Is there a case for emulating a fish or other sea borne creatures for propulsion of underwater vehicles?

Commodore (Dr) R K Rana, Veteran, PhD (IIT-M), MSc-Marine Engg (UK), BSc-Mech Engg (DU), ME†, CEng (UK), FIMarE (I), FIMarEST (UK), MASNE (USA)[a]; Nikhil Johnson; Prajakta Dongare; Sukratu Barve[b]; -

[a] *Independent Consultant, New Delhi, India;*
[b] *Centre for Modeling and Simulation, Savitribai Phule Pune University, Pune India*

Corresponding author. Email id: Rkrana14@gmail.com

Synopsis

Fish and other sea borne creatures have invoked interest in the minds of many professionals to study how they propel themselves in water and whether similar principles can be applied to the design of underwater vehicles.

Adopting these principles for propulsion had been a challenge some decades ago, but with the current technological progress in robotics, design analysis, advanced computing, precision manufacturing, 3D printing, sensors, actuation, image processing etc have rekindled an interest in this field, especially in the Indian context.

Moreover, with the thrust on development of unmanned autonomous systems, especially for the naval warfare, there is a case for looking at an efficient way to propel such vehicles that can stay underwater for a longer duration, move and navigate faster than those traditionally shaped and propelled by screw propellers or pump jets.

This paper looks at some of the basics of fish locomotion; technology trends; examples of the current developments; benefits of emerging technologies, investigate performance of some basic shapes of caudal fin of fish with the help of modern analytical tools such as Computational Fluid Dynamics and the way ahead.

Keywords – Fish, Fins, Propulsors, underwater vehicles, Robots

---

Authors Biography

Commodore (Dr) R K Rana, a veteran, having served in Indian Navy in variety of different roles, encompassing training, research, dockyard, staff, design of warships, indigenous products development and onboard ships, during long and illustrious career spanning more than 33 years. After taking premature retirement from the Navy, he joined Lloyd’s Register, the oldest Classification Society, where he (for more than 3-1/2 years) helped the company in strategizing and developing new business opportunities in the South Asian countries. As an independent consultant, he is now on a mission to enhance the global visibility of Indian entities, (academia, entrepreneurs, start-ups and industry), as well as find opportunities to extend their reach in Defence and Aerospace sectors.

Professor S Barve, completed his completed his post graduation from Indian Institute of Technology, Bombay, Mumbai, in Material Science and PhD (Physics) from Tata Institute of Fundamental Research and is highly respected amongst the scientific community. He is presently the faculty member and head of Centre for Modelling and Simulation at Savitribai Phule Pune University.

Nikhil Johnson and Prajakta Dongare are pursuing Master of Technology (Modelling and Simulation) at Centre for Modelling and Simulation at Savitribai Phule Pune University.

 http://doi.org/10.24868/issn.2515-818X.2018.018

1.0 Introduction

With the rapid increase in the popularity of the autonomous underwater vehicle systems and the need to have more efficient propulsion system so as to ensure longer ranges and acoustic silence, researchers are relying more and more on nature to find solutions. While the commercial sector is leading the change, the militaries are finding applications for these technologies. Though different organizations in India are also investing their R&D efforts in underwater domain, only a limited amount of research is in progress in biomimetics. Hence an initiative undertaken at the Center for Modeling and Simulation (CMS), Savitribai Phule Pune University, Pune, so as to be computationally competent to support the Navy.

A review of the literature in the domain of underwater propulsion, indicates that though underwater sea creatures, especially fishes have long been the subject of research to adapt their form of locomotion for naval underwater vehicles, the advancements in the field of biomimetics (both in basic understanding and in technology) is accelerating the adoption of bio-inspired propulsors in naval vehicles. The reference and bibliography sections provided at the end of this paper indicate the rapid progress being made by researchers across the globe.

The next section provides the basic concepts in fish locomotion with an emphasis on the propulsor. Technology trends in underwater robotics have been described subsequently which have led to lab scale experiments and prototypes becoming possible using biomimetics especially in underwater vehicle design. Analytical simulation studies aid in the design of such experimental devices and forms the core of the initiative at CMS, currently focussed on investigating the propulsor fin. Some results of this are addressed in section 6.0 of this paper, concentrating on isolating a design parameter and using fluid structure continuum models for its study. The conclusion follows containing an appreciation of adoption of biomimetics inspired naval underwater vehicles in near future and also the fact that the cross section of fin propulsors, ignored in previous studies, turns out to be an important design parameter.

2.0 Basics of Fish Locomotion

Many varieties of fishes/sea creatures in the ocean have evolved to meet specific behavioural characteristics. These characteristics demand different type of locomotion that gets achieved by arrangement of fins and/or necessary flexibility in their bodies.

Most common type of arrangement of fins which enable appropriate propulsion and manoeuvrability are as shown in the Figure 1[1].

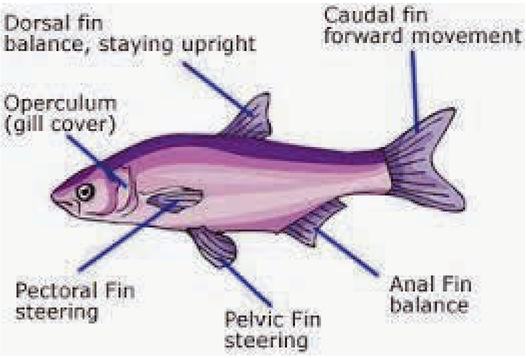


Figure 1 Typical arrangement of Fins on a Fish

The fins of the fish could be paired or unpaired. Paired fins are called pectorals and pelvic or ventral fins. The unpaired fins are the dorsa, caudal and anal. Each fin has a specific function, as mentioned in the Figure 1.

In general, there are two types of locomotion observed in a typical fish – namely the body and/or caudal fin (BCF) mode and the median and/or paired fin (MPF) mode. Majority of fish have chosen the BCF mode for their routine propulsion, which has been further divided (depending upon the fraction of the fish body involved in the lateral undulation), into four sub modes: anguilliform, subcarangiform, carangiform, and thunniform, as shown in the Figure 2 below [1].

 http://doi.org/10.24868/issn.2515-818X.2018.018

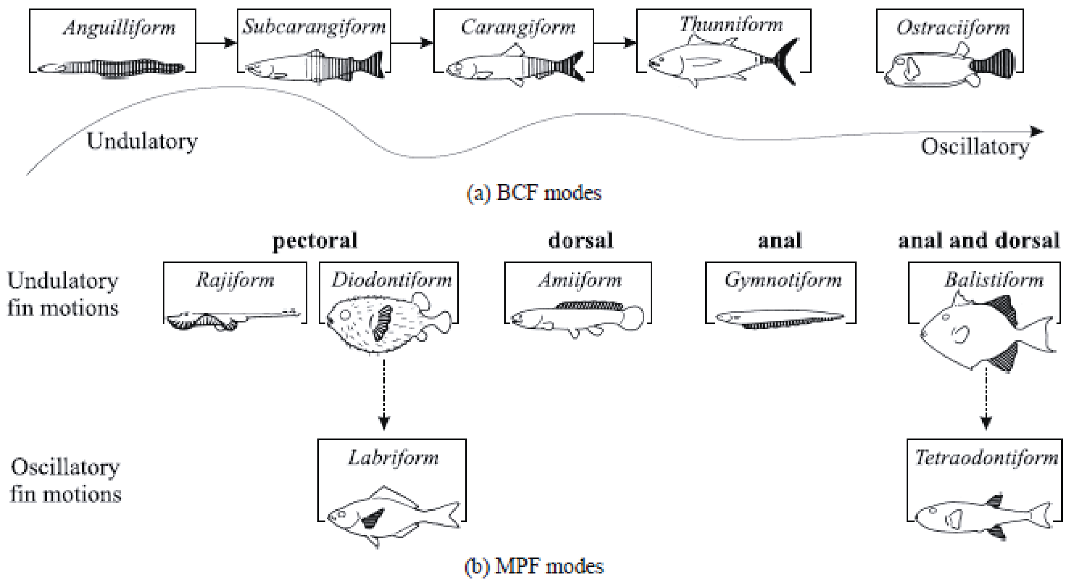


Figure 2 Swimming modes associated (a) BCF and (b) MPF propulsion. The shaded areas contribute to thrust generation.

In case of MPF, the fishes swim using combined behaviour of their two pectoral fins or both their anal and dorsal fins. They are able to achieve propulsion by preferentially using one fin air over the other and include undulatory and oscillation forms as shown in the Figure 3 above.

MPF is generally employed at slow speeds, offering greater manoeuvrability and better propulsive efficiency, while BCF movements can achieve greater thrust and accelerations.

An estimated 15% of the fish families use non-BCF modes as their routine propulsive means, while a much greater number that typically rely on BCF modes for propulsion employ MPF modes for manoeuvring and stabilisation [2].

2.1 Swimming Speed of Fishes

The swimming speed of fish is determined by its shape, size and build. In addition, fish generally cruise at a different speed than their all-out full attack speed.

From the table at Appendix 1, Koichi Hirata [3], one can note the high speed swimming speed of Tuna fish. Across the broad spectrum of fish form and movement, tunas are therefore most desirable as a vehicle platform as they are very streamlined, relatively rigid in the forebody and propel with low amplitude movements in conjunction with a high performance caudal fin.

2.1.1 Caudal Fins

The swimming abilities of fishes are determined, as shown in the Figure 3 by their body shapes, body structure, body cross section and shape and size of the fins, especially the Caudal fins, which play an important role and hence has attracted the interests of various researchers to study Propulsive efficiency of this fin. Some of the more common shapes are shown in the Figure 4.

