Review of Biomimetic Propulsion Methods Providing Improved Manoeuvrability for Autonomous Underwater Vehicles (AUVs).

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Abstract

The current conventional propeller based design of Autonomous Underwater Vehicles (AUVs) are failing to meet the increasing manoeuvrability standards required. This has led to a trend of looking to nature for inspiration in order to create alternative biomimetic propulsion systems capable of precise manoeuvres. Millions of years of evolution across a vast range of aquatic animal species has led to an array of swimming methods. These can be categorised into Body and/or Caudal Fin (BCF), and Median and/or Paired Fin (MPF), and further subcategorised according to the undulatory or oscillatory nature of the movement. Various different AUVs from a range of swimming forms have been considered. The designs all try to mimic the exact movement of the natural source in order to achieve results approaching that of the animal. The end result is a large set of differing propulsion techniques, of BCF and MPF varieties, offering better manoeuvrability while maintaining a high level of speed and efficiency. These present viable options for implementation in Functional AUVs. Further potential improvement can come from combining features of BCF and MPF swimming forms, however this technology still requires further research.

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1. Introduction

Autonomous Underwater Vehicles (AUVs) are a subclass of Unmanned Underwater Vehicles (UUVs), with the distinction being that an AUV is capable of operating without external support, either in the form of a tethered power supply or real time commands (1). The origins of the modern AUV can be traced back to the torpedo, for many years torpedoes were the only application for AUVs and hence early development was heavily focused on this single purpose. These design principles are still used in modern commercial AUVs for a wide variety of new applications, including seabed mapping, exploration and mine sweeping. Torpedoes were designed for speed and the ability to hold course. This lead to the so called torpedo shape AUV of today, which are most commonly propelled by propeller based thrusters (1) (2). Such AUV designs commonly have poor manoeuvrability with a 180° turn taking several body lengths in some cases (2). Design for manoeuvrability was not an issue in early applications, but now there is an ever increasing demand for more manoeuvrable and agile AUVs, which cannot be satisfied by the conventional design principles. This need for alternative propulsion methods has led to developers looking to nature for inspiration.

Nature provides a good opportunity to learn how to improve underwater propulsion techniques. Fish and other aquatic animals having optimised the process through evolution over a period of many years. The relative performance of such animals is significantly better than any AUV currently available. This can be categorised by considering the turning radii of both; many natural examples fall below half of the body length (0.5BL), compared with the more manoeuvrable AUVs having 2BL and more commonly 4BL (3) (4). This is in addition to the very fast rates of turning (in excess of 500°/s) that these animals are capable of (3). For these reasons it is very desirable to replicate the swimming modes of these creatures in order to create AUV propulsion systems.

In order to mimic the desired behaviour it must first be understood. There are two fundamental swimming methods to consider; Body and/or Caudal Fin (BCF), and Median and/or Paired Fin (MPF). BCF swimming are modes where the caudal fin and a percentage of the body create a translational wave in order to produce the required thrust. MPF swimming on the other hand uses pectoral, dorsal or anal fins to generate directed propulsion (5). Both of these methods can then be subcategorized into swimming modes, which can be ordered on an undulatory to oscillatory scale. Undulatory modes use a large area to propagate the wave, whereas oscillatory modes use smaller fins or a lower proportion of the body while moving them at a greater frequency. Fig 1 shows this classification (5).

Undulatory modes have higher manoeuvrability, but there are associated negative implications on speed and efficiency. It can also be said that MPF swimming is capable of better manoeuvrability than BCF, with up to six degrees of freedom possible. Theoretically therefore an undulatory MPF swimming mode would be best for manoeuvrability, however this is rarely the only design consideration for AUVs (2). As such modes will be considered across the full undulatory to oscillatory spectrum in both categories. The report will look at how these BCF and MPF swimming modes can be implemented as AUV propulsion methods in order to aid manoeuvrability. The circled modes in Figure 1 are the forms examined.

