Nature in Engineering for Monitoring the Oceans (NEMO): An isopycnal soft bodied approach for deep diving autonomous underwater vehicles

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***Abstract*— Taking inspiration from nature the NEMOdeep vehicle described in this paper is being developed as a laboratory demonstrator to showcase potential technologies to achieve small deep diving autonomous underwater vehicles. The design of the vehicle is a hybrid of conventional AUV components with engineered analogues of marine animal organs. The internal structure is comprised of a spine, ribs and sternum, which support a hydrodynamic fairing or 'skin'. The 'brain' and actuators are developed using pressure tolerant electronics, negating the need for pressure vessels. The pressure tolerant electronics are surrounded by light mineral oil which transmits the hydrostatic pressure uniformly to the components while also providing buoyancy. The internal fluid is more compressible than seawater and the batteries and internal structure are less compressible than seawater: a 'Buoyancy/Compressibility' organ is being developed to passively maintain neutral buoyancy over the 0 to 6000m depth range.**

***Index Terms*—Deep Diving, isopcynal, bio-inspired, AUV.**

I. Introduction

The ocean depths are the dominant ecosystem on the planet by volume, providing up to 97% of the biosphere, yet scientists have explored less than 1% of the oceans seabed [1]. Since, 81% of the world's ocean floors occur at water depths of between 3000m and 6000m, deep diving underwater vehicles provide an ideal platform for exploring this harsh environment.

Species of marine animals have evolved biological solutions to the challenges of high hydrostatic pressures and are able to survive, sometimes in large numbers, at the depths of the deepest ocean trenches, at ambient pressures of more than 100MPa [2]. As such they present a wealth of different evolved solutions to the problems of 'living' in the marine environment especially operation at high hydrostatic pressures. This work concentrates on the issues associated with operating over large depth ranges, and looks to nature for inspiration as to how to reduce the size of deep diving capable Autonomous Underwater Vehicles (AUVs).

A. Motivation

In conventional AUVs metal or composite pressure vessels provide watertight and gas-tight enclosures for the electronics and other systems to operate in essentially one-atmosphere dry internal spaces. To maintain the structural integrity of the pressure vessel with increasing water depth requires an increased wall thickness (assuming a constant material), this in turn leads to increased system mass. In order to maintain near neutral buoyancy this requires a reduction in mass of other systems (i.e. reducing the number of batteries), or increasing the volume of buoyancy material, leading to increased vehicle size and mass.

An example of the increasing vehicle mass with depth range is provided by the REMUS family of AUVs. The REMUS 100 is the most numerous AUV model of the family; it has a maximum operating depth of 100m and a mass of 37kg, the REMUS 600 has a maximum operating depth of 600m and a mass of 240kg and the REMUS 6000 is the largest with a depth range of 6000m and a mass of 884.5kg. However, this is not a completely fair comparison since the payload capacity and endurance of the vehicle also changes. The endurance of the three models is 10 hours, 70 hours and 22 hours for the 100, 600 and 6000 models respectively.

The increase in hydrostatic pressure with depth results in many underwater vehicles having a finite safe allowable depth prior to plastic collapse of pressure vessels. For manned military submarines this depth is typically 200-400m [3] while for AUVs this is can be 4000-6000m [4] or deeper for a few specialist survey AUVs [5]. Marine animals are found from the shallows to the deepest parts of the ocean (11,000m in the Mariana Trench) were they must be fully adapted to pressures in excess of 110MPa.

The influence of pressure on marine animal size is less clearly understood, attempts to explain body size in terms of pressure lead to varying conclusions depending on the class or species under consideration. Analysis of eight species of deep-sea benthic gastropods showed a clear trend for size to increase with depth [6]. Smith and Brown [7], investigated the influence of depth on the size of pelagic fish native to the north-east Pacific Ocean between 40^{o}N and 50^{o}N, over a depth range of 0-8000m. The relationship observed varied among classes and orders. Statistically significant relationships between maximum body length and mean depth of occurrence were observed for seven of the 12 orders. But the direction of these relationships varied. Collins *et al.* [8] investigated the relationship of benthic fish size with respect to depth for scavengers and predators of the north east Atlantic. The analysis showed a significant increase in body size for scavenging fish with increasing depth, while predatory fish showed a slight but significant decline with increasing depth. The discrepancies where explained in terms of food distribution, whereby scavengers become larger in order to increase endurance due to larger energy reserves and lower metabolic costs enabling them to survive on sporadic food items. It is worth highlighting that for marine animals changes in depth also result in changes in light, temperature and food availability and hence it is not always possible to identify which variable(s) influence size [2].