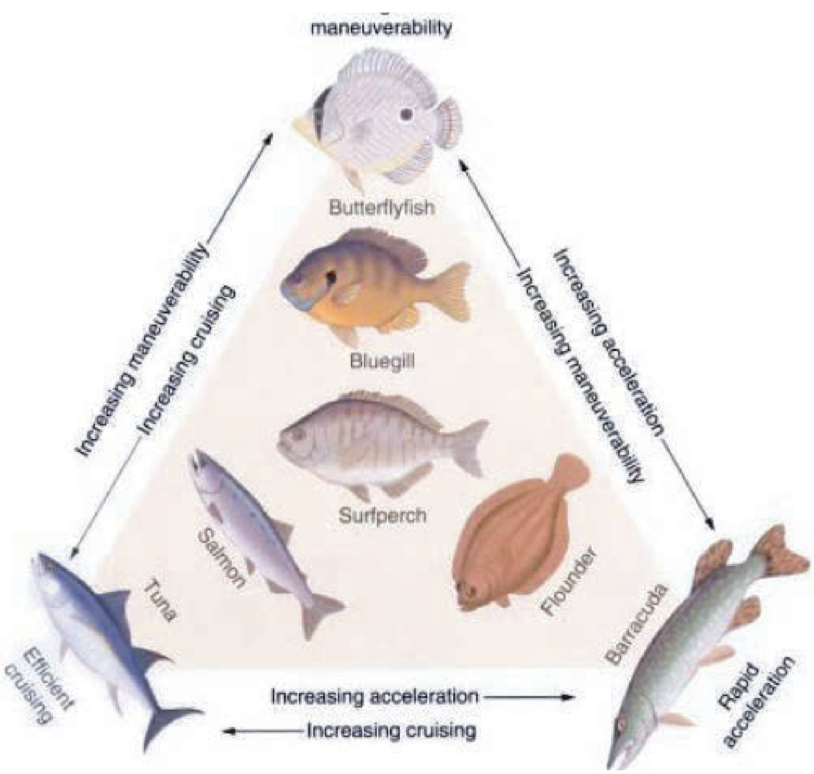


Figure 3: Examples of body shape specialization for three different swimming modes. [4]

One index of the propulsive efficiency of the caudal fin, based on its shape is its aspect ratio (=fin height * fin height /fin area).

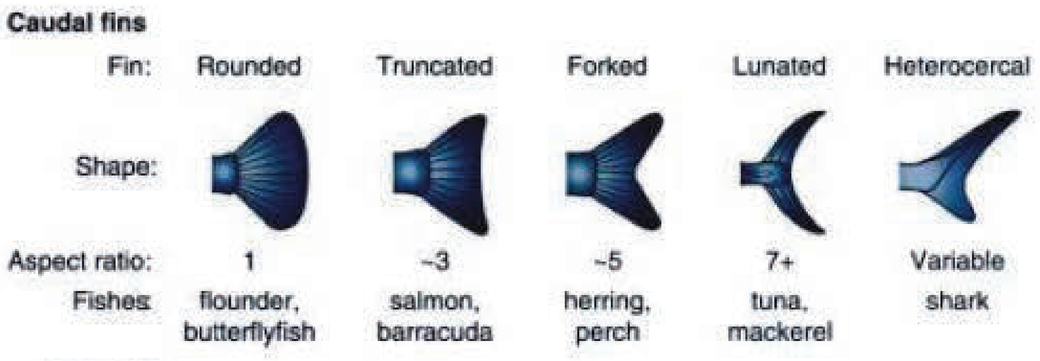


Figure 4 Examples of shapes and aspect ratios for caudal fins.

The caudal fins of fishes exhibit a range of profiles, shown in Figure 4 with increasing aspect ratios [4]. At the low end is a rounded caudal fin that is soft and flexible, which helps this fish to rapidly accelerate and manoeuvre. Truncate and forked fins produce less drag and are generally found on faster fishes, such as Tuna, The caudal fin is quite rigid for high propulsive efficiency, but is poorly adapted for slow speeds and manoeuvring.

Hence, it can be seen that fish locomotion is complex in nature involving not only the body movements, but also structures like fins. The caudal fin comes across as the most widely observed propulsors in sea creatures.

3.0 Technology Trends

With the advancements in every field, the traditional way of thinking is being challenged, as present day researchers are coming up with ingenious and better ways of understanding the physical phenomenon and solutions, as is evident in the succeeding paragraphs.

http://doi.org/10.24868/issn.2515-818X.2018.018

3.1 Soft Robotics. [5 - 7]

Body compliance is a salient feature in many natural systems. Compliant bodies offer inherent robustness to uncertainty, adaptability to environmental variation, and the capacity to redirect and distribute applied forces. In an effort to make machines more capable, researchers are now aiming to exploit this principle and design softness into robots.

Soft robotics, intended as the use of soft materials in robotics, is a young research field, going to **overcome the basic assumptions of conventional rigid robotics and its solid theories and techniques**, developed over the last 50 years. Moreover the investigations on soft materials are also necessary for more visionary research topics such as **self-repairing, growing, and self-replicating robots.**

3.2 Artificial Muscles

In order to overcome the challenges of the mechanical means of producing fish like motion, Kerrebrock, et al [8] have suggested use of artificial muscles which provides a new actuation strategy. Some of them are made of materials of low specific gravity, implying that they will be neutrally buoyant in underwater applications. These artificial muscles provide the required stability and are also acoustically silent due to their suppleness and reduced number of interconnecting mechanical components.

Kwang Jin Kim et al in their book Biomimetic Robotic Artificial Muscles [9] presents a comprehensive up-to-date overview of several types of electroactive materials with a view of using them as biomimetic artificial muscles. Recent advances made in several promising Electro Active Polymers (EAP), in particular the more popular ones - ionic polymer-metal composites (IPMC), conjugated polymers, and dielectric elastomers are considered.

3.3 Printable Hydraulics.

Whilst individual hydraulic components have been previously fabricated using 3D printing, which further required cleaning and assembling them to form a hydraulic system, MacCurdy et al [10] have mastered a new method that incorporates liquids directly into the designer’s material palette, enabling complex, functional, multi-part robotic assemblies that use hydraulic force transmission to be automatically fabricated, obviating the need for assembly.

These consist of printed rigid actuators, soft actuators, fluid pumps, a soft gripper and a functional hexapod robot. All designs are printed in a single step, Figure 5.

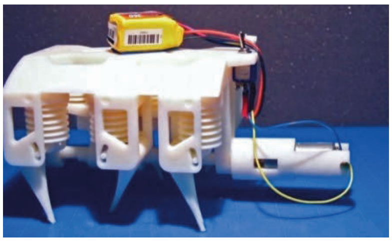


Figure 5 Hexapod robot with all mechanical parts fabricated in a single step.

Though printable hydraulics offers a rich design space for automatically fabricating ready-to-use, potentially disposable robots, the material and process limitations of current multi-material 3D printers sacrifice properties like mechanical strength, maximum elongation, fatigue lifetime and part resolution, relative to more specialized fabrication approaches.

These technical challenges are also likely to be overcome in the near future.

3.4 Fabrication Methodology for Elastomers

For many applications the disadvantages of printable hydraulics will be outweighed by the ability to automatically and rapidly fabricate entire robotic structures with force transmission elements embedded directly within the robot’s body.

http://doi.org/10.24868/issn.2515-818X.2018.018

New manufacturing processes are needed when dealing with specialised materials. Marchese et al [11] have reported their successful efforts in designing and fabricating soft fluidic elastomer robots.

They have experimentally validated each soft actuator morphology and fabrication process by creating multiple physical soft robot prototypes and described in detail in their paper.

Whilst the size of robots developed is small as of now, it is conceivable that such processes could be scaled up in the future for widespread manufacture, as the technology matures.

4.0 CURRENT EXAMPLES OF DEVELOPMENT

Many institutions across the globe are undertaking research work and have demonstrated the fact that emulating sea creatures is a possibility. Only a few examples of developmental work have been recorded in the succeeding paragraphs, but several more have been conducted [12 - 17].

4.1 Massachusetts Institute of Technology, USA

MIT, USA, is one of the leading institutions who have pioneered different technologies in variety of domains, one such being, developing robotic undersea creatures, replicating as closely as possible to the real ones.

They have slowly but steadily brought out improvements in the capabilities of robotic fishes from the earlier days of RoboTuna [18-19], Figure 6, to Vorticity Control Unmanned Undersea Vehicle (VCUUV) [20], Figure 7, to Mechanical Fins [21], Figure 8, to Flexible Robotic Fish [22], in 2014, Figure 9 to the present day Soft Robotic Fish, SoFi, in 2018, [23-25], Figure 10.