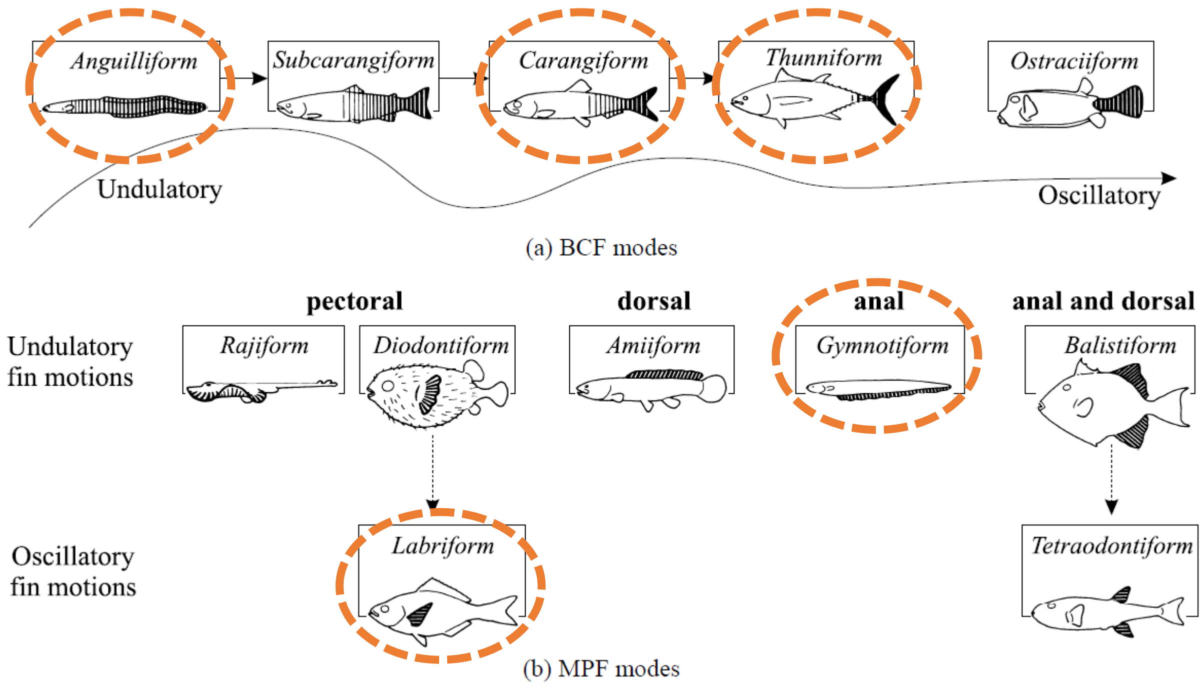

Figure 1: Diagram showing the categories of swimming modes (Circled modes are those considered in this report) (5).

2. Body and/or Caudal Fin (BCF)

BCF swimming offers potential improvement in manoeuvrability in comparison to conventional AUV propulsion methods. As well as improving speed, efficiency and longevity of swimming. There are various forms of BCF swimming, and the implementation of these specific modes reflects in the end performance.

2.1 Thunniform

The thunniform swimming mode is a very efficient and fast swimming form, it has therefore been considered significantly with regards to AUV propulsion. Not strictly known for its manoeuvrability it still offers a viable option compared to propeller propulsion.

The implementation of thunniform locomotion comes in the form of a simple oscillating mechanical fin, which represents a fish's caudal fin. The first example of such a machine is RoboTuna, designed at the Massachusetts Institute of Technology (MIT). RoboTuna was the precursor to the VCUUV (Draper Laboratory Vorticity Control UUV) although still successful in its own right (2). The VCUUV is based on a yellow fin tuna, with the body and fin designs coming from scaled up specimens, with only minor insignificant changes (6). This approach of following the tuna precisely is to produce a design closely mimicking its movement. This movement is replicated using a hydraulic driven link assembly, which actuates the four link assembly. This structure is shown in Figure 2.

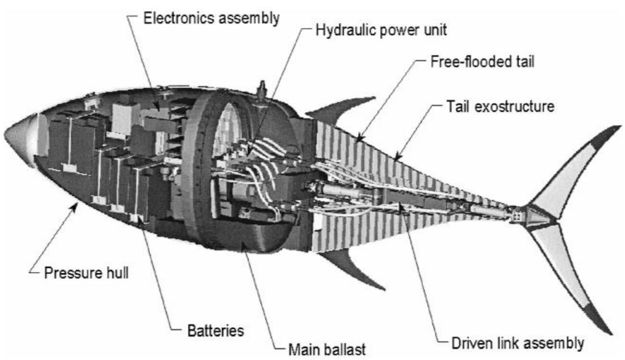

Figure 2: VCUUV schematic Diagram (6).

