Subs in Schools: Engineering a Reliable Depth-Control System and Pressure-Hull

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The "Subs in Schools" STEM project baseline remotely-controlled submarine kit suffers from several functional deficiencies; predominately its resistance to water ingress and effective depth-control. The aim of the project reported is determining whether the pressure-hull and depth-control system can be redesigned to significantly improve reliability, manufacturability and maintainability. Discussed is the intended approach for developing a new design and associated prototype. This includes construction and testing of the current design to identify limitations; conducting reliability analysis of the key components; presenting a proposed concept design for the improved version; and a summary of work completed to date. The tests on the existing model confirmed reports of leakage and limited depth-control functionality. Literature suggests that bulkhead penetrations are the primary weakness for water ingress; an argument supported by the experimental findings. The Failure Mode and Effect Analysis (FMEA) model in conjunction with the exponential random failure analysis model, is used to estimate the reliability of the pressure hull. A concept for a revised design is presented that will require proof of concept experiments and the subsequent manufacture of a testable prototype.

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

INTRODUCTION

Reengineering Australia's (REA) "Subs in Schools" (SiS) Technology Challenge invites school students to design, build and operate remotely-controlled submarines to compete in an annual national competition (soon to be international). The competitors are permitted to enter an REA-designed kit-model or alternatively, design their own submarine or variation of the kit-model. However, to date, no competitors have successfully manufactured a correctly functioning example of the REA entry-level submarine kit. Models invariably suffer from malfunctions associated with water ingress and a general inability to effect reliable depth-control [1]. The purpose of the kit is to provide the foundation to develop a functioning remote submersible fit to compete in the competition. The difficulty for it to perform basic submarine operations reliably, fundamentally undermines its intent and essentially renders it redundant. The overarching limitation of these aspects of the model appear to lie in a general lack of reliable functionality.

SCOPE/AIM

The reported study focussed on devising a solution to address the deficiencies in the kit-model's watertight integrity and depth-control system. While the baseline models may exhibit deficiencies in other areas; such as manoeuvrability, this project targets 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 for high school students. The scope involves assembling the existing kit design in accordance with the build manual [2] and testing for functionality. Identifying the deficiencies and determining the model's reliability, a revised design of the respective systems is to be conceived and manufactured. This prototype will then be tested, assessed for reliability and compared to the baseline design with recommendations to be submitted to REA.

CURRENT MODEL

The current SiS base kit-model required significant effort to complete construction. This was chiefly due to the ambiguous nature of the build manual [2]. Problems contributing to delays in the construction process included:

- Instructions often conflicted with images
- Several images were not relevant to the direction given
- Images were often unclear
- Terminology was vague, colloquial or incorrect
- Part numbers were not referenced in the instructions
- Lack of instructions/design drawings provided for manufacturing certain required parts
- Kit was incomplete
- Parts incompatible with 3D printed mounts
- Parts missing entirely
- No electrical drawings provided

DESIGN

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

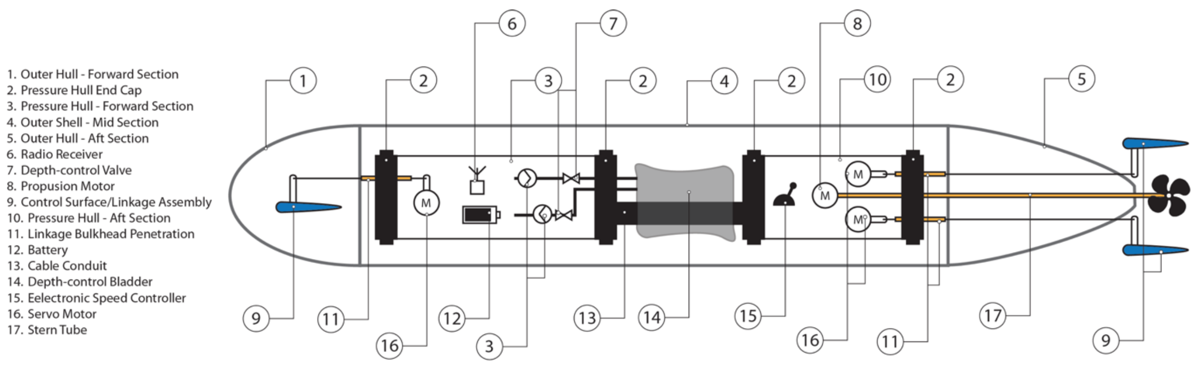

Figure 1 – Schematic diagram of SIS base kit

Depth-control is effected by 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 resurface, the procedure is reversed by means of a separate dedicated pump-valve system.