One key operational difference between AUVs and many marine animals is the importance of depth range. AUVs, marine mammals, birds and reptiles must initiate and finish 'missions' at the surface in order to recharge or breathe respectively, as such they must be adapted to operate at the range of hydrostatic pressures from the surface to the maximum dive depth. This is stark contrast to fish and other fully aquatic animals, which may operate at great depths but only experience small depth changes.

Investigation of the vertical distribution of marine organisms highlights three types of pressure resistance [9]; stenobathic-baraphobic species which are only found with a limited vertical distribution in shallow water, stenobathic-barophilic species which are only found with a limited vertical distribution in deep water and eurybathic which have a large vertical distribution and are to a great extent pressure independent (although not necessarily resistant to the effect of sudden pressure changes). For example tests on small or juvenile animals from the shallow western part of the Baltic Sea highlights several species of amphipods, isopods, molluscs, echinoderms and polychates with high levels of pressure tolerance. For example the experimental pressure limits after 1 hour at 10^{o}C at a salinity of 15 on the Practical Salinity Scale were 80MPa for *Mytilus edulis* (blue muscle), 75MPa for *Asterias rubens*, *Mya arenaria* and *Littornia littorea* (common starfish, softshell clam and common perwinkle) [9].

It is the *eurybathic* species which provide the inspiration for this AUV concept, by evolving pressure tolerant organs (systems) without the requirement for pressure resistant housings some species marine animals have seemingly decoupled the correlation of increasing mass with increasing depth observed in current AUV systems. The concept of pressure tolerant electronics is not new with research dating back to the 1950s [10]. Pressure tolerant electronics are electrical systems or components which can operate at high hydrostatic pressures without the use of pressure resisting housings enveloping them. Implicit in the definition is the use of an intermediate fluid surrounding the components which are kept in equilibrium with the surrounding ambient pressure. For AUV applications Bluefin Robotics Corporation pioneered the use of pressure balanced lithium polymer batteries, capable of operating at the ambient pressure at 6000m water depth [11]. Lithium polymer batteries have a solid electrolyte and can be manufactured with no void spaces. Hence, as long as they are packaged in a compensating fluid, and protected from contact with salt water they can readily be used on AUVs.

As well as surviving high pressures the vehicle also has to overcome buoyancy variations with depth driven by the relative compressibility of the AUV and the surrounding fluid. While typical seawater has a density of 1026 on the surface (T=15^{o}C and S=35), this increases to 1051 at 60MPa (~6000m). An incompressible vehicle which is neutrally buoyant on the surface will experience ~2.5% positive buoyancy at 60MPa. Therefore in order to maintain depth the vehicle must expend considerable energy maintaining vertical position. Alternatively, an isopycnal system has the same compressibility as seawater and as such experiences no buoyancy changes with depth. For both AUVs and marine animals the structure (skeleton) and actuation (muscles) are denser than water, consequently additional buoyant material must be used to achieve near neutral buoyancy. The selection of this buoyancy material can have a significant effect on the total compressibility of the system.

Since a deep diving AUV will typically experience significantly larger depth and therefore pressure changes than many marine animals, the compressibility of the constituent materials becomes important.

Various approaches to minimize or adapt to buoyancy variation with depth have been investigated or evolved in the engineered and natural worlds. 'Compressee', a spring-backed piston in a cylinder has been added to Swallow floats to give the float the compressibility of seawater [12]. The Seaglider vehicle a 1000m depth rated glider uses a specially designed pressure hull which consists of a series of arched panels supported by ring stiffeners with generous fillets [13]. This design allows significant hull deflection tuned to match the compressibility of seawater.

Many species of marine animals have their own solutions to maintain neutral buoyancy, species of benthic sharks use large volumes of the hydrocarbon squalene in their livers to provide buoyancy [14]. Some species of squid use ammonia rich solution to provide buoyancy [15]. The use of fluid buoyancy leads to the compressibility of the system being close to that of seawater.

This paper describes the design of a proof of concept physical model for a deep-diving soft-bodied liquid filled AUV currently under construction at the University of Southampton and the National Oceanography Centre. The aim is to produce a small lightweight vehicle capable of achieving near neutral buoyancy from the surface to 6000m water depth. The design of the vehicle draws inspiration from existing AUV and glider design as well as various marine animals.

