of interest to small-boat designers without access to a towing tank to verify CFD resistance results. As noted above, there is only one commercial towing tank facility in the Arab world, at the Military Technical College in Cairo, Egypt. Whilst this may be prohibitively expensive or restricted for a small business or university, the proposed device could be built at a fraction of the cost.

CONCLUSION

The project to develop a reliable Unmanned under water vessel's pressure-hull and depth-control system that is straightforward to manufacture and simple to maintain is well underway with half of the milestones already completed. The base-model has been completed and tested, with the applicable faults identified, and a design solution conceptualised. A detailed design is still needed with associated proof of concepts carried out.

The second objective of this work was to determine if a device that emulates towing tank testing could be designed and developed to measure the resistance and power of the model submarines in RE-Engineering Arab World competition in the future. To achieve this, a towing test facility was designed and a prototype was manufactured for proof of concept testing. The work proved that it is indeed possible to design a device that emulates towing tank testing for use in regional Schools' competitions. With further research and development, the device may also be used in university laboratories to aid student learning and by small-boat designers to validate resistance approximations.

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Dr Ahmed Swidan is a Marine Engineer with over 20 years of maritime experience across the navy, ship industry and academia. Dr Swidan is a Senior Lecturer at the AASTMT, an adjunct Professor at the University of New South Wales (UNSW) in Australia, a consultant for the Australian Maritime Safety Authority and a committee member of RINA. Previously Swidan was a Lecturer at the Australian Maritime College for six years.

Annex I

APPROXIMATION OF RESISTANCE ON RAW UUV MODEL

The following calculations are used to approximate the total resistance on the RAW model submarine and yields a value of 4.3252N. This is based on theoretical equations discussed in Chapter 4 of [7].

Table I: Particulars as measured from RAW UUV model.

Parameter	Assigned Symbol	Approximate Value
Length overall	L_{oa}	0.977m
Length of fore body	L_{fb}	0.095m
Length of parallel middle body	L_{pmb}	0.730m
Length of aft body	L_{ab}	0.152
Diameter	D	0.110m
Wetted surface of hull	S_{hull}	0.3076m^2
Casing factor	K_c	1
Fore body fullness factor	n_f	2.2
Frontal area of hull	A_F	0.0095m^2
Chord of sail	c_{sail}	0.2m
Maximum Thickness of sail	t_{sail}	0.029m
Wetted surface of sail	S_{sail}	4.3715x10^{-2} m^2
Chord of aft control surface	c_{acs}	0.059m
Maximum Thickness of aft control surface	t_{acs}	0.009m
Planform area of aft control surface	$A_{planacs}$	0.0024m^2
Chord of forward control surface	c_{fcs}	0.059m
Maximum Thickness of forward control surface	t_{fcs}	0.009m
Planform area of forward control surface	$A_{planfcs}$	0.0024m^2

For estimated resistance calculations, assume:

Velocity $V = 2ms^{-1}$

Density fresh water $\rho = 1000kg\,m^{-3}$

Kinematic Viscosity (of fresh water at 20°C) $\nu = 1.0005 \times 10^{-6} m^2 s^{-1}$

Hull Calculations

$$Re = \frac{VL_{oa}}{\nu} = 1.953 \times 10^6$$

$$C_{Fflat} = \frac{0.067}{(logRe - 2)^2} = 3.639 \times 10^{-3}$$

$$But\ C_{Fflat}\ also = \frac{R_{flatplate}}{0.5\rho S_{hull} V^2}$$

Where $R_{flatplate}$ is the resistance of the hull modelled as a flat plate.

$$\therefore solving\ gives\ R_{flatplate} = 2.2387N$$

However, this does not account for the effects of the form of the hull compared to that of a flat plate. Therefore, using equation

$$R_{Thull} = 0.5\rho V^2 S_{hull}(C_{Fformhull} + \Delta C_{Fformhull} + K_c C_{Phull})$$

Where $C_{Fformhull} = \frac{0.075}{(logRe-2)^2}(1 + K_F)$

And $K_F = \frac{0.3D}{L_{oa}} = 3.378 \times 10^{-2}$

$$\therefore C_{Fformhull} = 4.212 \times 10^{-3}$$

This is the skin friction component where K_F accounts for the form of the hull.

$\Delta C_{Fformhull}$ is a factor that accounts for the surface roughness of the hull. Surface ships add a value of 0.0004 however this does not account for additional resistance for vent holes and other surface inconsistencies. As this additional resistance factor is unknown, the surface ship value of 0.0004 is used and it is acknowledged that this is incorrect.

$$\therefore \Delta C_{Fformhull} = 0.0004$$

$$C_{Phull} = K_p \times C_{Fformhull}$$

$$Where\ K_p = \left[\zeta_{hull} + \zeta_{PMB}\left(\frac{L_{PMB}}{L}\right)^{\eta_{PMB}}\right]\left(\frac{L}{D}\right)^{\eta} = 0.2012$$

$$(\ \zeta_{hull}, \zeta_{PMB}, \eta_{PMB}\ and\ \eta\ and\ constants\ derived\ from\ research. See\ Table\ 4.2\ from\ reference)$$

$$\therefore C_{Phull} = 0.2012 \times 4.212 \times 10^{-3} = 8.476 \times 10^{-4}$$

$$\therefore R_{Thull} = 0.5 \times 1000 \times 2^2 \times 0.3076 \times (4.212 \times 10^{-3} + 0.0004 + 1 \times 8.476 \times 10^{-4})$$

$$R_{Thull} = 3.359N$$

Sail Calculations

$$R_{Tsail} = 0.5\rho V^2 S_{sail}(C_{Fformsail} + \Delta C_{Fformsail} + K_c C_{Phull})$$

$$C_{Fform,sail} = \frac{0.08}{(logRe - 2)^2}$$

$$Re_{sail} = \frac{Vc_{sail}}{\nu} = 1.999 \times 10^8$$

$$\therefore C_{Fform,sail} = 2.015 \times 10^{-3}$$

To account for surface roughness the surface ship factor is once again used.

$$\therefore \Delta C_{Fformsail} = 0.0004$$

$$C_{Psail} = 10 \times \left(\frac{t_{sail}}{c_{sail}}\right)^{1.75} \times C_{Fform}, sail = 6.8655 \times 10^{-4}$$

$$R_{Tsail} = 0.2712N$$

Control Surface Calculations

$$C'_{Tcs} = \left[2 + 8\left(\frac{t_{cs}}{C_{cs}}\right)^{4.5}\right] \times C_{Fform,cs}$$

$$Re_{cs} = \frac{Vc_{fcs}}{\nu} = 1.1794 \times 10^5$$

$$C_{Form,cs} = \frac{0.08}{(logRe - 2)^2} = 7.556 \times 10^{-3}$$

$$\therefore C'_{Tcs} = 2.453 \times 10^{-2}$$

$$R_{Tcs} = 0.5\rho V^2 A_{plan} C'_{Tcs} = 0.11578N$$

There are six control surfaces

$$\therefore \sum R_{Tcs} = 6 \times R_{Tcs} = 0.695N$$

Resistance Approximation Total

$$R_{Total} = R_{Thull} + R_{Tsail} + \sum R_{Tcs} = \mathbf{4.3252N}.$$