The VCUUV was found to have good manoeuvrability which approached that of the live animal which inspired the design. Anderson et al. (2002) report that the VCUUV was able to produce turning diameters consistent with that of a live tuna (0.94BL) for the given body length (2.4 - 3m) (6). The maximum yaw rate the VCUUV achieved in testing was 75°/s, compared to the 3 to 5°/s Anderson et al. (2002) calculated for a generic AUV.

The SPC-II robofish, developed by the Robotics Institute in Beijing University, uses a similar approach to the VCUUV. The SPC-II replicates the thunniform motion using a two link actuated caudal fin, which is attached to a rigid body. The resulting performance of the SPC-II robofish was a turning radius of 1BL and rate of 70°/s (7).

2.2 Carangiform

Carangiform is a mid-range undulatory to oscillatory swimming mode. Replicating it therefore offers the opportunity to create a propulsion system offering the best of manoeuvring and speed combined.

RoboPike from MIT is an example of carangiform swimming imitation, specifically that of a pike. The 80cm long RoboPike's tail movement comes from a simple four-vertebra backbone, with servomotors actuating the three joint system. The resulting performance from RoboPike as categorised by Kumph (2000) was a 17.5°/s turning rate being achieved (8).

Also in this category is the PF-300 from the Japanese National Maritime Research Institute (NMRI). This draws on the sea bream as inspiration, due to its excellent turning ability from its carangiform swimming style (2). The basic construction is similar to that of RoboPike, with the PF-300 having a simplified three-vertebra structure. The tail is a two joint system actuated by a servo motor housed in the body of the fish (9). A schematic view of the PF-300 sea bream inspired design is shown in Figure 3.

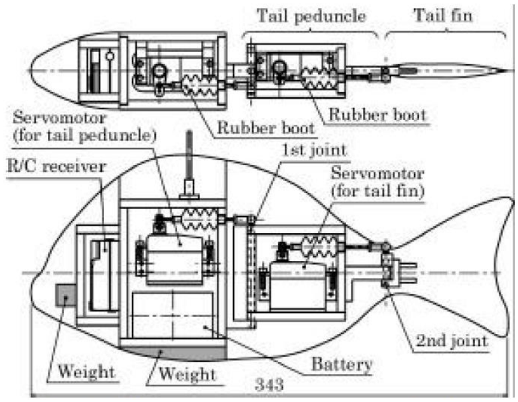

Figure 3: Schematic diagram of PF-300 (9).

With the prototype PF-300 Hirata et al. (2000) considered three turning modes each only using the tail fin for manoeuvring. The idea of this was to replicate the different motions of the see bream. The peak performance of the PF-300 in terms of manoeuvrability was found to be a turning diameter of 0.22BL and rate of 110°/s.

2.3 Anguilliform

Of the considered BCF swimming modes Anguilliform offers the best manoeuvrability in nature, therefore it offers the most potential for a purely manoeuvrable design of AUV.

Drawing inspiration from eels and their full body undulatory propulsion, the REEL robot was created by Ostrowski and McIsaac. This work formed the basis of further development of undulatory motion by Knutsen (10). The current robot design consists of five metal plates, with four mechanical links actuated by servo motors, which is all encased in plastic shells. The assembled robot is shown in Figure 4.

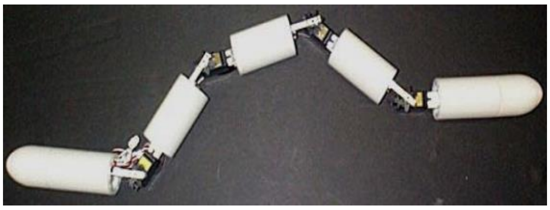

Figure 4: Photo of eel-like underwater robot (10).

The work of Knutsen along with Ostrowski and McIsaac is very much still in its development phase. The current robot is radio controlled and as such is not strictly an AUV rather just an UUV, but there is clear potential for this automation in future work. The movement of the adapted REEL robot requires a complex control system again still in development (10). Although as yet there are no tangible or quantifiable results from this design, it demonstrates the ability to replicate anguilliform swimming.

3. Median and/or Paired Fin (MPF)

MPF swimming can offer a large array of precise movement with up to six degrees of freedom. This can be implemented in either an undulatory or oscillatory form.