Experiment

Upon successful completion of the kit, the model was subjected to basic function tests in a controlled environment. A test bath was filled with fresh water and the model was placed on the surface in order to establish the hydrostatic behaviour of the vessel (Figure 2). In order to keep the vessel transversely upright, it was necessary construct a weighted keel. To neutrally trim the vessel, ballast (in the form of stainless-steel washers) were added to the forward and aft sections as required.

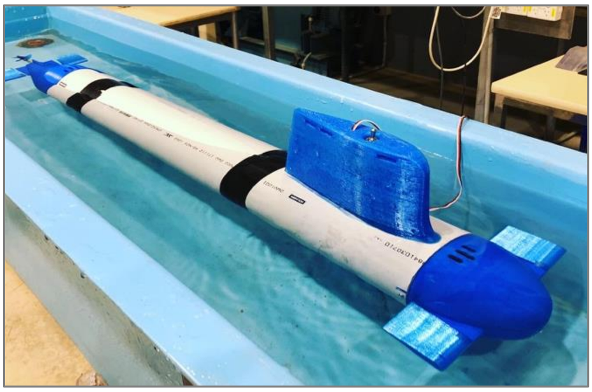

Figure 2 – Completed base kit-model surfaced in test bath

With the vessel floating freely, a test of the propulsion and control surfaces was carried out. All systems functioned correctly on the surface and there was no evidence of water leakage into the pressure-hull.

The depth-control system was tested next. The submersion pump was activated, and the vessel began to dive. The hydrostatic behaviour of the vessel changed instantly. The vessel began to trim forward with constant redistribution of the ballast being necessary to keep it neutrally trimmed. The submersion process was noted as being particularly sluggish and due to the outer shell being entirely opaque, it was impossible to determine the status of the inflatable bladder. The time taken to fully submerge to a depth of 200mm was approximately five minutes.

Once submerged, a function test of propulsion and control surfaces was re-conducted. All systems functioned correctly. However, when the surfacing pump was activated, the vessel would only fully surface by the head (or stern), depending on how the ballast was distributed. This process was also sluggish with the vessel not able to fully surface at any point. Upon completion of the test, the model was dismantled for diagnosis. It was found that the water-tightness of the pressure-hull had not held and, although they were still functioning, the electronic components were partially submerged in water in both sections.

The water was drained, and the model dried before conducting a secondary test. This test was conducted as in the previously described manner. However, during this test the bladder was pre-pressurised to determine the ability of a positively pressurised hull to resist water ingress. During the second descent, air was observed to escape from the bow-plane linkage seal (see Figure 3). It was determined that these seals were the most likely source of leakage in the forward and after sections of the pressure-hull.

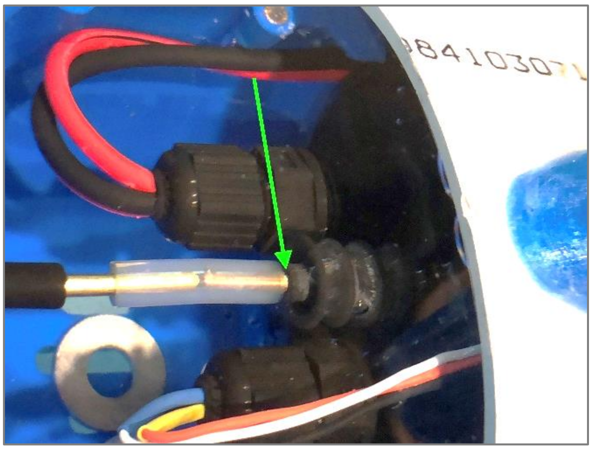

Figure 3 – Image of the bow-plane linkage seal (leakage point indicated)

Experimental Results/Identified Problems

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.

Interestingly, these two problems appear to be coupled. As predicted in the literature, pressure-hull water ingress appears to be isolated to the bulkhead penetrations; specifically, the bellow seals that fit over the bow-plane control linkages (Figure 3). 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 vacuum state 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 displacement of the vessel beyond the buoyant capability of the depth control system, 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.

