USING BIO-INSPIRATION TO IMPROVE CAPABILITIES OF UNDERWATER VEHICLES

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ABSTRACT

There are over 750,000 marine species ranging in size from a few micrometers to dozens of meters, all of which, through the natural process of evolution, have arrived at “successful” solutions to surviving and operating in the ocean space. Many of these species have capabilities and functionality which have much in common with the engineered capabilities required for underwater vehicles e.g. propulsion/locomotion, manoeuvrability/agility and the ability & resilience to operate at depth. Indeed, in many examples, it appears the biological solutions exhibit superior performance compared to the technological alternative, yet in biology these capabilities are achieved by different and diverse means.

In this research an extensive study on the capabilities of marine animals has been conducted in relation to the equivalent capability on AUVs. And the biological solutions to propulsion, agility, depth and vehicle (or animal) architecture have been focused on. This paper will present the approach adopted, some specific studies and key results from using a bio-inspired approach to improving AUV engineering capabilities.

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Nomenclature

s
AUV
BL
C_b
COT
D
D_d
Eco (Speed)
FR
L
M
MA
Re
ROV
R_{Yaw}
kg
U
V
\rho
\rho_{SW}

Second
Autonomous Underwater Vehicle
Body Length
Block Coefficient
Cost of Transport
Diameter (Subscripts as relevant)
Derived Diameter
Economic (speed)
Finessness Ratio
Length
Mass (Subscripts as relevant)
Marine animal
Reynolds Number
Remotely Operated Vehicle
Yaw Radius
Kilo gram
Speed (Subscripts as relevant)
Volume (Subscripts as relevant)
Density
Density of sea water

INTRODUCTION

Man-kind has a long history in ocean exploration and exploitation; from early exploration with divers in Greek and Chinese cultures, c.4500 B.C., to the genesis of ship-borne deep-sea research in the 17th Century by the likes of Sir James Clark Ross. In the 19th Century technological advances have seen human descents to the deepest regions of the ocean, when in 1960, Jacques Piccard and Don Walsh reached a manned decent to the deepest known place in the oceans in excess of 10km (Blidberg, 2001).

The current Status of AUV Technology

Improved access for deep water exploration has been facilitated by Unmanned Underwater Vehicles, initially ROVs and more recently, with increased sophistication of computers, Autonomous Vehicles. Nevertheless, there is still further demand for improved underwater capability.
beyond that currently possible with existing AUVs. For example, in the offshore industry there is demand for accessing and exploring deep waters for survey, inspections and maintenance. Similarly, there is high demand in the scientific community for improved deep-water capability for discovery and study of deep-water species, pharmacological sampling and environmental research. Furthermore, military and security agencies are constantly striving for improved capabilities in all aspects of underwater technology.

More agile and manoeuvrable AUVs with larger operating ranges can satisfy these demands by performing desired missions with more precision and cost-efficiency. Benefiting from the collective abilities of hybrid ROVs and intervention underwater vehicles is another aim of new vehicle designs (Kermorgant & Scourzic, 2005). However, currently there are restrictions in AUV capabilities including depth capabilities, speed, manoeuvrability and power. For example, the gathered database in this research shows that only 29% of the AUV types operate deeper than 3000m, whereas the deepest waters are 8000–11000m deep. In the UK, AUTOSUB6000 is the deepest diving AUV, to a depth of 5600m (Thaidian News, 2009). Furthermore, compared to other marine vehicles, AUVs are relatively slow and have limited speed ranges, with even the fastest, e.g. “Alister” and “SeaOtter” at 4.12m/s, being below 10m/s (AUVAC, 2010).

**Possible inspiration from nature**

Nature has been a source of inspiration for researchers and inventors over the last three millennia (Vincent, 2001) and systems found in nature are continuously evolving, with those surviving in their specific environment having superiority over those extinguished over time. The greatest part of Earth’s biodiversity, ~90% of the major groups of living species, is in the oceans (Madin, 2005) and marine animals have specifically adapted to thrive in underwater conditions (e.g. high water pressure, lack of air, etc.). Initial research in this project has identified marine animals with specific superior characteristics; e.g. high-speed or large depth range. Furthermore, examples of superior overall performance are evident; this being achieved through multi-functionality in biological systems. The *Sailfish*, for example can achieve a speed of over 30m/s and marine animals have been found at the extremes of the oceans’ depth.