II. Vehicle Description

It is not the aim of this study to create a 'biomimetic' AUV, instead we are looking for inspiration from nature to solve specific engineering problems. Where the engineered world has a more appropriate or efficient solution this is used in preference to a biologically inspired solution.

The design of the vehicle is a hybrid of conventional AUV components with engineered analogues of marine animal organs. Details of the NEMODeep vehicle are presented in Table I and Figure 1. The internal structure is comprised of a spine, ribs and sternum, which support a hydrodynamic fairing or 'skin'. The 'brain' and actuators are developed using pressure tolerant electronic, negating the need for pressure vessels. The pressure tolerant electronics are surrounded by light mineral oil which transmits the hydrostatic pressure uniformly to the components while also providing buoyancy. The internal fluid is more compressible than seawater and the batteries and internal structure are less compressible than seawater: a 'Buoyancy/Compressibility' organ is being developed to passively maintain neutral buoyancy over the 6000m depth range. The requirement to demonstrate the performance of the concept physical model under hydrostatic loads from the surface to 6000m, equivalent, restricts the maximum size of the vehicle to the internal diameter of the large pressure pot at the National Oceanography Centre, Southampton (952mm diameter). The following subsections discuss the design and function of the various components of the AUV.

TABLE I. NEMODeep Key Design Parameters

Parameter	Value
Length	0.85m
Maximum Diameter	0.2m
Dry Mass (No internal Fluid)	3.5kg
Total Mass	12 kg
Hull Form	Parson's X-35 body [16]
Depth Limit	6000+m

A. Hull Fairing – 'Skin'

Conventional AUVs are of two basic types, those that have an outer hull that is the pressure hull, for example the REMUS [17] or GAVIA family [18] of AUVs, and those whose outer hull is a non-structural providing a hydrodynamic fairing as a protective cover for the pressure vessels and other vehicle systems inside as in, for example, the Autosub family [19, 20] and Delphin2 vehicle [21]. For the NEMOdeep vehicle a soft-bodied, essentially pressure tolerant approach is proposed. However, the impermeable outer cover, and its properties are still of great importance.