Assuming these water tight integrity problems can be solved, the performance of the current depth-control system remains unsatisfactory. Even functioning with no leaks, responsiveness is low and the time to reach depth, unacceptable. The source of the problem appears to also be with the fundamental design of the depth-control system. The pumps currently transfer air (sourced from the pressure-hull) in and out of the bladder. The compressive property of air is most likely reducing the efficiency of the pump as the vacuum pressure in the hull increases. Theoretically, this means that the responsiveness of the depth-control system degrades as the depth increases.

RELIABILITY ANALYSIS

A crucial factor influencing further functional testing of the submarine is the pressure-hull's considerable vulnerability to water ingress. In this section, determining the reliability of the various components that potentially contribute to failure of the pressure-hull are discussed. 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 [3-8]. 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 the repeated collection of reliability data.

The pressure-hull assembly is composed of several components that effect its ability to maintain watertight integrity. These components and their functional relationship with respect to failure, are presented in Figure 4. From the components identified, a subsequent failure mode effect analysis was carried out as presented in Table 1.

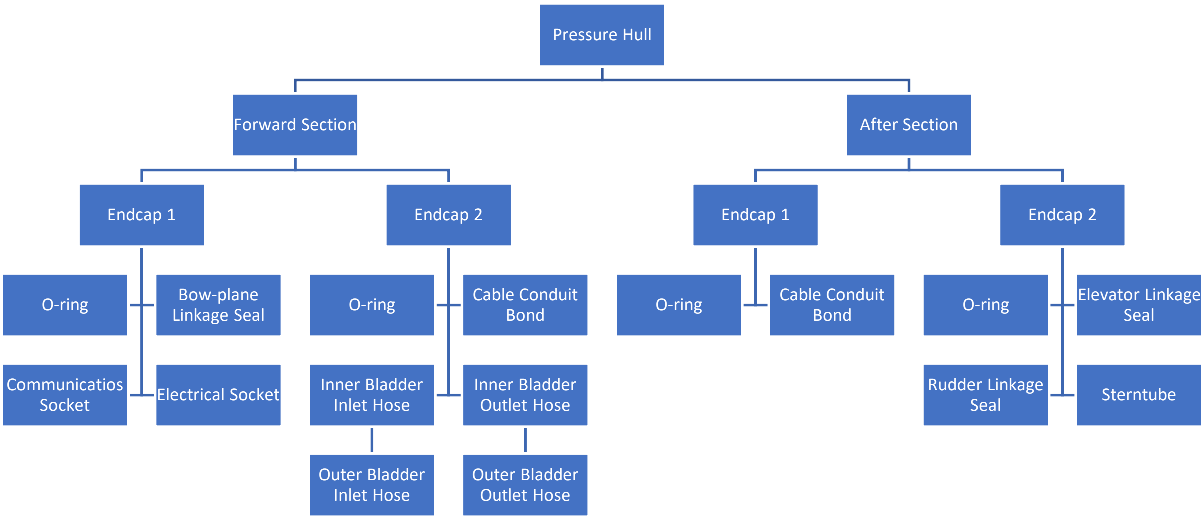

Figure 4 - Functional Component Layout: SiS Kit Model Pressure-Hull

By considering the estimated likelihood of failure along with observations from the experiment, the Mean Time to Failure (MTTF) was approximated. These values were determined by discussing their feasibility with a competition subject matter expert and a conferring with a reliability-engineering specialist. The constant failure rate was calculated by the relationship:

$$\lambda = \frac{1}{MTTF} \qquad (1)$$

The resulting failure rates can be viewed in Table 2.