3.1 Labriform

Tokai University have created an MPF propelled AUV, based on a black bass. The black bass was chosen for its use of pectoral fins to manoeuvre. The AUV called Bass-II has two mechanical pectoral fins each powered by two servo motors. The fins themselves are rigid flat stainless steel plates 6.2 times larger than the actual bass (11). The motors moves the fins to replicate two fundamental forms of motion observed in the fish, these are; a lead lag motion in the horizontal plane, and a feathering motion, which is a twisting motion of the fin pitch. The combination of these two movements can create forward and backward swimming, as well as turning on the horizontal plane. This use of two motors per fin allows six degrees of freedom, by controlling relative phase and magnitude of the yaw and pitch oscillations. Kato et al. (2000) have shown Bass-II to have a high level of manoeuvrability, this is especially true for lateral swimming. Precision manoeuvres could still be performed using this mechanism with currents up to 0.05m/s (2) (11).

Researchers at MIT have also created an AUV mimicking the labriform swimming mode called RoboTurtle. This is inspired by a sea turtle and the design of which is shown in Figure 5.

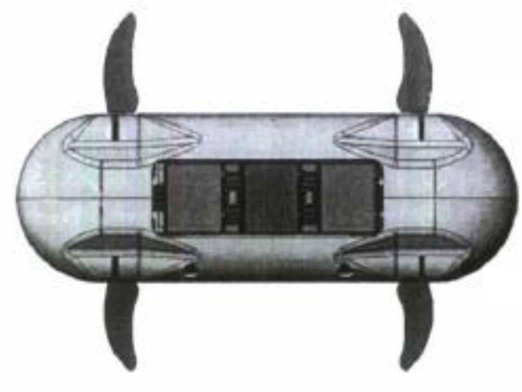

Figure 5: Plan view of the complete RoboTurtle (12).

RoboTurtle uses a four fin system, similar to Bass-II each fin is self-contained with two motors, however they instead provide movement in roll and pitch. Again as in the robotic bass the manoeuvring is controlled by changing the phase and amplitude of the oscillations (12). In Figure 6 the actuated fin design is shown in detail.

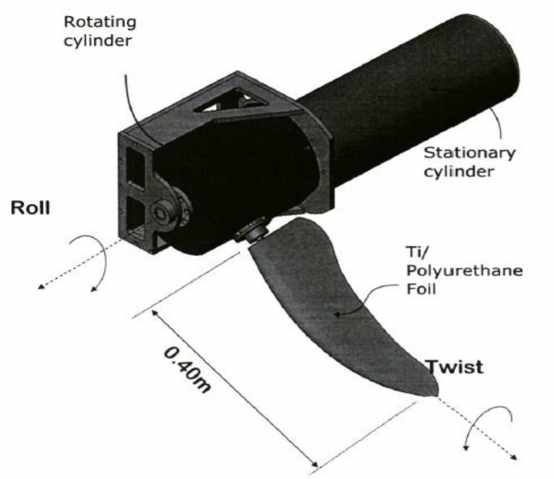

Figure 6: RoboTurtle fin design (12).

Licht (2008) reports that this biomimetic propulsion system leads to significant improvements over conventional AUV turning performance, even exceeding it by a factor of two. RoboTurtle demonstrates a minimum turning radius of 0.7BL, and heading rate of 40°/s at cruising speeds of 0.75BL/s (12).

Festo have produced a penguin design AUV using similar principles. The Festo Aqua Penguin, shown in Figure 7, uses two pectoral fins in a labriform swimming mode. Like the RoboTurtle, the Aqua Penguin fins move in roll and pitch. Roll being controlled by a single DC motor shared by both fins, and pitch control is achieved by individual motors for each fin. The variation in pitch angles, as well as the amplitude and phase of oscillations provides the manoeuvrability. Festo claim to have almost perfectly imitated the aquatic flight of penguins, leading to the ability of the AUV; to manoeuvre in spatial conditions, turn on the spot and swim backwards – which even real penguins can't do (13).

Figure 7: Festo Aqua Penguin design (13).

3.2 Gymnotiform

Undulatory type MPF locomotion is a little researched but relevant area. North Western University have developed a ribbon fin device drawing from the gymnotiform swimming mode of the black ghost knifefish. Knifefish use a ribbon like anal-fin, which runs most the length of their body, as their main propulsive mechanism. They move by oscillating the ribbon fin the opposite direction to motion, creating a propulsive force, the direction of movement is easily changed by reversing the wave direction. Lateral movement is achieved by simultaneously sending waves from the head and tail ends towards the centre of the fin, this cancels longitudinal forces while increasing the vertical force (14) (15). The ribbon fin device aims to replicate this behaviour to create a viable propulsion system, a schematic diagram of the device is shown in Figure 8.