Figure 6 Robo Tuna II at MIT, USA

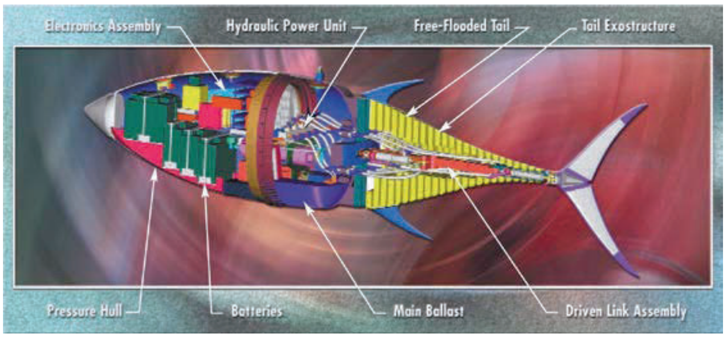


Figure 7 A drawing of the VCUUA, built at MIT

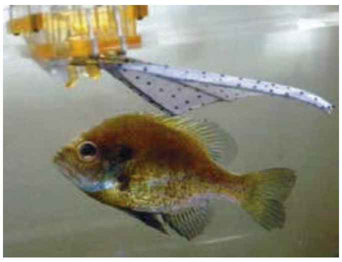


Figure 8 A bluegill sunfish swims in an MIT laboratory tank near a prototype of a robotic fin designed with the fish's fin as a guide.

 http://doi.org/10.24868/issn.2515-818X.2018.018

Figure 9 Robotic Flexible Fish

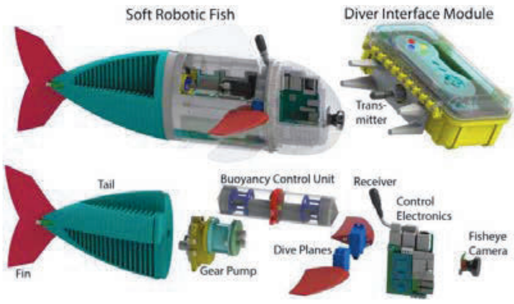


Figure 10 (a) Soft Robotic fish in coral reef and (b) Various parts of Soft Robotic fish

This work builds on previous generations of robotic fish that were restricted to one plane in shallow water and lacked remote control, whereas the soft robotic fish can swim in three dimensions to continuously monitor or undertake surveillance.

4.2 Biorobotics Laboratory [26]

Biorobotics Lab, part of the Institute of Bioengineering in the School of Engineering at the EPFL, Switzerland, is working at the intersection between robotics, computational neuroscience, nonlinear dynamical systems, and machine learning.

Their aim is to build biologically inspired amphibious snake (or eel/lamprey-like), salamander, fish and centipede-like robots. Figures 11 to 13. They are currently testing the control of different types of locomotion using central pattern generator models inspired by our numerical studies of lamprey locomotion.

Figure 11 Amphibious snake. The latest generation is Amphibot III, which can swim with speeds similar to a human.

Figure 12 - Salamandra robotica II. It can swim, crawl, and walk. Has been shown to be robust against damage, as this robot could lose parts of its body and still be able to walk.

Figure 13: Pleurobot
Because of its low center of mass and segmented legs it can navigate over rough terrain without losing balance and with a waterproof skin it can also swim.

 http://doi.org/10.24868/issn.2515-818X.2018.018

4.3 Pulsed Wakes or Steady Jets [27]

Lydia Ruiz et al [28] built an ingenious submarine that can propel itself with pulses, kind of like a jellyfish, or with a continuous jet, like a normal sub. They carefully designed the device so that it always uses the same motor, the same transmission and the same body, whether it's pulsing or producing a steady jet.

Indeed, the group found that **pulsed propulsion was almost always 20–40% more efficient** than the baseline steady jet. At low pulse rates, though, the energy saved through increased efficiency didn't make up for the extra energy required to spin the ring to make the pulsed jet. But at high pulse rates, the group saw an overall energy saving.

4.4 Royal Navy [29 - 30]

In a bid to encourage the present generation of young scientists and engineers, Royal Navy has earmarked an innovation fund (£800 m) and conducted an open challenge for the futuristic submarines that resulted in some very interesting concepts, which mimic real marine life forms. These encompassed technologies, at different maturity levels. Some of the concepts are shown in Figure 14.

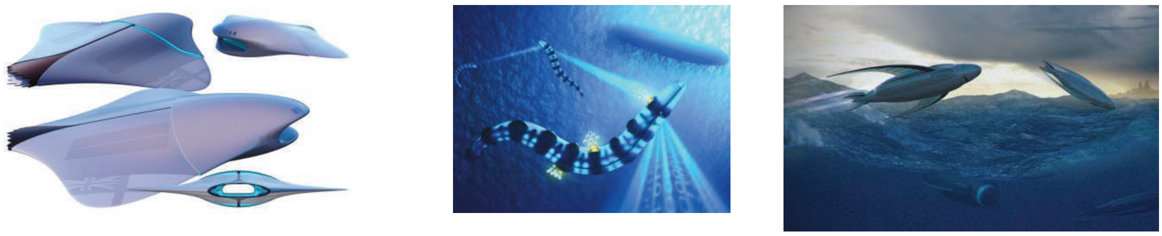


Figure 14 Manta Ray shaped submarine, unmanned eel-like structures equipped with sensors, and flying fish-shaped torpedoes designed to swarm enemy targets.

The whale shark/manta ray-shaped mothership would be built from super-strong alloys and acrylics, with surfaces which can morph in shape. With hybrid algae-electric cruising power and propulsion technologies including tunnel drives which work similarly to a Dyson bladeless fan, the submarine could travel at unprecedented speeds of up to 150 knots.

4.5 European Union [31]

The EU supported COCORO project's robot swarms not only look like schools of fish, they behave like them too. The project developed autonomous robots that interact with each other and exchange information, resulting in a cognitive system that is aware of its environment, Figure 15.

Figure 15: Scientists have created underwater robot swarms that function like schools of fish

The point being underlined here is that the present day technology is enabling deriving the best practices of the underwater living world, in developing more efficient machines.

 http://doi.org/10.24868/issn.2515-818X.2018.018

5.0 Emerging Technologies

The doubling of computer processing speed every 18 months, known as Moore's Law [32 - 33], is just one manifestation of the greater trend that all technological change occurs at an exponential rate. This one innovation has been the back bone of advancement in all other fields, (be it materials, manufacturing, etc) because the sheer computing power available at the desk of researchers has allowed them to use the modern analytical simulation tools to get a deeper understanding of the subject matter.

Since technology has always played a key role in shaping the outcomes of the wars, the armed forces have been quick to adopt the emerging technologies. Whilst in the 18th to middle of 20th century, it was the military that was spearheading the technology development, later taken over by the Space applications in the latter half of the 20th century. 21st century is witnessing emergence of disruptive technologies (Robotics, Artificial Intelligence, additive manufacturing, advanced materials, etc) in the commercial world that are being increasingly adopted by the military.

All navies have found that one of the **major costs in** operating their platform has been the **Human being**. Enhanced level of sophistication of the control systems and automation, has progressively enabled consistent reduction in manpower on board naval ships and submarines in the 20th century

5.1 Benefits

The emerging technologies of 21st century are enabling self-repair and autonomy [34] and are benefiting the navies as they do not have to put too many people in harm's way. This has a direct implication on the **costs of operating a naval asset**.

With the cost effective sensors technology one can now position larger number of sensors directly embedded into the structures or used in a non-invasive way to sense the same parameter (pressure, temperature, torque, force, thrust, flow, stress, strain etc), thereby increasing the **reliability** of the systems, Artificial Intelligence with deep and machine learning as its subset, will enable preventive and predictive capabilities and help in enhancing **availability and maintainability**.

Disruptive technologies provide navies with a means to sense, comprehend, predict, communicate, plan, make decisions and take appropriate actions to achieve mission goals. This provides operators with new technologies across the spectrum of expeditionary kinetic and non-kinetic capabilities required to defeat traditional threats decisively and confront irregular challenges effectively.

5.2 Maturity of Technology

Technology Readiness Level (TRL), is a helpful knowledge-based standard and shorthand for evaluating the maturity of a technology or invention. Technology forecasting that takes into account the TRL, provides a general idea about the time when a technology can be commercially and gainfully utilised for any application, including different types of naval assets.

Based on the definition of TRL, and the available literature in the open domain, the authors have tried to provide such a level to some of the emerging technologies mentioned in Section 3 of this paper above that would find their way in the propulsors for bio inspired naval underwater applications.

Technology	Technology Readiness Level
Advanced Materials	
Soft Robotics.	6
Artificial Muscles	5
Advanced Manufacturing	
3 D Printable Hydraulics	5
Fabrication of Elastomers	6

As per the practice in vogue, TRL 5 means the basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. TRL 6 indicates representative prototype system has been tested in a relevant environment and represents a major step up in a technology's demonstrated readiness.

It is opined that within next two to three years the TRL of all the above technologies is likely to reach 9, and would therefore be available for some naval applications (smaller in size equipment). As the robustness of these advanced materials and advanced manufacturing technologies increases in smaller size naval assets, the confidence to try them out on bigger assets will grow.

Yaseer [35] has also proposed that whilst TRL should be used as a measure of maturity of all the individual technologies, for qualification and readiness assurance, it can be complemented with an Integration Readiness Level (IRL) scale, to address IRL between the inserted technologies, along with a system readiness level (SRL) scale to assess the overall project status. This provides a composite metric for determining the system readiness level for project delivery.

5.3 Efficiency

Researchers from different parts of the world have eagerly studied the bioinspired propulsors and have invariably come to the conclusion that these are more efficient than the traditional propellers and pumpjets. Some of them have defined propulsive efficiency in their own ways and compared the same for different types of caudal and pectorol fins mentioned in section 2, or pumpjets (as in a jelly fish). Examples are Aspect ratio of Caudal fins (section 2 above); or Cost of transportation.

Buren and Smits, in their paper [36] have compared the cost of transportation, another form of expressing propulsive efficiency, amongst four major types of aquatic swimmers (oscillatory, undulatory, pulsatile, and drag-based) and break down their mechanisms for thrust production (drag-based, lift-based, added mass, and momentum injection), Figure 16. Despite large differences in size and swimming mechanisms, one can see that most organisms swim between 0.5 and 1.5 body lengths per second. This is a typical cruising speed, and the maximum swimming speed can be very different among different swimmer types. However, drag-based swimmers have a notably higher cost of transport than the others because, as most drag-based swimmers do not necessarily solely live in water, and many have evolved to also walk or fly.