Table 1 – Failure Mode Effect Analysis of SiS Kit Model Pressure-Hull

Component	Failure Mode	Failure Cause	Consequence	Likelihood	Reliability Analysis Model
Bow-plane Linkage Seal	Water Ingression	Pressure Overload	Electronics System Failure /Reduction of Buoyancy	High	Random Failure
Elevator Linkage Seal	Water Ingression	Pressure Overload	Electronics System Failure /Reduction of Buoyancy	High	Random Failure
Rudder Linkage Seal	Water Ingression	Pressure Overload	Electronics System Failure /Reduction of Buoyancy	High	Random Failure
Stern Tube Seal	Water Ingression	Degradation of Lubricant/ Pressure Overload	Electronics System Failure /Buoyancy Failure	Possible	Random Failure
O-ring - Forward Section Endcap 1	Water Ingression	Pressure Overload	Electronics System Failure /Buoyancy Failure	Low	Random Failure
O-ring - Forward Section Endcap 2	Water Ingression	Pressure Overload	Electronics System Failure /Buoyancy Failure	Low	Random Failure
O-ring - After Section Endcap 1	Water Ingression	Pressure Overload	Electronics System Failure /Buoyancy Failure	Low	Random Failure
O-ring - After Section Endcap 2	Water Ingression	Pressure Overload	Electronics System Failure /Buoyancy Failure	Low	Random Failure
Electrical Connector Socket	Water Ingression	Shock Fracture	Electronics System Failure /Reduction of Buoyancy	Low	Random Failure
Aerial Connector Socket	Water Ingression	Shock Fracture	Electronics System Failure /Reduction of Buoyancy	Low	Random Failure
Cable Conduit Bonds	Water Ingression	Shock Fracture	Electronics System Failure /Buoyancy Failure	Low	Random Failure
Outer Bladder Inlet Hose	Water Ingression	Pressure Overload	Electronics System Failure /Buoyancy Failure	Low	Random Failure
Inner Bladder Inlet Hose	Water Ingression	Pressure Overload	Electronics System Failure /Buoyancy Failure	Low	Random Failure
Outer Bladder Outlet Hose	Water Ingression	Pressure Overload	Electronics System Failure /Buoyancy Failure	Low	Random Failure
Inner Bladder Outlet Hose	Water Ingression	Pressure Overload	Electronics System Failure /Buoyancy Failure	Low	Random Failure

Table 2 - Constant Failure Rates of Pressure Hull Components

Component	Approximated Mean Time to Failure (MTTF)	Calculated Constant Failure Rate Per Hour, λ
Bow-plane Linkage Seal	1.25h	0.80
Elevator Linkage Seal	1.25h	0.80
Rudder Linkage Seal	1.25h	0.80
Stern Tube Seal	4.00h	0.25
O-ring - Forward Section Endcap 1	24.00h	0.04
O-ring - Forward Section Endcap 2	24.00h	0.04
O-ring - After Section Endcap 1	24.00h	0.04
O-ring - After Section Endcap 2	24.00h	0.04
Electrical Connector Socket	36.00h	0.03
Aerial Connector Socket	36.00h	0.03
Cable Conduit Bonds	48.00h	0.02
Outer Bladder Inlet Hose	72.00h	0.01
Inner Bladder Inlet Hose	72.00h	0.01
Outer Bladder Outlet Hose	72.00h	0.01
Inner Bladder Outlet Hose	72.00h	0.01

The subsequent reliability of each component is calculated using the exponential relationship:

$$R(t) = e^{-\int_0^t \lambda dt} = e^{-\lambda t}, t > 0 \qquad (2)$$

This yielded the following failure rates:

$R_{link.seal}(t) = e^{-0.80t}$
$R_{o-ring}(t) = e^{-0.04t}$
$R_{socket}(t) = e^{-0.03t}$
$R_{cndt.bnd}(t) = e^{-0.02t}$
$R_{stn.tbe}(t) = e^{-0.25t}$
$R_{hoses}(t) = e^{-0.01t}$

A summary of the reliability parameters is presented in Table 3. By analysing the resulting data, it is observed that the reliability of the pressure-hull is dominated by the reliability of the linkage seals. This suggests that by improving the reliability of these components, the functionality of the pressure-hull will be significantly improved. The comparative reliability of each component was then plotted over a submerged operating period of twenty hours (Figure 5).

Table 3 - Summary Results from Exponential Reliability Analysis: Pressure Hull Components

