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Fish-Inspired Robots: Design, Sensing, Actuation, and Autonomy - A Review of Research

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Abstract

Underwater robot designs inspired by the behavior, physiology, and anatomy of fishes can provide enhanced maneuverability, stealth, and energy efficiency. Over last two decades, robotics researchers have developed and reported a large variety of fish-inspired robot designs. The purpose of this review is to report different types of fish-inspired robot designs based upon their intended locomotion patterns. We present a detailed comparison of various design features like sensing, actuation, autonomy, waterproofing, and morphological structure of fish-inspired robots reported in the past decade. We believe that by studying the existing robots, future designers will be able to create new designs by adopting features from the successful robots. The review also summarizes the open research issues that need to be taken up for the further advancement of the field and also for the deployment of fish-inspired robots in practice.

Keywords:
Fish-inspired Robots, Swimming Modes, Body and/or Caudal Fin, Median and/or Paired Fin, Underwater Robotics, Bio-inspired Robotics

1. Introduction

Fishes possess a diverse set of locomotion capabilities as well as body morphology enabling them to survive and perform complex tasks in harsh and to some extent adverse aquatic habitats. Extensive research efforts for incorporating the functional features of fishes in the design of unmanned vehicles and robots [1, 2, 3, 4] have led to two robot design philosophies, namely, bio-inspiration and bio-mimicry. In bio-inspiration, functional aspects of biological organisms are incorporated in a robot by using a top-down design approach, i.e., by integrating components like electrical motors, machined and mechanically assembled components. Biomimicry on the other hand mimics the biological anatomy via a bottom-up approach of aggregating units akin to biological cells and thereby impart biological functionality in the robotic platform. Biomimicry is difficult to achieve due to prohibitive complexity of biological cells. Bio-inspiration is thus considered as a pragmatic design approach and used extensively for designing fish-inspired robots. In this paper, therefore, we survey and report the ongoing research work in the area of fish-inspired robotics - focusing on sensors, actuators, and autonomy aspects of the robot design.

We believe that this paper will help robotics engineers to compare fish-inspired robot designs in terms of various technical features like operating speed, actuating frequencies, sensors, actuators, and issues related to control and autonomy. Future designers will thereby be able to create new designs by adopting features from existing successful designs.

The earliest reported fish-inspired robots were TwiddleFish developed at Duke University, North Carolina [5] and RoboTuna developed at MIT, Massachusetts [6]. This followed development of many other fish-inspired robotic platforms till date. Review papers in the area of fish-inspired robotics have been written in past from time to time and the difference between earlier research papers and the present review are enumerated below.

- Sfakiotakis et al., [7] performed a detailed review of fish locomotion modes and its biomechanics.

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- Bandyopadhyay [8] surveyed the mechanisms of delayed stall, molecular design of artificial muscles and the neural approaches to the actuation of control surfaces in robots based on the pectoral fins.
- Another notable review paper in the area of fish-inspired robotics reported by Bandyopadhyay et al., [9] focused on hydrodynamic analysis of fins.
- Long [5] reviewed the design principles used for functional as well as structural biomimetics in the case of fish-inspired robots and presented three case studies to explain the same.
- Chu et al., [10] performed a review in the area of development of smart actuator based bio-mimetic underwater robots.
- Du et al., [11] provides details related to structural design issues and actuation of several representative fish-inspired underwater robots.

In the current review paper, we have performed an extensive survey of fish-inspired underwater robots focusing particularly on the functionality of locomotion. We believe that this review paper will be helpful to the robot designers as a reference to the state of the art in the area of fish-inspired robotics and in making the choice of sensors, actuators, and controllers based on the intended locomotion as well as the desired level of autonomy. In particular, this review presents a detailed comparison between fish-inspired robot designs based on number of actuators used per unit robot length, speed, robot mass per actuator, turning radius and thrust per actuator. This paper also presents a detailed comparison between biological sensors found in fishes and their robotic counterparts. We describe different levels of autonomy implemented in fish-inspired robots. A description of sealing or waterproofing methods used by fish-inspired robots is also explained in this review paper. The paper also outlines the open research issues that require attention for the further advancement of the field as well as for deploying fish-inspired robots in practice.

A vast literature exists in the area of fish-inspired robotics, therefore it is not possible to discuss every published fish-inspired robot design in this paper due to the space constraints. We categorize fish-inspired robots based on locomotion modes to organize the vast literature. The scope of this paper includes robots with both smart and traditional actuation. Further, in order to focus the discussions, we have limited the scope of the paper as described below.