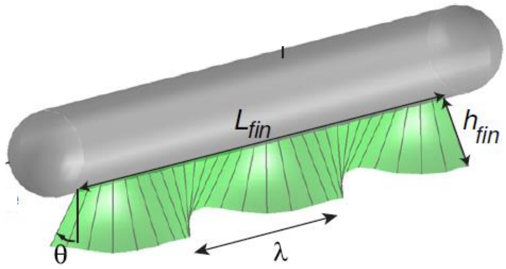

Figure 8: Ribbon fin propulsion mechanism (15).

The ribbon fin device consists of eight brass rod rays which are connected together by a flexible latex sheet. These rays are actuated individually by servo motors located in the rigid body. The actuation in the roll plane forms sinusoidal propulsion waves, which translate into either forward or backwards motion depending on the wave direction. Introducing offsets into the undulatory fin movement can reproduce a variety of different manoeuvres. The result is a concept that with the right calibration can emulate the six degree-movement manoeuvrability displayed by a knifefish, which could form the basis of an AUV propulsion system (2) (14).

4. Discussion

The purpose of this review was to identify bio-inspired propulsion systems, which could provide higher levels of manoeuvrability in comparison to the conventional propeller propulsion used in most AUVs. From understanding the basic swimming methods of aquatic animals suitable swimming modes were identified, in both BCF and MPF swimming types, which could potentially provide the solution to this problem. The question was then whether these principles arising from nature could be mimicked, and mechanical AUV designs produced using them.

BCF swimming modes all tend to operate in a similar manner, using actuated tail fins. The differences occur in the number of moving joints, which increase as the swimming modes become undulatory in nature. This method of replicating BCF swimming produces good results. Figure 9 shows turning length and rate, along with the maximum speed of these AUV designs, against an arbitrary scale representing the oscillatory to undulatory nature of the movement.

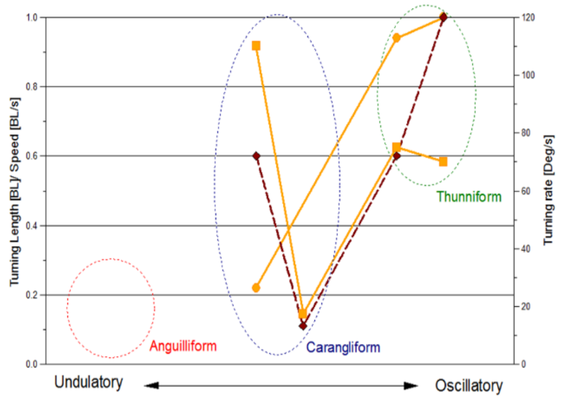

Figure 9: Graph showing manoeuvrability and speed of BCF biomimetic propelled AUV designs.

The graph shows that the mechanical versions of the BCF swimming modes in comparison to each other follow the same trend we see in nature. As in, thunniform propulsion delivers the highest speed while carangiform has a greater manoeuvrability at the expense of some speed. This indicates that the replicated motion is at least a fair representation of its natural inspiration.

The success of thunniform and carangiform motions is not replicated by anguilliform based propulsion systems. To create anguilliform motion requires a complex system, with a significantly higher number of moving parts and motors in comparison to its more oscillatory fellow BCF modes. The very principle of the motion has its own impracticality, as the requirement for full body movement leaves little space for the on board equipment required in a functional AUV.

For applications which require a very high level of manoeuvrability, and where speed is not so critical, MPF swimming is perhaps a better option. MPF swimming gives six-degree of freedom movement, and there are already many successful examples of this motion implemented in mechanical devices. The use of pectoral fins in an oscillatory manner is the most commonly used method. The fins oscillate in a combination of yaw, pitch and roll movements, depending on the specific design, to create this desired six-degrees of freedom. This has achieved good results across a number of devices. Undulatory MPF swimming has also been replicated, again with good results. Both are viable options for use in future AUV propulsion systems.

It has been recognised that a combination of BCF and MPF swimming could create a superior AUV propulsion system. For some this is the logical progression, and as such there is a limited amount of research available on the subject. The fundamental goal of this area of research is to combine inherently high speed BCF swimming, with the capability to carry out the precise manoeuvers multi axis MPF swimming offers (2).