Component	R(t)	λ(t)	Approximate (MTTF)
Bow-plane Linkage Seal	$e^{-0.80t}$	0.80	1.25h
Elevator Linkage Seal	$e^{-0.80t}$	0.80	1.25h
Rudder Linkage Seal	$e^{-0.80t}$	0.80	1.25h
Stern Tube Seal	$e^{-0.25t}$	0.25	4.00h
O-ring - Forward Section Endcap 1	$e^{-0.04t}$	0.04	24.00h
O-ring - Forward Section Endcap 2	$e^{-0.04t}$	0.04	24.00h
O-ring - After Section Endcap 1	$e^{-0.04t}$	0.04	24.00h
O-ring - After Section Endcap 2	$e^{-0.04t}$	0.04	24.00h
Electrical Connector Socket	$e^{-0.03t}$	0.03	36.00h
Aerial Connector Socket	$e^{-0.03t}$	0.03	36.00h
Cable Conduit Bonds	$e^{-0.02t}$	0.02	48.00h
Outer Bladder Inlet Hose	$e^{-0.25t}$	0.01	72.00h
Inner Bladder Inlet Hose	$e^{-0.25t}$	0.01	72.00h
Outer Bladder Outlet Hose	$e^{-0.25t}$	0.01	72.00h
Inner Bladder Outlet Hose	$e^{-0.25t}$	0.01	72.00h

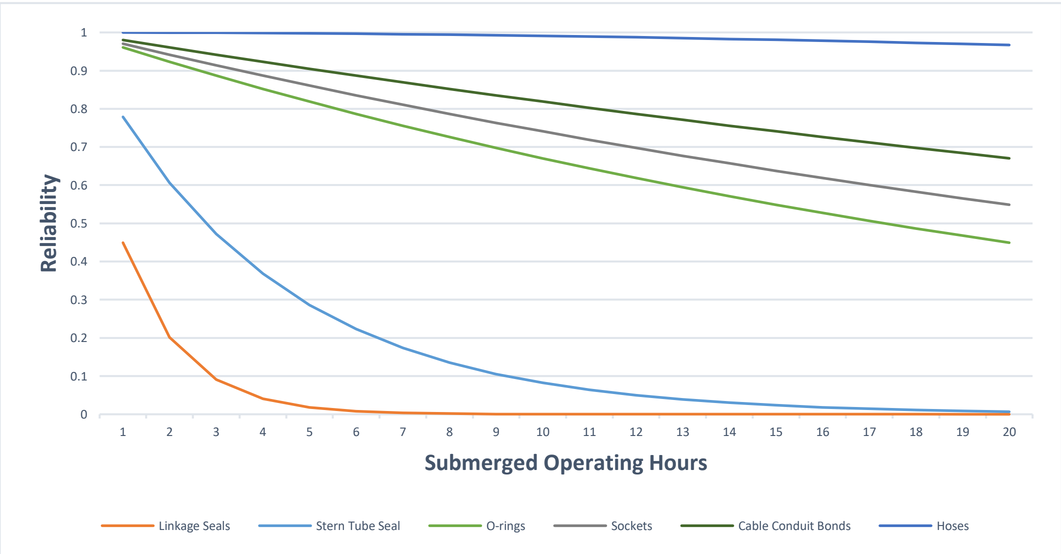

Figure 5 - Reliability of Pressure-hull Components as a Function of Time

PROPOSED DESIGN

Design Requirements

Based on the results from preliminary experiments, relevant literature and the intent of the SiS competition, several requirements were formulated for the redesign. The requirements are presented in Table 4 and reflect a significant improvement in reliability.

Table 4 – Design Requirements

Mandatory	Desirable
Pressure hull must reliably resist water ingression	The design should incorporate as many existing components as possible
Depth-control system must function correctly and reliably	The design should allow for ease of maintenance/access
Desired depth must be capable of being reached in a timely manner	The design should be as simple as reasonably possible
The redesign must be capable of being manufactured by SiS applicants	
The depth-control system must be of a VBS type	
The depth-control system must be capable of functioning while stationary	
The vessel must be able to adjust trim without the use of control planes	

Concept Design

The revised design attempts to draw on Burcher and Rydill's philosophy of simplicity in the pressure-carrying envelope [9]. In addition, a two-tank system has been adopted in light of the prevalence of this configuration found in the literature [10-13]. The proposed general arrangement and new components have been designed with special consideration given to ease of manufacturing, maintainability and robustness.

To combat the water ingress problem, the control surface servo motors are to be mounted external to the pressure- hull (see Figure 6-5, 13). Water resistant servos will be supplemented for the existing servos. This relocation will remove the requirement for moving components to penetrate the pressure-hull and reduce all bulkhead penetrations to cable runs, water pipes and the stern tube (Figure 6-15). The static nature of these remaining penetrations will make sealing and consequently manufacturing, much easier.