**The research challenge**

This paper is reports on research carried-out at Newcastle University. The aim of this research is to improve the performance of AUVs by investigating novel technologies, inspired by marine animals, as well as generating bio-inspired design techniques and implementation methods. To achieve this aim, two main objectives are being pursued:

- Investigating bio-inspiration
  - Provide a greater understanding of marine biological organisms and systems for engineering application
  - Create a new way of thinking in engineering design
  - Use biological systems to improve engineering technology
- Application of bio-inspiration
  - to applied the lessons learned from nature to improve depth, speed and manoeuvrability of AUVs (NEMO, 2011)

**A brief on Bio-Inspiration**

Considering all the potentials nature has to offer to improve engineering design techniques, one may learn from nature, using the relevant novelties while leaving the undesirable ones, in order to relate engineering requirements to biological function. This is different from mimicking nature; therefore NEMO is not aiming to build a robotic fish.

**METHODOLOGY**

In terms of vehicle specification, the principal engineering challenges associated with AUVs are propulsion, manoeuvring and depth capabilities, as well as the storage and efficient use of energy. Therefore, more speed, greater endurance and depth of operation, more agility, reduced fuel consumption and advanced, cost-effective, designs and technologies are amongst the wish-list for AUVs demands; however, an optimum mixture of these features will result in a new generation of AUVs. These features of both AUVs and marine animals were analysed in this research.

**Investigating marine animals and AUV capabilities**

Data on the existing capabilities of 73 types of AUV was collected from a wide variety of sources, including AUV manufacturers, journal and conference publications and industry intelligence publications (e.g. Funnell, 2007 and AUVAC, 2010). The majority of gathered data for AUVs has been from specification sheets or existing trial results for the vehicle. For some AUVs (especially the bios-mimicking ones) data is not from trials but predictions of the manufacturer, which is assumed to be sufficiently accurate to perform a general comparison.

In addition, a similar database was established for the “engineering” specifications of marine animals, including physical characteristics, anatomy, physiology, hydromechanics and their taxonomic relations and classifications. Data is collected for 10 different classes of
marine animals including bony fish, marine mammals, sharks & rays, penguins, etc. micro organisms are not studied in this research due to their size disparity to AUVs. Data has mainly been collected from either technical papers and books (e.g. Thillart et al. 2007, Rivera et al. 2006, Hoelsel, 2002, Fish, 1998 and Jefferson et al, 1993) as well as databases published over the internet (e.g. Froese, 2011 and Appeltans et al, 2010). Where multiple data for a single species has been collected from different sources, average values have been derived and used. Furthermore, multiple sources are sometimes used to gather the full dataset for a given species. In some cases, dimensions have been derived from photos of the species, where the scale factor is known.

This presented interesting challenges; because it required addressing truly interdisciplinary literature and much of the published data regarding the capability of marine animals is not presented in engineering terms and is often presented for entirely different purposes. There are a number of studies which are in engineering terms, including various publications of marine animal hydrodynamics whereas many other publications, while providing material of interest in this research are provided for the purposes of life-science and biological research.

The number of species investigated was originally over 200, from which a subset of 127 with sufficient published data for comparison has been entered in the final database; this is due to some species being unreachable or not have been completely studied. In these cases, by considering taxonomically close relationship between certain animals, investigating a species in a family is sufficient for the purpose of this research.

Individuals of the same species are different in geometry and performance (e.g. their body shape is dependant to their environment and emotional conditions); therefore, gathered data is a mean of all existing data for a certain species. The data are stored in a database for constant use, comparison and update. The database includes data on general characteristics (dimensions, kinematics, depth of operation, etc.), structure, mechanisms and taxonomy.

A CONTRAST BETWEEN MARINE ANIMALS and AUVs

To highlight the relative superiority and limitations of biological systems and AUVs, the stored data have been analysed to make the following comparisons:
- Variations in body forms
- Speed and agility
- Depth capabilities
- Maneuuvrability
- Energetics

These are considered next, each in turn.