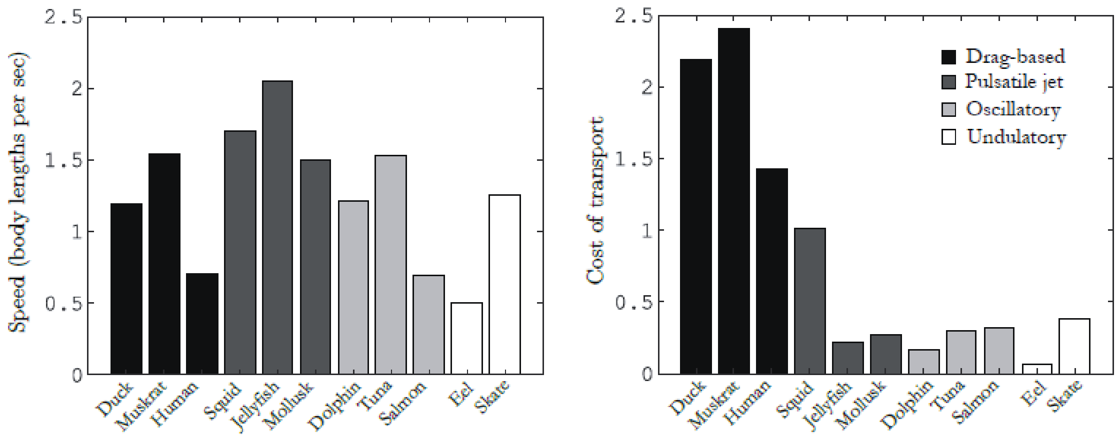


Figure 16 Relative swimming speed and cost of transport for oscillatory, undulatory, pulsatile jet and drag based swimmers.

Fish et al [37] have examined detailing the kinematics of the pectoral fin movements swimming over a range of speeds and by analysing simulations based on computational fluid dynamic potential flow and viscous models for Manta, the largest marine organisms and the base model for study by Royal Navy as well (See section 4.4). They concluded that **Manta's propulsive efficiency was nearly 89 %** when they swim at routine and high speeds.

As regards the propulsive efficiencies of the underwater robotic vehicles made/simulated by different researchers, it has not reached the levels observed in undersea creatures yet. But with the work in progress and armed with the higher level of understanding/knowledge of different creatures, researchers can combine/optimise the best features of number of undersea creatures in a robotic mechanisms to achieve even higher efficiencies compared to the live creatures.

 http://doi.org/10.24868/issn.2515-818X.2018.018

6.0 Analytical Studies

Most of the experimentation has been carried out at prototype level and has been informed by observations of sea creatures as described earlier. Although evolution mechanisms of nature might provide high performance designs, analytical aids are expected to improve upon them further.

6.1 Overall Focus

The study of fish locomotion has been very active for the last several decades, and includes work by research groups in the fields of biology, [38-42] applied mathematics, [43-46] and engineering [47-48]. Many of these studies consider models of swimming fish—flexible foils or sheets which represent caudal fins as propulsors — and which oscillate in a steady oncoming flow at a prescribed speed. These studies have greatly improved the understanding of how thrust forces depend on the body shape and motion [49]. However, it is noted that in these studies **the thickness profile has not been extensively prioritized** while it may well be an important design parameter for engineering propelling fins.

Further, the phenomenon of hydrodynamic resonance, between the caudal fin and the body of the fish has been noted for its importance in the design soft robotic fishes [50]. Together, the tail oscillation and body stiffness affect the body-fluid resonance which is conjectured to promote efficiency of propulsion. The possible effect of this would need to be minimized while studying thickness profiles as an isolated design parameter.

As the first step beyond the above studies, **the focus is on simulating a rectangular foil (flap) with varying thickness profiles, (both rigid and flexible) swivelling in water at a fixed frequency and amplitude.**

The scientific models used to represent such soft robotic devices employ principles of continuum mechanics. Unlike most of other situations where the model can be restricted separately to the fluid portions or to the solid portions of the device, in soft robots it is important to incorporate transmission of mechanical (as well as thermal or other) flow or deformation fields between the solid and fluid portions. While the formulation of the mathematical model is not conceptually challenging in terms of partial differential equations, it turns out that the numerical methods used for discretization of such models (termed as multi-physics models) pose considerable difficulty [51-52] and require the use of special numerical techniques for solving the resulting difference equations. The difficulty is compounded by the algorithms that need to be employed with numerical arti-facts like the added mass effect which need to be addressed [51]. In such a situation, open source analytical software tools were chosen to conduct these simulations.

6.2 Analytical Software Tools

The following software tools have been used for analytical work at Centre for Modelling and Simulation, Pune

- Calculix [53] – For the structural differential equation models.
- Stanford University Unstructured, SU2 [54] – for the fluid governing equations.
- Paraview [55] - post-processing the fluid simulation results, including the grid deformation visualizations.
- preCICE [56] - (Precise Code Interaction Coupling Environment) is a coupling library for partitioned multi-physics simulations.

The coupling is performed by preCICE using the resources of the individual solvers via MPI or TCP-IP to create a single overall simulation. Of particular importance are the coupling schemes used. The non-linear fixed point equations are solved using Quasi-Newton methods. These methods try to approximate the inverse Jacobian of the residual operator of the non-linear coupling equations. Anderson Acceleration has been used to prevent the solution from diverging due to strong instabilities or oscillations. This method assumes an initial guess J_inv^0 = 0 and solves the least squares problem. This method was selected as it is a matrix-free method and of low computational cost. [57].

Communication of data is done by sending the displacements evaluated from the Calculix mesh to the SU2 mesh while forces are conveyed from SU2 mesh to the Calculix mesh. The data from each mesh is captured through the use of individual adapters which are built to send data from the specific solver through the preCICE coupling library to the corresponding mesh.

As the density of the structure is much higher as compared to the fluid, an explicit coupling scheme is necessary. This means that the grid deformations must be matched, per coupling step. This is done iteratively within the preCICE library until convergence of the meshes is obtained.

6.3 Discussions of Results

Having resolved the computational challenges through number of iterations, this section presents the results obtained for two rectangular flaps both of the same length, 20 cm with width of 10 cm. The cross section of the two however is different, Figure 17. The rigidity of the flaps has been varied to observe the change in thrust force generated during flapping. The frequency and amplitude have been kept the same at 1 Hz and 0.20cm.

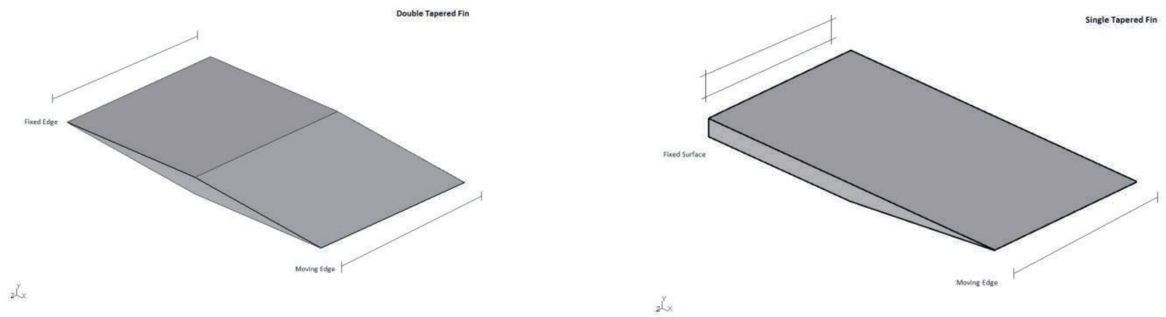


Figure 17 Shape and cross section of two types of fins – double tapered and single tapered

Figures 18 and 19 show the pressure field in cases of double and single tapered flaps with other properties and parameters maintained the same between both of them.

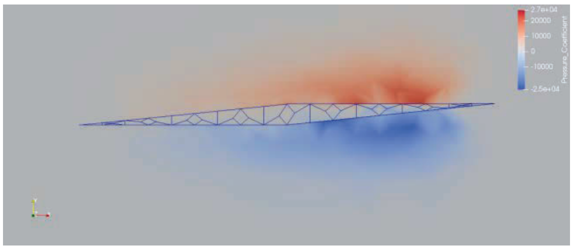


Figure 18 Pressure field of double tapered fin

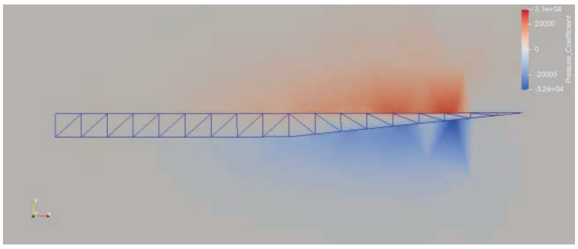


Figure 19 Pressure field of double tapered fin

The double tapered flap deforms upwards near the fixed edge in a more pronounced manner as compared to the single tapered flap and forces the fluid nearby accordingly. However, a significant difference is not observedin the fluid pressure profiles between the two cases especially towards the fixed edge. The free part of the fins thus appears to play an important role in the difference seen below in the thrust variations with time. Further the double tapered flap appears to lead to more fluid pressure variations along its length as compared to the single tapered fin.