The revised depth-control system includes forward and aft ballast tanks which operate independently to effect pitch/trim control without the use of the control surfaces (see Figure 5-3, 11). The new system transfers water from the external environment into sealed ballast tanks via a pump and valve arrangement designated to each tank. While the pumps and valves will be located within the pressure-hull, there no longer exists an interface between the pressure-hull and the ballast tanks. This should aid in reducing the load on the pressure-hull seals and stern tube as pressure will only be a function of the vessel's depth. In addition, the positive displacement of water instead of air should increase the responsiveness of the system due to water's more efficient displacement. The intention is to utilise the pumps only for filling the tanks and to employ the pressurised air within as a means to jettison the water when surfacing.

This will reduce the need for additional hardware and added complexity. To aid with alignment, maintenance and robustness, a series of structural components have also been designed. The redesign includes a forward and aft separable self-aligning collar assembly. The forward and aft ballast tanks can be separated from the main pressure-hull by means of a bayonet fitting included in the collars. The collars also include a void space for fitting electrical connectors with a slot where wires can penetrate and be loomed along the inside of the outer shell. The new design is intended to be capable of being integrated with the existing outer shell components and has attempted to minimise substitutions for fundamental parts in the current kit where possible.

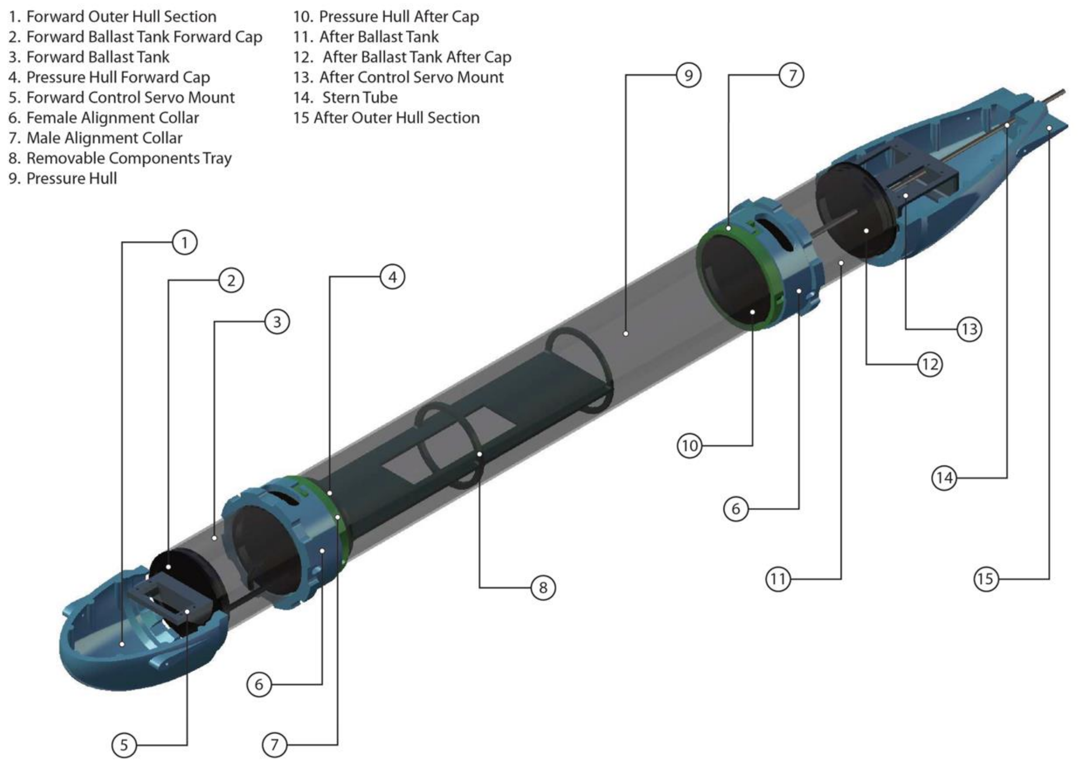

Figure 6 – The proposed redesign for the pressure hull and depth-control system

CONCLUSION

At this stage of writing, the project to develop a reliable 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. However, there is still work to be achieved in the coming months. A detailed design is needed with associated proof of concepts experiments carried out. In addition, reliability modelling; suitable for accurately analysing both the existing system, and the revised prototype, needs to be implemented.

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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