Variations in body forms

AUVs and especially marine animals have many different body forms and large variation in size; it would be ideal to compare their body forms to include resistance characteristics to the study. However, due to insufficient data for both groups, it is not possible to make direct comparison in terms of length, breadth, height and volume. On the other hand, Body Length and mass are generally available; furthermore, notwithstanding minor differences, MAs and AUVs are approximately neutrally buoyant (the variation of density is relatively small, even between floating and sinking marine animals); therefore they have an average density of water ($\rho_{SW} = 1025\, \text{kg/m}^3$).

Noting the limitations, comparing some measure of fineness is desirable. If we idealise any marine animal as an elliptical body of revolution (many MAs have fusiform body shapes which are wide in the middle section and tapered at both ends) and fit the same volume of the animal to it and keep the body length the same, by working out the equivalent diameter, $D_d$, the ratio of overall length to this equivalent diameter, $\frac{L}{D_d}$ is expected to be an indication of fineness ratio. To test this approach, it is first applied to AUVs for which body diameter is known. That is by comparing the fineness ratio ($\frac{L}{\text{quoted } D_{max}}$) of an AUV with the one of a neutrally buoyant elliptical body of revolution of the same length, if the assumption regarding density is correct, the expectations are, to see a correlation between the two values.

Considering the elliptical body of revolution as Figure 1, the derived diameter is calculated as follows:

Block coefficient of a cylindrical AUV is defined in the form of:

$$C_B = \frac{V_{AUV}}{\frac{1}{2}D^2L}$$  \hspace{1cm} (1)

$$M_{AUV} = \rho V_{AUV} = \frac{\pi D^2}{4} L C_B \rho$$  \hspace{1cm} (2)

$$D = \sqrt[3]{\frac{4M}{\pi \rho L}}$$  \hspace{1cm} (3)

And $$D_d = \sqrt[3]{\frac{3}{2}} D = \sqrt[3]{\frac{6M}{\pi \rho L}}$$  \hspace{1cm} (4)

Figure 1: Side view of an elliptical body of revolution showing $D_d$ as compared to the diameter, $D$ of the cylinder with the same volume and length
The results are illustrated in Figure 2 which highlights strong correlation between derived and actual fineness ratios based on actual diameter of the AUV.

By knowing the actual diameter of AUVs and validating the approach, same steps are performed for marine animals; the results of fineness ratios are illustrated in Figures 3 (for AUVs) and 4 (for MAs). Due to the large size variance in marine animals, the graph only illustrates MAs with BL<10m, with larger animals being whales (with fusiform bodies) and whale shark (elongated body); these large animals follow the same trend as smaller ones except for the 27m Fin whale which is more slender than other fusiforms ($\frac{L}{D_d}<11.9$) and whale shark being more slender than other animals with elongated oval cross-sectioned bodies ($\frac{L}{D_d} < 11.2$). Note that contours for different L/D_d (also known as Fineness ratio (FR)) have been placed with side views of the equivalent elliptical bodies of revolution provided for clarity.

By comparing the Figures 3 & 4, marine animals exhibit higher fineness ratios; while AUVs have $1<\frac{L}{D_d}<15$, animals range between $2.8<\frac{L}{D_d}<67$ with leatherback turtle and sea lamprey having the lowest and highest values in respect. The space-frame AUVs have the lowest fineness ratios while torpedoes have the highest. The only fusiform body animal with $\frac{L}{D_d} > 15$ is marine iguana; the reason being the consideration of its long tail in overall length. As expected, auguilliform species have the highest ratios.
**Speed and Agility**

Figure 5 illustrates the absolute speed of marine animals with different modes of swimming while the two dashed lines represent the highest economic and maximum speed of all AUVs in the database. Figure 6 is the equivalent presentation in terms of relative speed; i.e. speed has been normalised in terms of Body Length per second (BL/s).

Comparing AUVs and animals the superior speed capability of marine animals is very significant. While the maximum economic speed of all AUVs is 2.5m/s and their maximum speed capability 4.12m/s marine animals can have optimum speeds more than 6m/s and with their maximum capability up to 35m/s. (Optimum speed is the speed at which the animal has lowest energy expenditure.)