 http://doi.org/10.24868/issn.2515-818X.2018.018

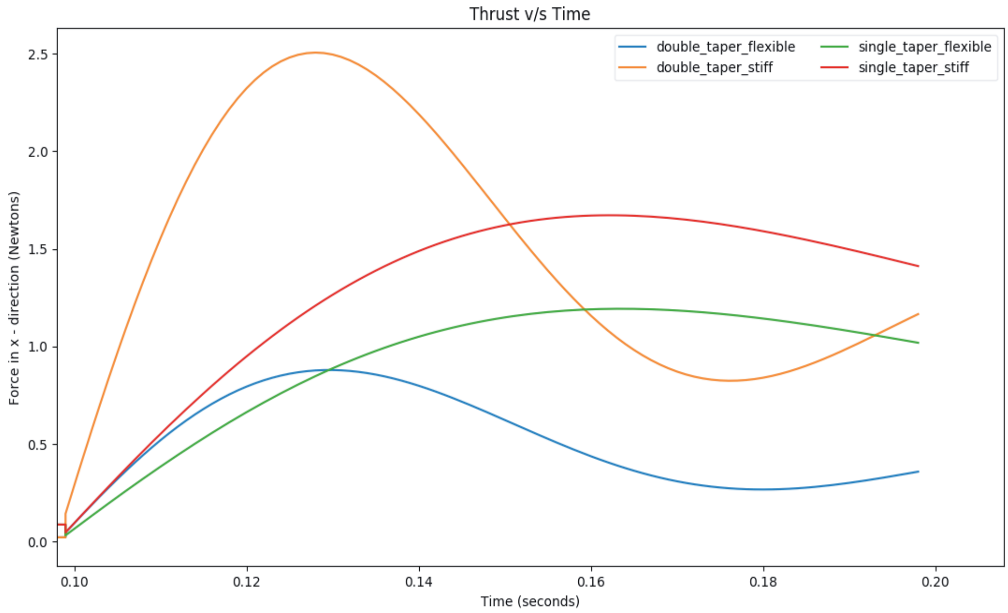


Figure 20 Variation of thrust produced

Figure 20 shows the variations of thrust produced with time for four cases. The double tapered cases are less monotonically behaved as compared to the single edged ones. This feature suggests that thickness profiles would be important in the design considerations for example regarding performance in terms of vibration and noise.

Further a comparison of the maxima of thrust (Fx) and lateral forces (Fy) exerted on each fin case during the oscillations is shown in the table below. The respective ratios indicate individual performance as regards to propulsion.

Fx/Fy	**Rigid**	**Flexible**
Single Taper	249.62	178.11
Double Taper	80.25	28.19

It can be observed that propulsion performance considerations would lead the designer to choose the single tapered fin over the double tapered one. Thus, propulsion performance might need to be traded off with noise and vibration considerations during design of flexible fins.

6.3.1 Modal Analysis:

Figures 21, to 24, show displacement for single and double tapered fins during the modal analysis, respectively. One can observe that there are more localized modes excited in the single tapered fin.

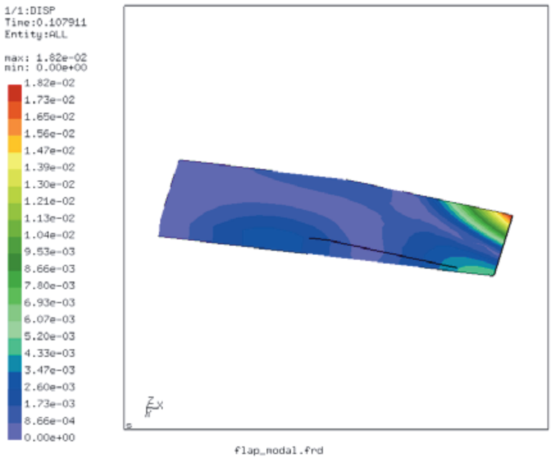


Figure 21 Single tapered – flexible fin

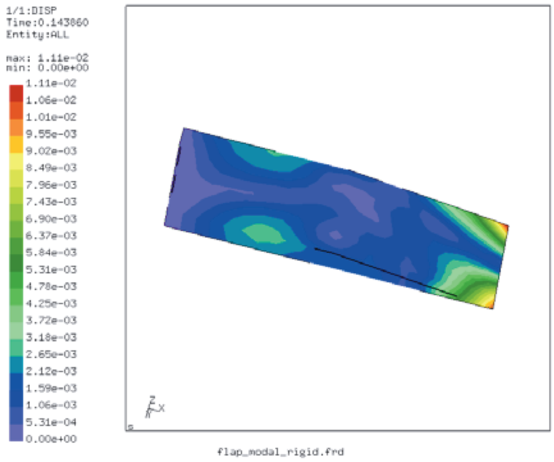


Figure 22 Single tapered – rigid fin

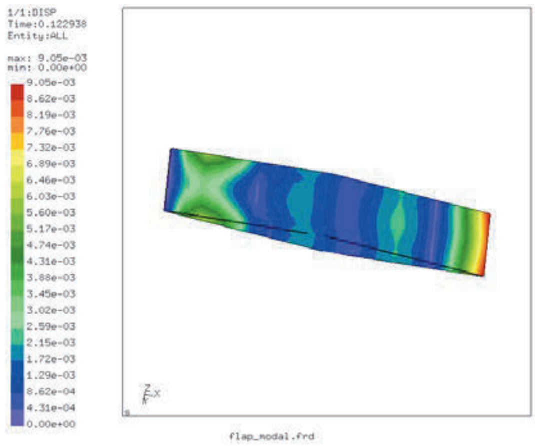


Figure 23 Double tapered – flexible fin

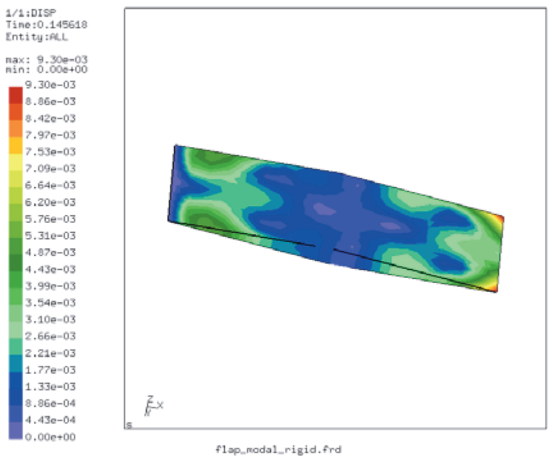


Figure 24 Double tapered – flexible fin

Eigenvalue outputs from modal analysis for both types of fins are tabulated in Table 1 and also presented in Figure 25.

It is observed that most of the Eigen modes of the double tapered fin are of higher frequencies as compared to the single tapered fin. However, the range of frequencies is 10 times lesser than the flapping frequency (1Hz). One can hence expect no body resonances to count in the physical effects considered while designing thickness profiles above. However these simulations could be used to study such effects as body fluid resonances.

	Double Tapered Flexible Fin		**Double Tapered Rigid Fin**	
Mode No	**Eigenvalue**	**Frequency**	**Eigenvalue**	**Frequency**
1	0.5966	0.1229	0.8371	0.1456
2	0.6460	0.1279	0.9001	0.1510
3	0.7159	0.1346	0.9172	0.1524
4	1.3291	0.1834	1.1203	0.1684
5	1.3486	0.1848	1.1205	0.1684
6	1.6486	0.2043	1.1804	0.1729

	Single Tapered Flexible Fin		Single Tapered Rigid Fin	
Mode No	Eigenvalue	Frequency	Eigenvalue	Frequency
1	0.4597	0.1079	0.8170	0.1438
2	0.5857	0.1218	0.8576	0.1473
3	0.7292	0.1359	0.8658	0.1480
4	0.7449	0.1373	0.9264	0.1531
5	1.0534	0.1633	1.0340	0.1618
6	1.3967	0.1880	1.0882	0.1660

Table 1 Eigenvalues of both shapes

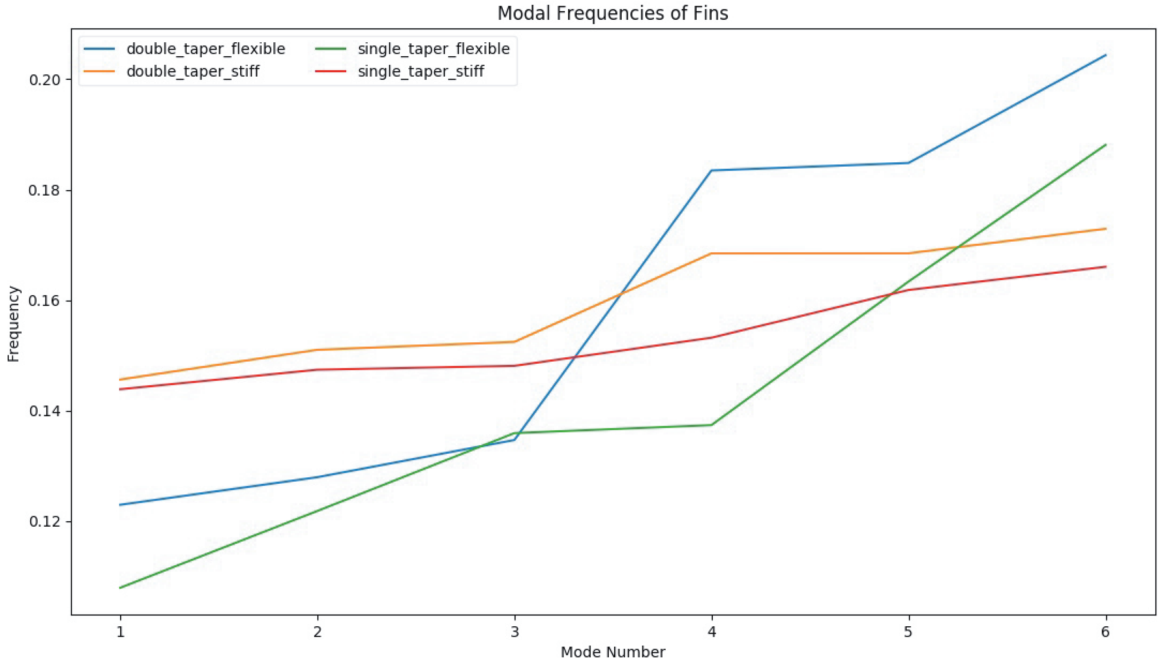


Figure 25 Eigenvalues at different mode numbers

7.0 Conclusions and Way Ahead

Ongoing development of propulsors for the submarines, from screw propellers to contra-rotating propellers to shrouded propellers to pumpjet [58], the propulsive efficiencies have reached nearly 70 %, with a fair amount of reduction in the acoustic signatures. Further, with recent advances in computational modelling, materials research, and manufacturing, it is possible to take advantage of the flexibility and anisotropic properties of composites to enable passive morphing capabilities to delay cavitation and improve overall energy efficiency, agility, and dynamic stability. [59].