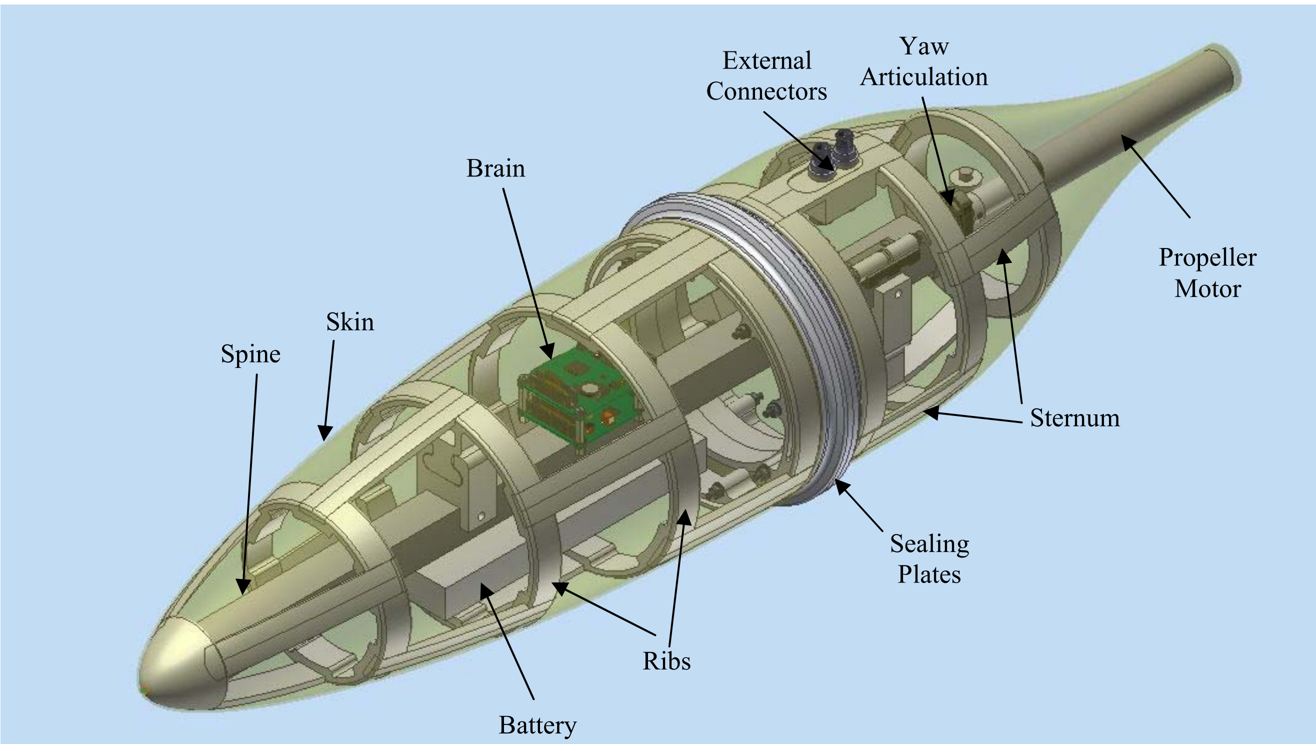

Fig. 1. Schematic of NEMOdeep concept (missing rear control planes and propeller)

Study of the range of outer covers from marine organisms provide the following examples from which to draw bio-inspiration:

- Exoskeletons – are hard external skeletons (often referred to as shells) that support and protect an animal's body, these are rigid and resistant components, from biopolymers such as chitin (crustacea) [22], or with the addition of minerals e.g. calcium carbonate in an organic matrix of the complex protein conchiolin (e.g. molluscs), or silica (the plankton radiolaria and diatoms). Exoskeletons can be viewed as analogous to the solutions used on current AUVs
- Skin – in nature skin is a flexible continuous covering that protects the internal organs from the external environment, it is a selectively permeable barrier permitting the transfer of some molecules and preventing the transfer of others. For example common dolphin (Dolphinus delphis) skin is permeable to water but not to sodium [23]. Fish skin is a non-isotropic material composed mostly of fibres of the protein collagen, as long fibrils, forming "alternating layers of right and left helices wrapped around the long axis of the animal" [24]. The "wind angle" range is wide (45˚ to 80˚). This arrangement provides for flexibility and change in shape, but also a supporting framework.

For the NEMOdeep vehicle the 'skin' provides an impermeable barrier between the seawater and the internal fluid surrounding the internal 'organs' of the AUV, it must be flexible enough to allow the hydrostatic pressure to be transmitted to the internal fluid, and allow for volume changes throughout the vehicle system.

The following were considered when selecting the 'skin' material and the manufacturing process:

- Permeability of the material.
- Compatibility of the material to both the internal fluid and seawater.
- Complex curvature of the skin.

The bow skin has been created by dipping a male mold in liquid PVC. The stern skin which has a greater requirement for flexibility has been created by a mixture of welding and vacuum forming of 0.5mm and 1mm polyurethane film.

B. Internal Fluid

The use of pressure tolerant electronics requires them to be placed in an intermediate fluid or soft material which transmits the hydrostatic pressure uniformly to the components. Since it is envisaged that this liquid will also help provide buoyancy the chosen fluid must be less dense than water. When selecting the internal fluid the following issues were considered: -

- For correct operation of the electronic components must not conduct electricity.
- The environmental impact of this liquid was considered as in the event of failure this liquid may be released into the environment.
- The compressibility of the fluid will impact on the buoyancy change experienced by the vehicle with respect to depth.
- The cost per kilogram of buoyancy.
- The potential hazards associated with human exposure to the liquid.
- Any transport limitations associated with the liquid;
- The behavior of the fluid in contact with the skin material and other internal components.
- The viscosity of the fluid, since, it is envisaged that the propeller motor will operate directly in the internal fluid for simplicity.

A database of 44 potential liquids was generated; an extract of this database is presented as Table II. Many of the lower density liquids which are typically alkanes and alkenes are not suitable due to being extremely harmful, flammable, damaging to the environment, and or toxic to fish. Mineral oil appears to be one of the most promising buoyancy liquids. While ideally it's density would be lower it is non-hazardous and the cost per kilo of buoyancy is low in comparison to syntactic foam (£165/kg buoyancy – machined).

C. Structure - 'Skeleton (Spine, ribs and Sternum)'

While many marine animal species are invertebrates (i.e Crustaceans, Molluscs etc), many of the most recognizable marine animals are vertebrates (e.g. fish, marine mammals, marine reptiles). The body of a vertebrate is supported by a framework of connective tissue which packs and binds the various parts together [25], the endoskeleton of cartilage and bone represents a highly specialized form of the general connective tissue system, it provides the body with its basic shape, facilitates movement and protects the internal organs from external forces, [26]. Bone is a complex living tissue in which the extracellular matrix is mineralized, providing rigidity and strength to the tissue while still maintaining some elasticity, [27].