When considering absolute speed, thunniform swimmers (in which only less than 1/3 of the body is involved in the swimming and propulsion power is mainly produced by oscillation of the rear fin) have the highest values. Both in terms of their maximum capability (the highest point) and also their optimum speed, indicated as the lowest point or the start of the line on the figure. Fast swimmers have generally fusiform body shapes with circular or oval cross-section; however some animals with elongated body forms and compressed cross sections that have thunniform swimming mode are amongst highest burst speed swimmers (e.g. Sailfish). As for marine mammals, undulatory swimming is superior to oscillation (flapping) of side flippers as performed by stellar sea lions.

However, when comparing relative speed (BL/s), some relatively smaller marine animals which have subcarangiform or carangiform swimming mode (which are similar to thunniform in terms of caudal fin (rear fin) oscillation but a larger proportion of the body contributes to the oscillation of the tail and the muscle distribution is different as well) such as Atlantic Mackerel although their optimum speed (speed with lowest energy expenditure) is much less (e.g. for the Mackerel, maximum relative speed is 26.15 BL/s while the optimum is only 5.05 BL/s). AUVs capabilities are very low compared to animals; the highest relative economic speed is 0.96 BL/s with the highest maximum speed not exceeding 2.06 BL/s.

The Reynolds number (Re) in which the animal swims should also be considered; e.g. Atlantic Mackerel has a Re range of $7.69 \times 10^5$ to $3.98 \times 10^6$ while sailfish swims in Re up to $1.14 \times 10^8$. As for AUVs, when considering $U_{opt}$, they have a Re range of $2.8 \times 10^5 < Re <2.1 \times 10^7$ with Hammerhead AUV which has the highest economic speed has a Re $<7.1 \times 10^6$.

As discussed in the previous section the relatively high fineness ratios of animals compared to AUVs, may to some extent explain the high propulsion speed evident in nature. It is also realised that when analysing burst speeds, lift base swimmers especially penguins as well as thunniform swimmers with high speed capability have higher FR; however this does not comply to other forms of swimming and it can be concluded that propulsion capability is the dominant factor affecting speed capability. However, fast swimmers ($U>5$ BL/s) have a fineness range of $4<FR<15$.

Legend for Figure 5 & 6
1100_BCFAnguilliform, 1200_BCFSubcarangiform, 1300_BCFCarangiform, 1400_BCFThunniform, 1500_BCFOstraciform, 2111_OMPLabriform, 2112_OMPFLiftbaseFlapping, 2300_UMPFGymnotiform, 2400_UMPFBalastiform, 3000_JetForm
Figure 5: Absolute speed capability

Figure 6: BL/s speed capability

(Legend explained on previous page)
**Depth Capabilities**

For marine animals, one of the factors affecting their ability to exist at depth or to migrate through a depth range is their buoyancy control mechanism. As indicated by Pelster, 2009, marine animals have various buoyancy control systems; these include: gas bladders (used by many fish usually living in shallow water), lipid bladders (e.g. in mid and deep-water fish such as myctophids and orange roughy), lipid in the liver (e.g. in sharks), hydrodynamic lift (e.g. marine mammals; however they also use the air in their lungs and possibly the change in the density of the lipid above their heads). Turtles adjust the depth (in which they are neutrally buoyant) with the remaining air in their lungs. And finally, penguins remain positively buoyant, therefore they have a passive gliding surfacing; this also applies to Right whales which are positively buoyant. Figure 7 is an indication of depth range per unit mass; so the results are based on a trade off between absolute depth capability and mass (an indication of size). The figure shows that deep-water especially mid-water fish (e.g. the largest values belong to pacific viper fish ($\Delta D = 4365m$), mid-water eel pout ($\Delta D = 2100m$) and Sea Lampray ($\Delta D = 2200m$) which has a swim bladder) have the best depth range/mass capability with most of the mammals and sharks having the lowest capability, however, other than physical limits, motivation or “mission” of the animal is another key reason for deep or shallow diving; i.e. species do not always dive to their maximum capability. AUVs in Figure 7, are clustered within the same range of small marine mammals, which have superior relative depth range over larger animals, however much less capable compared to most of fish.