The question that one therefore needs to ask oneself is whether it is worth exploring emulating a fish or any other sea creature for UW vehicle applications in the Navy**. The answer does not turn out to be simple**.

With the extensive research on fish type of locomotion, development of new materials to enhance flexibility of the structures of UW vehicles; growing confidence in the autonomous operations etc is causing a paradigm shift in the way naval wars are going to be fought in future.

Though Soft Robotic fishes, with caudal and pectoral fins, have been tried out successfully in a coral reef, and having been developed with the goal of being as non-disruptive as possible in its environment, from the minimal noise of the motor to the ultrasonic emissions of the communications system, it has direct application in the naval domain, with a Special Forces warrior, directing a mine towards an enemy target from a remote location.

http://doi.org/10.24868/issn.2515-818X.2018.018

Swarming, as new concept of warfare will be the order of the day, since large sums of money has already been invested in similar civilian applications for monitoring of coral reef; pollution on the sea bed; inspection of subsea pipelines and offshore structures etc.

From the current progress in the underwater robotics field, it is opined that the smaller the size of the underwater vehicle, easier is the adoption of fish type of locomotion, as has been demonstrated by different researchers. It is reckoned that time frame likely (for adoption of fish locomotion) for different underwater vehicles are as follows;

Vehicle	Likely Adoption by
Smaller submarines	20 years
Larger submarines	40 years
Special Operations Vehicles for divers and special forces	10 years
Torpedoes (in the present form)	20 years
Remotely Operated Vehicles	4-5 years
Unmanned Underwater Vehicles	4-5 years
Underwater mines	2-3 years

Bandhopadhyay [60] in chapter titled ” Highly Manoeuvrable Biorobotic Underwater Vehicles” in the handbook of Ocean Engineering, has contended that the emergent, low-speed platforms complement existing higher speed naval capabilities and are not substitutes for any existing mature system; in this sense, their utility depends on the imaginative nature of future operation concepts – a process that is unpredictable. The greater potential of the biorobotics approach is limited by a serious lack of progress in so-called strong artificial muscle technology, as well as by a lack of understanding of nonlinear temporal control and sensing and how they should be integrated.

However, as per Ray Kurzweil [61], if one look at the implications of exponential growth, it creates a very different picture of the future and it’s not intuitive. Problems that may seem intractable now could become eminently solvable in the near future. Not only should this inform investing and planning for the future, it should also change what one thinks of as possible for humanity. Soon, things which one could barely have imagined decades before might be within reach.

As regards the progress in finding efficient propulsors from the Indian context, there is some traction in the positive direction at CMS, Pune, where they have been able to demonstrate, with the help of FSI studies, that the cross section of the fin is an important design parameter in any study informing biomimetic engineering of fin propelled vehicles.

Having overcome the initial computational challenges, the work is in progress at CMS to undertake similar exercise for other shapes of fins commonly found in fishes, as shown in Figure 5, and compare the results to see which one of them is more efficient than others. It is also intended to analyse these fins with different flexibility, depending on the progress in elastomers properties as well a combination of rigid and flexible material.

References

[1] Dr. David M. Lane, Michael Sfakiotakis, Dr. J. Bruce C. Davies, “Review of Fish Swimming Modes for Aquatic Locomotion”, Submitted to the IEEE Journal of Oceanic Engineering, December 1998.

[2] J.J. Videler, *Fish Swimming*. London: Chapman & Hall, 1993.

[3] Koichi Hirata, Swimming Speeds of Some Common Fish, October 1, 1999, http://www.nmri.go.jp/oldpages/eng/khirata/fish/general/speed/speede.htm

[4] James L Sumich, John Francis Morrissey, “Introduction to Biology of Marine Life”, eight edition, Jones and Bartlett Publishes, USA

[5] http://www.robosoftca.eu/

[6] http://groups.csail.mit.edu/drl/wiki/index.php?title=Soft_Robotics

[7] http://softrobotics.org/basic-information/

[8] Peter A. Kerrebrock, Jamie M. Anderson, Joel R. Parry, "Application requirements of artificial muscles for swimming robots", July 2001, Proceedings of SPIE - The International Society for Optical Engineering. DOI - 10.1117/12.432686

[9] Kwang Jin Kim, Xiaobo Tan, Hyouk Ryeol Choi, David Pugal, "Biomimetic Robotic Artificial Muscles", https://www.worldscientific.com/worldscibooks/10.1142/8395#t=aboutBook

[10] MacCurdy, R.; Katzschmann, R.; Kim, Y. & Rus, D. "Printable Hydraulics: A Method for Fabricating Robots by 3D Co-Printing Solids, and Liquids". 2016 IEEE International Conference on Robotics and Automation (ICRA), 2016

[11] Andrew D. Marchese, Robert K. Katzschmann, and Daniela Rus, 2015, "A Recipe for Soft Fluidic Elastomer Robots", Soft Robotics, Volume 2, Number 1, 2015, Mary Ann Liebert, Inc., DOI: 10.1089/soro.2014.0022

[12] Jacob Aron, Robotic fish shoal sniffs out pollution in harbours, Innovation - 22 May 2012, https://www.newscientist.com/article/dn21836-robotic-fish-shoal-sniffs-out-pollution-in-harbours/

[13] DARPA Plans to Develop "Flying Submarine", https://www.naval-technology.com/news/news89904-html/

[14] EvoLogics Bionic Observation and Survey System (BOSS) Manta Ray - the stunningly lifelike subsea robot for automated monitoring, 28 Jul 2017.https://www.youtube.com/watch?v=qv5UmykFSJU –

[15] http://www.nmri.go.jp.

[16] Realistic robot carp created: First robot fish with autonomous 3-D movement in Asia, June 26, 2013. https://www.sciencedaily.com/releases/2013/06/130626113027.htm?utm_medium=cpc&utm_campaign=ScienceDaily_TMD_1&utm_source=TMD

[17] Swarm of underwater robots mimics ocean life; Researchers collaborate on new technology study using 'robotic plankton', January 24, 2017, https://www.sciencedaily.com/releases/2017/01/170124111358.htm

[18] https://en.wikipedia.org/wiki/RoboTuna.

[19] http://tech.mit.edu/V115/N49/robotuna.49n.html.

[20] Jamie M. Anderson and Narender K. Chhabra, "Maneuvering and Stability Performance of a Robotic Tuna", Integrative and Comparative Biology Feb 2002 : Vol. 42, Issue 1, pg(s) 118- 126, https://doi.org/10.1093/icb/42.1.118

[21] Engineers Are Building Robotic Fin For Submarines. https://www.sciencedaily.com/releases/2007/07/070730181502.htm?utm_medium=cpc&utm_campaign=ScienceDaily_TMD_1&utm_source=TMD

[22] https://www.newscientist.com/article/dn25225-robot-fish-changes-direction-with-a-quick-tail-wiggle/ - 14 March 2014

[23] https://www.newscientist.com/article/2164331-watch-this-robotic-fish-flap-its-fins-in-fijis-rainbow-reef/ - 21 March 2018

[24] Robert K. Katzschmann, Joseph DelPreto, Robert MacCurdy and Daniela Rus, "Exploration of underwater life with an acoustically controlled soft robotic fish', *Science Robotics* 21 Mar 2018: Vol. 3, Issue 16, eaar3449; DOI: 10.1126/scirobotics.aar3449

[25] https://www.csail.mit.edu/research/sofi-soft-robotic-fish

[26] https://biorob.epfl.ch.

[27] Eric Tytell, 2011, “Pulsed Wakes Are (Sometimes) Better Than Steady Jets”, Journal of Experimental Biology

[28] Ruiz, L. A., Whittlesey, R. W. and Dabiri, J. O. 2011,“Vortex-enhanced propulsion”. J. Fluid Mech.668, 5-32.

[29] Sir Robert Hill, September 2017, “Racing Human Powered Submarines”, Ingenia Issue 72

[30] Matt Burgess, Aug 2017, “The Royal Navy has gazed into the future... and it looks pretty fishy”, https://www.royalnavy.mod.uk/news-and-latest-activity/news/2017/august/28/170828-royal-navy-unveils-radical-future-submarine-concepts

[31] Underwater robot swarms use collective cognition to perform tasks, May 28, 2015, https://www.sciencedaily.com/releases/2015/05/150528083639.htm

[32] https://en.wikipedia.org/wiki/Moore's_law

[33] Technology Grows Exponentially - https://bigthink.com/think-tank/big-idea-technology-grows-exponentially

[34] Global Marine Trends 2030, published in 2013, available freely at www.lr.org

[35] S Yasseri, “Subsea system readiness level assessment”, Underwater Technology Vol 31 No 2, Spring 2013

[36] Tyler Van Buren and Alexander J Smits, “Bio-inspired underwater propulsors – Project Bio inspired propulsion”. Jan 2018. https://www.researchgate.net/publication/322818882_Bio-inspired_underwater_propulsors

[37] Fish, F. E., Schreiber, C. M., Moored, K. W., Liu, G., Dong, H., & Bart-Smith, H. (2016), “Hydrodynamic Performance of Aquatic Flapping: Efficiency of Underwater Flight in the Manta” .Aerospace, 3(3), 1-24.http://dx.doi.org/10.3390/aerospace3030020

[38] R. Bainbridge, “The speed of swimming of fish as related to size and to the frequency and amplitude of the tail beat,” J.Exp. Biol. 35, 109–133 (1958).