The vertebral column (spine) acts as the primary longitudinal girder of the vertebrate body [28], its form is related to its function as a supporting rod, a base for attachment of body and limb muscles, to provide protection of the spinal cord and nerves and allow flexibility for locomotion [29]. The number of vertebrae in the spine is within certain limits characteristic for a given species; cod have typically 53, European eel, 114, Killer Whale has between 50 and 54, Atlantic white sided dolphin has 77-82 and mackerel 31, although the specific number does vary between individuals of a species, [30] [31]. A flexible spine comprising of many individually actuated vertebra allows some fish species to turn in a diameter shorter than their length [32]. Such performance is beyond conventional rigid AUVs, which typically have a turning diameter of 3 to 5 body lengths [33]. However, the complexity and cost of developing a highly actuated spine is not considered part of this project.

TABLE I. POTENTIAL BUOYANCY LIQUIDS

Liquid	Density at 25ºC (kg/m3)	Cost per kilo of buoyancy (£/kg buoyancy)	Volume per kilo of buoyancy (l/kg buoyancy)	Bulk Modulus at 1atm 25oC (GPa)	Hazards				
					Flammable	Harmful	Toxic	Irritant	Dangerous for the Environment
Pentane (anhydrous >99%)	626	£93.98	1.57	0.47	Y	Y			Y
Hexane (anhydrous 95%)	659	£173.22	1.80	0.62	Y	Y			Y
Decane	730	£554.58	2.47	0.92		Y			
White Spirits (Chemistry Grade)	780	£63.27	3.18			Y			Y
Ammonia soloution (2.0M in ethanol)	785	£1,162.50	3.27		Y				
Mineral Oil (light oil)	840	£23.00	4.54	1.70					
Squalene (98%)	858	£934.13	5.14	1.53					
Seawater (nominal)	1025	-	-	2.37					

A noticeable difference between teleost fish and marine mammals is the path of the spine through the body. In marine mammals the spine runs close to the top of the animal with all the major internal organs suspended below. For fish the spine typically runs closer to the centerline of the body. This difference is potentially due to the evolutionary path of marine mammals and the desire to maximize lung capacity.

For the NEMOdeep vehicle the spine (aluminium box section) provides structural rigidity for the vehicle allowing it to be lifted in air. It will also act as a wiring loom onto which the 'arterial and nervous system' will be distributed throughout the vehicle. A single point actuation at the stern will allow the use of vectored thrust steering in the horizontal plane. The batteries will be actuated to move forwards and aft along the spine to provide pitch control. While we will tune the compressibility of the vehicle to match that of seawater, it is not our intention to ensure a constant longitudinal center of buoyancy (LCB). Active movement of the batteries will allow the vehicle to correct for small changes in the LCB.

The 'ribs' (waterjet cut polypropylene) over the fore body provide structural support for the vehicle when in air and also assist the skin in maintaining the hydrodynamic shape of the vehicle, connecting the ribs are 18 'sternum', due to the complex shape of these parts these are being manufactured using selective laser sintering.

D. Control Electronics – 'Brain'

The vehicle requires a control and data acquisition and logging capability sufficient to communicate with the user, measure the external pressure within the pressure test vessel, measure the differential pressure across the outer covering of the model, measure the internal temperature, monitor the energy source and operate the thrusters and actuation. A key requirement for compatibility with the bio-inspired approach is that the module should be pressure tolerant and resistant to the buoyancy material within the vehicle. A suitable control and logging module has been designed at NOC for use with microsystem sensors (Ed Waugh). This has been proven to be pressure tolerant in an inert, non-conducting liquid environment to 60MPa.

E. Passive Buoyancy control - 'Buoyancy/Compressibility Organ'

The internal fluid (light mineral oil) is more compressible than seawater, and the batteries and internal structure are to be made from materials less compressible than seawater, the 'Buoyancy/Compressibility' organ will be tuned to passively maintain neutral buoyancy over the 6000m depth range. To achieve it will comprise of a mixture of micro balloons (low compressibility) in a permeable bag and compressible organic liquids.