Figures 8 and 9 show the absolute depth capability of AUVs and MAs; it is realised that AUVs can already reach great depths and while there are many deep living animals, this does not indicate that they are always deep divers or that they can travel all the way up to the surface. The data suggest that AUVs perform with similar capability to marine animals with the same mass; however, it is interesting that many marine animals including many fish and some penguins can reach higher relative depth range with less mass; therefore further study is required to clarify the mechanism of this behaviour and possible bio-inspired techniques. As well as different buoyancy control systems, deep-water fish have soft bodies and low $\frac{M}{BL}$ ratio compared to shallow water fish and air-breathing animals.

Fish exist at the greatest depths and are found at the widest depth range. Interestingly, some species belonging to the same family (therefore closely genetically related) have significantly different depth capabilities. The two most significant examples are snailfish and cusk eel; although most of the cusk eels have depth ranges not more than 600 meters, deep sea cusk eel swims in depth of 3110 to 8370 meters. And a recently discovered type of snailfish has been found in the deepest depths of ocean trenches over 7500m (National Geographic, 2010), while Agonopsis chiloensis which is also a snailfish cannot swim deeper than 400 meters.

Marine mammals are the deepest air-breathing divers; they achieve their desired depth with less energetic cost compared to when they are forward swimming. This is achieved by shutting down their unused systems, reducing their heart rate and more important by gliding instead of swimming; in dives deeper than 300m, gliding is performed 60-95% of the total dive; this reduces their cost of diving to a great extent. (Williams et al, 2000)

![Figure 7: Depth range as a function of mass (Log-Log graph) comparison of Marine Animals and AUVs (shown with crosses) – Graph excludes species seen in one depth and therefore have no depth range](image-url)
Manoeuvrability

One of the parameters to be considered as a manoeuvrability measure of a vehicle is the radius of turning when changing directions, which is especially important in high speeds or when the vehicle mission is to chase and observe a marine animal.

![Manoeuvrability Diagram](image)

Figure 10: Yaw radius ($R_{yaw}$) or turning radius per unit length of AUVs and MAs

As the ring in Figure 10 encompassing the marine animal data highlights, AUVs have very large $R_{yaw}$ in comparison with marine animals; this makes them less manoeuvrable. High manoeuvrability is achieved by multi joint flexible bodies, so that as shown in Figure 11, flexible bodies such as black ghost and elephantnose fish have $R_{yaw} < 0.05BL$ while for fast swimming fish with more rigid bodies such as tunas $R_{yaw} > 0.45BL$ which is even more than some marine mammals and sharks. Figure 11 shows the turning data in Figure 10, in range consistent with the most of the data within the ring.

![Manoeuvrability Diagram](image)

Figure 11: $R_{yaw}$ for various classes of MAs: Circle=Fish, Plus=Shark, Star=Mammal, Cross=Turtle, Triangle=Penguin

For clarity, two species with large $R_{yaw}$ are not included in this figure; Basking shark (BL=7m, $R_{yaw}=0.97BL$) and Humpback whale (BL=15.2m, $R_{yaw}=0.82BL$) which is a slow swimmer.

Energetics

Energetics can be investigated as Cost of transport (COT), or as energy storage capability which relates to endurance.

Considering COT: this is a measure of energy expenditure required to swim at a given speed. It is measured as Joules per metre kilogram body mass ($\frac{1}{kg\times m}$). For marine animals, it is derived by measuring the oxygen consumption rate of the animals swimming at a given speed and converting O$_2$ consumption to produced energy by using the oxy-calorific value of oxygen (13.59 kJ/mgO$_2$, Elliott and Davison (1975)). Figure 12 shows that AUV are clustered within a small speed range but within this range, they have lower COT compared to many of the marine animals. This however excludes larger marine animals such as whales which indicates that larger the animal size, lower the mass specific COT.

![Energetics Diagram](image)

Figure 12: COT comparison of AUVs and MAs

Although, illustrating the COT at optimum speed (as presented in Figure 12) is beneficial for AUVs vs. MAs comparison, however, animals do not always operate at their optimum speed. Due to their high speed range capability, COT for animals, unlike AUVs, is a curve. This subject has been extensively studied and calculations carried out to produce the COT curve for different marine animals in various speed and Re ranges in Phillips et al, 2011; therefore, complete details are not provide in this paper.