[39] R.W. Blake, “The mechanics of labriform locomotion. I. Labriform locomotion in the angelfish (Pterphyllum eimekei): an analysis of the power stroke,” J. Exp. Biol. 82, 255–271 (1979).

[40] R. E. Shadwick and G. V. Lauder, Fish Biomechanics (Academic, New York, 2006).

[41] F. E. Fish and G. V. Lauder, “Passive and active flow control by swimming fishes and mammals,” Annu. Rev. Fluid Mech. 38, 193–224 (2006).

[42] U. K. Muller, J. Smit, E. J. Stamhuis, and J. J. Videler, “How the body contributes to the wake in undulatory fish swimming flow fields of a swimming eel (Anguilla anguilla),” J. Exp. Biol. 204(16), 2751–2762 (2001).

[43] M. J. Lighthill, “Hydromechanics of aquatic animal propulsion,” Annual Rev. Fluid Mech. 1(1), 413–446 (1969).

[44] T. Y. Wu, “Hydromechanics of swimming propulsion. Part 1. Swimming of a two-dimensional flexible plate at variable forward speeds in an inviscid fluid,” J. Fluid Mech. 46(2), 337–355 (1971).

[45] J. A. Sparenberg, “Survey of the mathematical theory of fish locomotion,” J. Eng. Math. 44(4), 395–448 (2002).

[46] K. Singh and T. J. Pedley, “The hydrodynamics of flexible-body manoeuvres in swimming fish,” Physica D: Nonlinear Phenom. 237(14–17), 2234–2239 (2008).

[47] M. Sfakiotakis, D.M. Lane, and J. B. C. Davies, “Review of fish swimming modes for aquatic locomotion,” IEEE J. Ocean.Eng. 24(2), 237–252 (1999).

[48] M. S. Triantafyllou, G. S. Triantafyllou, and D. K. P. Yue, “Hydrodynamics of fish like swimming,” Annu. Rev. FluidMech. 32, 33–53 (2000).

[49] Andrew D. Marchese, Cagdas D. Onal and Daniela Rus (2014) “Autonomous Soft Robotic Fish Capable of Escape Manoeuvres Using Fluidic Elastomer Actuators Soft Robotics”

[50] Kohannim S, Iwasaki T. (2014) “Analytical insights into optimality and resonance in fish swimming”, J. R. Soc. Interface 1120131073

[51] Y. Bazilevs, K. Takizawa, and T.E. Tezduyar, “Computational Fluid Structure Interaction: Methods and Application”, Wiley, February 2013, ISBN 978- 0470978771

[52] H.J.-P. Morand and R. Ohayon, “Fluid-Structure Interaction: Applied Numerical Methods”, Wiley, 1995, ISBN 978-0-471-94459-1

[53] Dhondt, G. “The Finite Element Method for Three-Dimensional Thermomechanical Applications”, Wiley, 2004.

[54] Thomas D. Economon, Francisco Palacios, Sean R. Copeland, Trent W. Lukaczyk, and Juan J. Alonso. “SU2: An Open-Source Suite for Multiphysics Simulation and Design”, AIAA Journal, Vol. 54, No.3(2016), pp. 828-846.

[55] Ahrens, James, Geveci, Berk, Law, Charles, ParaView: An End-User Tool for Large Data Visualization, Visualization Handbook, Elsevier, 2005, ISBN-13: 978-0123875822

[56] H.-J. Bungartz, F. Lindner, B. Gatzhammer, M. Mehl, K. Scheufele, A. Shukaev, and B. Uekermann: preCICE - A Fully Parallel Library for Multi-Physics Surface Coupling., Computers and Fluids,Elsevier,141, 250–258, 2016.

[57] Joris Degroote, Klaus-Jürgen Bathe, Jan Vierendeels, “Performance of A New Partitioned Procedure Versus A Monolithic Procedure In Fluid–Structure Interaction”

[58] https://www.aspistrategist.org.au/pump-up-the-pump-jet/

[59] Yl Yound, MR Motley, R Barber, EL Chae, N Garg, “Adaptive Composite Marine Propulsors and Turbines: Progress and Challenges”, Applied Mechanics Reviews · September 2016, DOI: 10.1115/1.4034659

[60] Bandyopadhyay P.R. “Highly Maneuverable Biorobotic Underwater Vehicles. In: Dhanak M.R., Xiros N.I. (eds) Springer Handbook of Ocean Engineering”. Springer, Cham, 2016.

[61] www.kurzweilai.net

Bibliography

US Navsea Event, Aug 2017, Battlespace Preparation in Contested Environment, - Advanced Naval Technology Exercise – Newport.

J Eisenhuth and BW Mccormick. "Design And Performance Of Propellers And Pumpjets For Underwater Propulsion", AIAA Journal, Vol. 1, No. 10 (1963), pp. 2348-2354.

Mohsen Asadnia et al, “Artificial fish skin of self-powered micro-electromechanical systems hair cells for sensing hydrodynamic flow phenomena”, J. R. Soc. Interface 12: 20150322., http://dx.doi.org/10.1098/rsif.2015.0322

Godoy-Diana R, Thiria B.2018, “On the diverse roles of fluid dynamicdrag in animal swimming and flying”. J. R. Soc.Interface 15: 20170715, http://dx.doi.org/10.1098/rsif.2017.0715

Nick Gravish, George V. Lauder, “Robotics-inspired biology”, Journal of Experimental Biology, 2018, 221: jeb138438 doi: 10.1242/jeb.138438 Published 29 March 2018

Silas Alben, Charles Witt, T. Vernon Baker, Erik Anderson, and George V. Lauder, “Dynamics of freely swimming flexible foils”, Phys. Fluids 24, 051901 (2012); doi: 10.1063/1.4709477

Videler JJ, Hess F. 1984 “Fast continuous swimming of two pelagic predators, saithe (Pollachius virens) and mackerel (Scomber scombrus): a kinematic analysis”. J. Exp. Biol. 109, 209 – 228.

Fish FE, Rohr JJ. 1999, “Review of dolphin hydrodynamics and swimming performance”, Technical Report 1801. San Diego, CA: SPAWARS System Center.

Sfakiotakis M, Lane DM, Bruce J, Davies BC. 1999,“Review of fish swimming modes for aquatic locomotion”. IEEE J. Ocean Eng. 24, 237 – 252.(doi:10.1109/48.757275)

Li G, Mu¨ller UK, van Leeuwen JL, Liu H. 2016, “Fish larvae exploit edge vortices along their dorsal and ventral fin folds to propel themselves”. J. R. Soc. Interface 13: 20160068, http://dx.doi.org/10.1098/rsif.2016.0068

Ramananarivo S, Godoy-Diana R, Thiria B. 2013, “Passive elasticmechanism to mimic fish-muscle actionin anguilliform swimming”. J R Soc Interface 10: 20130667, http://dx.doi.org/10.1098/rsif.2013.0667

P.W. Webb “Designs for stability and maneuverability in aquatic vertebrates: What can we learn ?,” in Proc. of the Special Session on Bio-Engineering Research Related to Autonomous Underwater Vehicles, 10th Intern. Symposium on Unmanned Untethered Submersible Technology, New Hampshire, USA, pp. 85-108, September 1997.

B.F.Feeny, “A complex orthogonal decomposition for wave motion analysis, J.Sound Vib. 310(2008)77–90

http://www.auvsifoundation.org/home

http://www.robotic-fish.net/index.php?lang=en&id=robots

http://robotics.sciencemag.org/

https://www.sciencedirect.com/science/journals

https://www.sciencedaily.com/releases/2016/05/160518120240.htm?utm_source=TMD&utm_medium=cpc&utm_campaign=ScienceDaily_TMD_1

http://groups.csail.mit.edu/drl/wiki/index.php?title=Soft_Robotics

R Liebe, "Flow phenomenon in Nature - Vol 1 - A challenge to engineering design". By

http://groups.csail.mit.edu/drl/wiki/index.php?title=Soft_Robotics

https://www.csail.mit.edu/person/robert-katzschmann#publications

https://www.csail.mit.edu/research?f[0]=research_area:9

Neurotechnology for biomimetics robots, edited by Joseph Ayers, Joel L. Davis, Alan Rudolph

Tuna – Physiology, Ecology and evolution. By B A Block and E D Stevens

Centrarchid Fishes: Diversity, Biology and Conservation, edited by Steven Cooke, David P. Philipp

Journal of Ichthyology, Volume 16

Active and passive smart structures and integrated systems 2007: 19-22 March, 2007, San Diego, California, USA, *Volume 6525 of Proceedings of SPIE--the International Society for Optical Engineering*

Stephen Childress, Mechanics of Swimming and Flying, https://books.google.co.in/books?id=YZ2zOzsvTLoC&pg=PA112&dq=caudal+fins+efficiency&hl=en&sa=X&ved=0ahUKEwihvP76qavaAhVLqY8KHTM-Buo4FBDoAQhAMAU#v=onepage&q=caudal%20fins%20efficiency&f=false