A direct comparison between BCF and MPF swimming machines is not entirely possible or indeed fair. They both have their advantages, but these are specific to certain applications. As such to identify an ideal solution in a general sense would be flawed in its reasoning. The unifying factor between the two swimming mechanism is their significantly improved manoeuvrability compared to standard propeller propulsion.

As eluded to previously, the specific design should be chosen with a task in mind, as to create a set of design criteria to determine the optimal method. In line with this Figure 10 shows the turning rate, as a measure of manoeuvrability, against speed for a selection of the AUV designs encountered in this review.

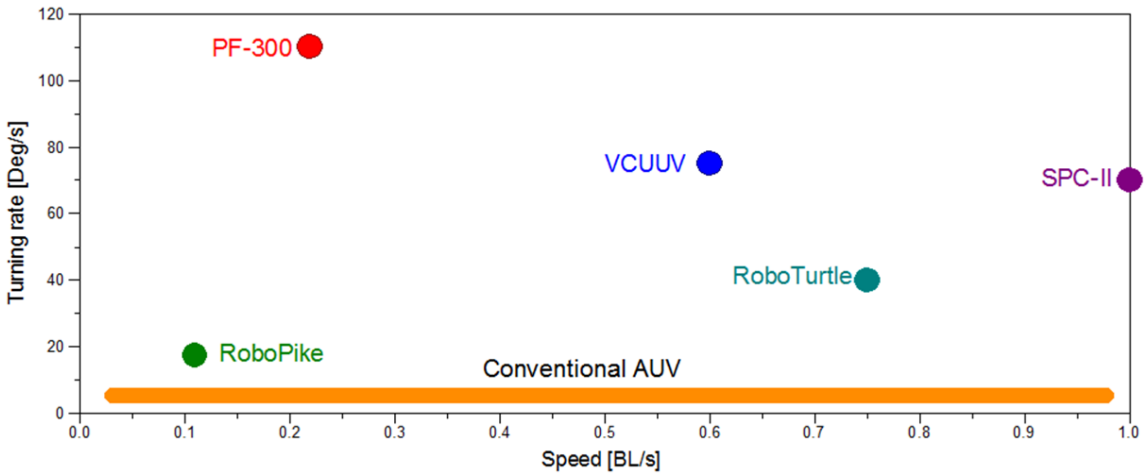

Figure 10: Graph of turning rate against speed for selected AUVs.

Figure 10 indicates the wide range of biomimetic propulsion options available, all of which better the manoeuvrability of conventional propulsion methods. This allows specific swimming modes to be chosen from secondary and tertiary requirements, such as speed or efficiency, to suit a given application.

5. Conclusion

The current conventional propeller based systems fundamentally lack the degree of manoeuvrability that ever evolving AUV applications require. With little progress in advancing these methods, an alternative solution is required.

Looking to nature for inspiration provides a large array of methods to consider. Undoubtedly the swimming modes observed in aquatic animals can overcome this shortfall in performance in their natural forms. The problem is replicating the motion to match the animal's performance as close as possible.

The full undulatory to oscillatory ranges of both BCF and MPF swimming forms have been considered. All modes can be mechanically replicated, if sometimes only in prototype form short of a full AUV. Results of the different methods are generally positive and look as if they can provide genuine alternative methods of propulsion. The exception to this is perhaps anguilliform swimming, as this undulatory BCF form has no immediate practical applications, due to its obvious drawbacks.

Simply stated biomimetic propulsion systems can, and surely will in the future, replace propeller propulsion in order to achieve better degrees of manoeuvrability. This significant improvement in manoeuvrability has been shown to not limit or impair other important attributes of an AUV, such as swimming speed and efficiency. In regards to this, the review has also demonstrated that a large spectrum of properties can be achieved by the different swimming forms. For example thunniform and labriform are completely different motions, and exhibit different desirable characteristics. However either will improve on the manoeuvrability of conventional propulsion systems. Therefore biomimetic AUVs must not be purely designed for manoeuvrability to achieve the necessary level thereof.

Finally both BCF and MPF mechanisms are worthy alternative propulsion systems in their own right, but coupling them together to harness the best properties in each will provide potentially the best comprehensive solution.

As such, this is a prime area for further research on the subject of biomimetic propulsion for manoeuvrability.

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