Figure 13 illustrates the COT for MAs over various speed ranges; it is realised that COT on its own is not a complete measure of the energy expenditure of a species, speed range should also be considered; e.g. killer whale has a high COT when compared with fish at speeds less than 1m/s however its optimum speed is more than 2.5m/s, at which it has COT even less than a sturgeon. In addition the operation range of a killer whale is $3 \times 10^6 < Re < 2 \times 10^7$ which is the highest between the compared animals.
Endurance: Endurance refers to the time an animal can continue living normally without feeding and where there is data available, it is provided in analogy with power reserves of AUVs. So this is an indication of energy storage capability. Energy is stored in animals in the form of lipids and fatty acids and consumed when food is not readily available. The fat and sugar reserves of a fish represent its equivalent ‘battery’ capacity and provide a measure of autonomy when combined with known COT and optimum speed values.

As part of this research, specific calorific value testing of the blubber of two marine mammals was conducted in a laboratory experiment; the result show specific energy of more than 30 MJ/Kg for the blubbers; this value compared to batteries such as Lithium Polymer or Nickel Metal hydride with less than 0.5 MJ/Kg (Huggins, 2010) highlights that marine animals consume a high quality fuel. (Phillips et al, 2011).

Endurance (h) of several marine animals (light circle) and AUVs (dark circle) are shown in Figure 15, in which the size of the circle is an indication of COT value. The graph shows a significant high endurance within marine animals compared to AUVs. Sperm whale with the highest endurance (5000 Km) and other marine mammals that are long migrants, have large energy storage as blubber which is consumed during long migrations; therefore size is important for these animals in order to store the required energy content. However silver eels also use their stored energy during migration but they have a very low COT which reduces the amount of energy usage and where possible, they use the water current instead of swimming to go forward.

Figure 15: Endurance as a function of relative speed for MAs (light circles) and AUVs (dark circles)

OPTIMUM SYSTEM SELECTION

After comparing the capabilities of biological and engineering systems, it is realised that there are systems in certain species or a or a group of species exist that under certain circumstances exhibit superior to AUVs in one or more of the studied capability (i.e. speed, depth, etc.); this are usually achieved by various approaches. However, in some cases, given the scarcity of the available data and the ambiguity of the data, the challenge is how to take the data on MAs and use it to improve AUVs. Bearing in mind the aim of this research is not to make a robotic fish, but to take good bits, and use them constructively for engineering purpose. For optimum and multi dimensional use of the available data and various biological systems an algorithm is being developed in order to highlight optimum performing system,
In this paper, various characteristics of AUVs and marine animals have been compared to highlight the relative superiority and limitations of biological and engineering systems. The comparisons mainly highlight that:

- In terms of body forms, marine animals have significantly higher fineness ratios compared to AUVs while most of the high speed animals have a fineness ratio range of $4 < FR < 15$.
- Thunniform swimming is used for fast swimming by both fish and marine mammals, however smaller fish with carangiform swimming and some types of penguins with flapping swimming mode have high BL/s Speed.
- Although, AUVs are relatively capable at deep diving, many fish can reach deeper depths with less mass, therefore further research may clarify the reason by which they achieve this. One lesson to be learned from marine animals, especially marine mammals is to reduce the energy expenditure during diving by configuring the control surfaces for maximum gliding capability instead of swimming.
- In terms of manoeuvrability, the significant superior turning performance of marine animals is evident; this is achieved by their multi joint flexible bodies.
- Energetics is the most interrelated comparable characteristic between the two groups. It can be measured by COT (energy consumption during swimming) or by endurance. The comparison shows that, although compared to many marine animals, AUVs have less COT when swimming at their economic speed, however their speed range is very limited.

Many characteristics have been studied in this paper, which all seem significant with different importance, in order to accomplish a defined mission. Therefore an optimum selection means has being developed to collect all of these criteria together for a better overall comparison.

The comparisons show that optimisation is required and necessary; bio inspiration is a different approach because even the traditional AUV designs are to some extent inspired by nature; however, in most cases the inspiration has only been a first start (idea) but maybe the importance of nature has not always been appreciated and the analysis not been pursued as profound as it should have been.

REFERENCES