F. Propulsor and actuation

Numerous authors have quoted the high propulsive efficiency of many marine animals, for example propulsive efficiency of psuedo killer whales of 0.9 [34], bottlenose dolphins at 0.81 [35], these values are high compared to those of a typical propeller open water efficiency of 0.5-0.8 [36]. Consequently, significant research effort has been applied to mimicking biological propulsion systems, for example see DLVCUUV robotic tuna [37], robotic dolphin [38], Finnegan robotic turtle [39], and soft-bodied robot fish [40]. However, current actuator efficiencies mean that the electric motor and propeller combination still provides a comparable level of total propulsion system efficiency, with comparatively easy control and design [41]. As such, a conventional propeller and brushless DC motor combination will be used to propel the NEMOdeep vehicle.

Sealing of a rotational shaft is a possible source of leakage into the internal fluid, the solution adopted is similar to that used on many deep diving vehicles is to use a magnetic coupling between the internal DC motor and gearbox and the external propeller.

G. Power Source

The use of pressure tolerant LiPo batteries has been demonstrated on a number of vehicles [11, 19] and this approach will be used on the NEMOdeep vehicle.

H. Rigid Rear Control Surfaces

An elongated three dimensional body without control surfaces acting at an angle of attack in an ideal fluid experiences a pure couple, termed the 'Munk moment' which tends to increase the angle of attack. Control surfaces are required at the rear of the vehicle to overcome the Munk moment by generating a restoring moment, to ensure the dynamic stability of the vehicle. On many flight style AUVs the rear control surfaces are movable to provide control authority in yaw and pitch. For this vehicle the one point actuation on the spine allows generation of vectored thrust in the horizontal plane and fore-aft movement of the batteries provides the pitch actuation.

III. Predicted Weight, Buoyancy and Compressibility

The soft bodied approach means that the NEMOdeep vehicle will have an unusual mass breakdown; this is illustrated in Table III. The use of mineral oil as the main source of buoyancy impacts the mass of batteries that can be carried. Typically batteries account for between 5% and 45% of the mass of a vehicle, dependent on mission requirements [42], the NEMOdeep concept sits at the lower end of this spectrum, which will have an impact on the range of the vehicle.

TABLE II. Mass Breakdown for the NEMOdeep Prototype

Liquid	Percent of Vehicle Mass	Percent of Vehicle Volume
Spine	1.95%	0.72%
Ribs	3.80%	4.23%
Sealing Plates	2.90%	3.22%
Sternum	3.25%	2.83%
Skin	3.54%	3.11%
Fixings	0.90%	0.12%
Articulations	2.08%	0.00%
Battery	6.05%	2.74%
Motors	0.83%	0.00%
Brain	0.67%	0.37%
Clamping Ring	4.67%	0.58%
Internal Fluid	58.90%	69.05%
Buoyancy Organ	4.60%	7.67%
Other	5.85%	5.35%
Total	100%	100%

The advantage of using a fluid more compressible than seawater as the main source of buoyancy is that it is possible to tune the compressibility of the system to minimize buoyancy variations with depth, compensating for the structural materials and batteries which are less compressible than seawater. Predicted system buoyancy variations are shown in Figure 2, for various combinations of buoyancy materials.

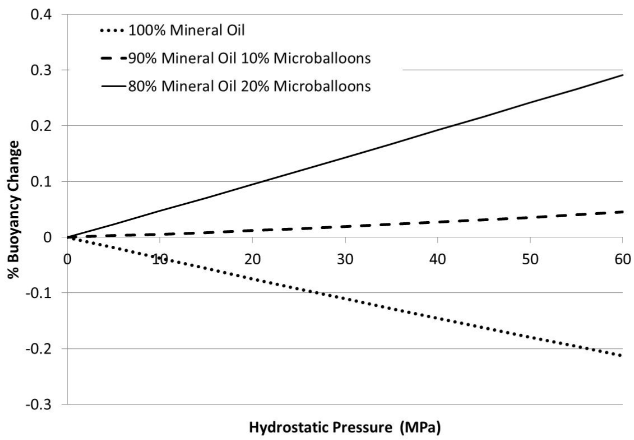

Fig. 1. Isothermal buoyancy changes of system using various mixtures of buoyant materials

IV. Conclusions

A bio-inspired design of a small deep diving AUV is presented, using a soft bodied approach. The vehicle is designed as a laboratory demonstrator, which will be trialed in the National Oceanography Pressure pot in the near future.

The concept demonstrates the ability to minimize buoyancy variations over large hydrostatic pressure ranges, by tuning the compressibility of the system using buoyant fluids that compress at a faster rate than seawater.

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