Ronald Victor Tait, Frances Dipper, Elements of Marine Ecology,https://books.google.co.in/books?id=BzlDvZ0ObYkC&pg=PA137&dq=caudal+fins+efficiency&hl=en&sa=X&ved=0ahUKEwihvP76qavaAhVLqY8KHTM-Buo4FBDoAQhQMAg#v=onepage&q=caudal%20fins%20efficiency&f=false

https://www.google.co.in/search?q=caudal+fins+efficiency&hl=en&tbm=bks&ei=bkjKWsuGD8jbvgTg_4OwCA&start=20&sa=N&biw=1366&bih=654&dpr=1

https://marinerobotics.mit.edu/biblio?page=1

https://www.sciencedirect.com/science?_ob=ArticleListURL&_method=list&_ArticleListID=-1259176065&_sort=v&_st=17&view=c&_origin=related_art&panel=citeRelatedArt&_mlktType=Journal&md5=b420238ff6a928bad3ee1ffb4c02c6fa&searchtype=a

http://groups.csail.mit.edu/drl/wiki/index.php?title=Printable_Hydraulics

Deepak Trivedi, Chris Rahn, William Kier, Ian D. Walker. "Soft Robotics: Biological Inspiration, State of the Art, and Future Research"; October 2008, Applied Bionics and Biomechanics 5(3):99-117, DOI 10.1080/11762320802557865

Dimitrios Tzeranis, Evangelos Papadopoulos, George Triant afyllou, "On the Design of an Autonomous Robot Fish", June 2003,
https://www.researchgate.net/publication/242295282_On_the_Design_of_an_Autonomous_Robot_Fish
https://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/actuators-comp.pdf

Yoseph Bar-Cohen, "Electroactive Polymer (EAP) Actuators as Artificial Muscles: Reality, Potential, and Challenges", Published: 2004, DOI: 10.1117/3.547465 , PDF ISBN: 9780819481122 | Print ISBN: 9780819452979

Guo-Ying Gu, Jian Zhu, Li-Min Zhu and Xiangyang Zhu, "A survey on dielectric elastomer actuators for soft robots", Published 23 January 2017, IOP Publishing Ltd, Bioinspiration & Biomimetics, Volume 12, Number 1

J. Eisenhuth and b. W. Mc cormick. "Design and Performance of Propellers and Pumpjets for Underwater Propulsion", AIAA Journal, Vol. 1, No. 10 (1963), pp. 2348-2354.

Andrew D. Marchese, Russ Tedrake and Daniela Rus, 2015, "Dynamics and trajectory optimization for a soft spatial fluidic elastomer manipulator", The International Journal of Robotics Research 1–20, DOI: 10.1177/0278364915587926

Cosimo Della Santina_, Robert K. Katzschmann_, Antonio Bicchi, Daniela Rus, 2018, "Dynamic Control of Soft Robots Interacting with the Environment".

Robert K. Katzschmann, Andrew D. Marchese, and Daniela Rus, "Autonomous Object Manipulation Using a Soft PlanarGrasping Manipulator", SOFT ROBOTICS, Volume 2, Number 4, 2015, DOI: 10.1089/soro.2015.0013

Andrew D. Marchese, Robert K. Katzschmann, and Daniela Rus, "Whole Arm Planning for a Soft and Highly Compliant 2D Robotic Manipulator"

Andrew D. Marchese, Konrad Komorowski, Cagdas D. Onal, and Daniela Rus, "Design and Control of a Soft and Continuously Deformable 2D Robotic Manipulation System"

Shuguang Li, Robert Katzschmann, and Daniela Rus, 2015,“A soft cube capable of controllable continuous jumping”, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)

Matt Denton, December 2016, “Engineering Personality in to Robots”, Ingenia Issue 69.

Sir Robert Hill,September 2017,“Racing Human Powered Submarines”, Ingenia Issue 72

Matt Burgess, Aug 2017, “The Royal Navy has gazed into the future... and it looks pretty fishy”,

Jeffrey Lin and P.W. Singer June 1, 2017, “China is developing a warship of naval theorists' dreams”, https://www.popsci.com/futuristic-chinese-warship-concept-is-making-waves

X Sun, N Kato and H Li;Nov 2011, “Effects of Cross Section and Flexibility of Pectoral Fins on the swimming Performance of Biomimetic Underwater Vehicles”

Meliha Bozkurttas, James Tangorra, George Lauder, Rajat Mittal, 2008, “Understanding the Hydrodynamics of Swimming:From Fish Fins to Flexible Propulsors for Autonomous Underwater Vehicles”, Advances in Science and Technology, www.scientific.net.

Global Marine Fuel Trends, published in 2014, available freely at www.lr.org

Global Marine Technology Trends 2030, published in 2015, available freely at www.lr.org

Global Marine Technology Trends 2030, (Autonomous Systems) published in 2015, available freely at www.lr.org

Poul Andersen, Jens J. Kappel, Eugen Spangenberg, Aspects of Propeller Developments for a Submarine, First International Symposium on Marine Propulsors - smp’09, Trondheim, Norway, June 2009.

Keh-Sik Min, et al, Study on the contra rotating propeller system design and full scale performance prediction method, International Journal of Naval Architecture and Ocean Engineering, 2009, pp 29 – 38.

Dimitrios Laskos, Design and Cavitation Performance of Contra-Rotating Propellers, M Sc Thesis, MIT, June 2010.

John Carlton, Modern Propellers and Propulsion, Butterworth-Hienemann, Third Edition, 2012.

Brockett Terry E, On the Maximum Efficiency of Some Marine Propulsors in Open Water, International Shipbuilding Progress, vol. 50, no. 1,2, pp. 147-169, 2003.

Kohannim S, Iwasaki T, . 2014, “Analytical insights into optimality and resonance in fish swimming”. J. R. Soc. Interface 11: 20131073, http://dx.doi.org/10.1098/rsif.2013.1073.

DS Barrett, MS Triantafyllou, DKP Yue, MA. Grosenbaugh and MJ Wolfgang, “Drag reduction in fish-like locomotion”, August 1999, Journal of Fluid Mechanics 392, DOI 10.1017/S0022112099005455.

Zuo Cui, Zixuan Yang, L Shen, H Z Jiang, “Complex modal analysis of the movements of swimming fish propelled by body and/or caudal fin”, April 2018, , Wave Motion 78, DOI 10.1016/j.wavemoti.2018.01.001.

Michael S. Triantafyllou and George S. Triantafyllou. “An efficient swimming machine”. Scientific American, 272(3):64-70, March 1995.

David S. Barrett. Propulsive Efficiency of a Flexible Hull Underwater Vehicle. PhD thesis, Massachusetts Institute of Technology, 1996.

Manta Droid Underwater Robot, 05 Dec 2017, https://www.youtube.com/watch?v=rWJElQQNEeg

“BIKI: First Bionic Wireless Underwater Fish Drone - Underwater Drone”, https://www.youtube.com/watch?v=0hRHWa2urys --

Motion control of a bio-inspired underwater robot with undulatory fin propulsion, 15 Nov 2015, https://www.youtube.com/watch?v=ytKzx2Xsukk

PHORCYS 571 K.R.S (biomimetic robotic fish), 29 Oct 2010, http://www.grobot.gr, https://www.youtube.com/watch?v=etsuJ3PcBCI -

Saroj Saimek and Thanasit Suasan, High -Accuracy Fish Robot contest 2, 29 Aug 2011, https://www.youtube.com/watch?v=CK-iizv04Is

Robot shark from WIZARD, Korea, 11 Sep 2009, http://www.wizard-fx.com, https://www.youtube.com/watch?v=1QGyxfigkCY.

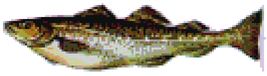
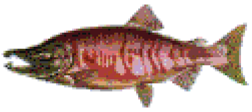
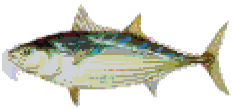
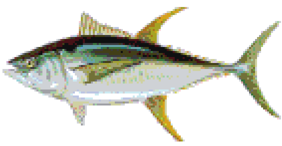
Robotic Shark, 22 Nov 2009, https://www.youtube.com/watch?v=S-8WN1bnM9k

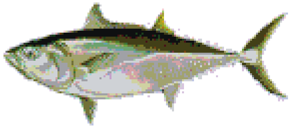
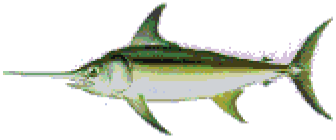
Robert K Katzschmann, Austin de Maille, David L Dorhout, Daniela Rus, “Cyclic Hydraulic Actuation for Soft Robotic Devices”, 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Daejeon Convention Center, October 9-14, 2016, Daejeon ea

Dynamics of freely swimming flexible foils Silas Alben, Charles Witt, T. Vernon Baker, Erik Anderson, and George V. Lauder.

Appendix 1

Type of common fishes and their speeds

 Herring	Speed = 6 km/h = 1.67 m/s = 3.7 MPH Length = 0.3 m V/L = 5.6
 Pike	Speed = 6 km/h = 1.67 m/s = 3.7 MPH Length = 0.5 m V/L = 3.3
 Carp	Speed = 6 km/h = 1.67 m/s = 3.7 MPH Length = 0.8 m V/L = 2.1
 Cod	Speed = 8 km/h = 2.22 m/s = 5 MPH Length = 1.2 m V/L = 1.9
 Mackerel	Speed = 11 km/h = 3.06 m/s = 6.8 MPH Length = 0.5 m V/L = 6.1
 Salmon	Speed = 45 km/h = 12.5 m/s = 28 MPH Length = 1.0 m V/L = 12.5
 Bonito	Speed = 60 km/h = 16.7 m/s = 37 MPH Length = 0.9 m V/L = 18.6
 Small Tuna (KIHADA)	Speed = 60 km/h = 16.7 m/s = 37 MPH Length = 3.0 m V/L = 5.6

 Black Tuna	Speed = 80 km/h = 22.2 m/s = 50 MPH Length = 3.0 m V/L = 7.4
 Swordfish	Speed = 96 km/h = 26.7 m/s = 60 MPH Length = 4.0 m V/L = 6.7

http://doi.org/10.24868/issn.2515-818X.2018.018