- We have included robot designs reported in the last decade. Some older representative references have also been cited to point the readers to clarify specific related concepts.
- We have focused on two specific categories of fish-inspired robot designs, namely, (1) body and/or caudal fin (BCF) and (2) median and/or paired fin (MPF) based locomotion [7, 12, 13]. Although, literature on fish swimming often characterize the diversity of swimming patterns by the number of waves on the body and present a complex taxon-based naming scheme (e.g., Anguilliform, Carangiform, etc.) to describe different modes of locomotion (e.g., [7, 12, 13]). Such classifications are however fraught with numerous exceptions [14] and are based on a highly simplified 2D view of fish swimming. In the field of fish-inspired robotics, however, many researchers still name their robots based on aforementioned locomotion categories. Thus, in this review paper, we are also following the nomenclature used by the roboticists.
- We have included some representative designs based on amphibian-inspired robots. However, we have concentrated only on underwater swimming aspect of amphibious-inspired robots.
- Some studies related solely to robotic fin design have been included in this review.

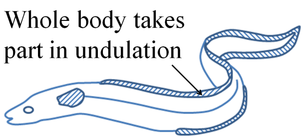
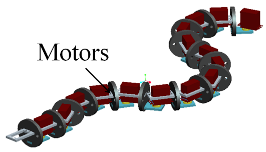
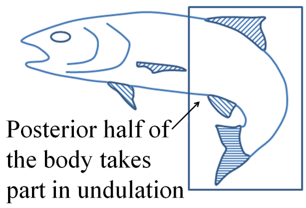
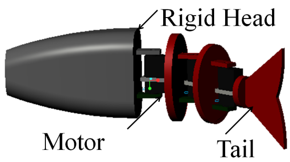
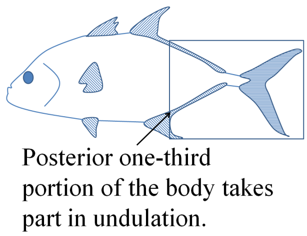
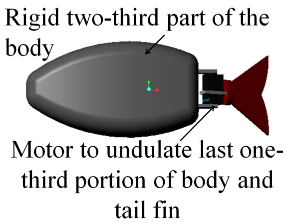
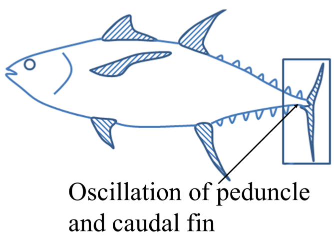
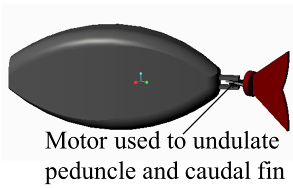
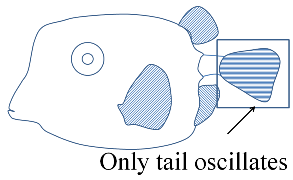
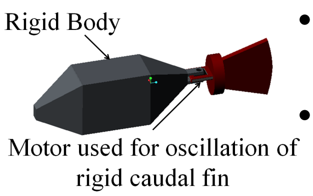
2. Robots Based on Different Types of Swimming Locomotion

This section presents a review of fish-inspired robot designs emphasizing upon the key aspects that play important role in exhibiting specific types of locomotion.

2.1. Robots Based on BCF Locomotion

In BCF locomotion, body undulation waves are generated which move towards the caudal fin, thereby producing propulsion. BCF locomotion is usually performed by fishes to cruise at a relatively higher speed compared to MPF locomotion. Based on the movement characteristics, BCF locomotion is further classified into two types, namely, (1) undulatory motion and (2) oscillatory motion. Undulatory motion is generated as a wave of muscle contraction that moves from the head to the tail and can be classified into Anguilliform, Subcarangiform and Carangiform locomotion. Oscillatory motion, on the other hand, involves swiveling of the body and the caudal fin in order to propel the fish and can be classified into Thunniform and Ostraciiform locomotion. Robots have been designed based on some of the aforementioned categories (see Table 1) and are described in this section.

Table 1: Robot design schema inspired by BCF locomotion

Diagram of Fish	Representative CAD model	Typical mimicked features	Remarks on performance
Anguilliform 		• Hyper-redundancy and full body undulation. • Increase in amplitude of undulation from head to tail. • Motion of robot in direction opposite to the movement of undulatory waves.	• High Maneuverability. • Low speed and hydrodynamic efficiency.
Subcarangiform 		• Undulation of posterior half of the robot. • Heavy body with more rounded anterior portion. • Caudal fin with low aspect ratio.	• Speed higher than Anguilliform locomotion. • Maneuverability lower than Anguilliform locomotion.
Carangiform 		• Undulation of posterior one third portion of the robot. • Stiff caudal fin. • Moderately narrow necking of peduncle. • Concentration of mass towards the anterior portion of the body. • Angle of inclination of the caudal fin altered while moving from side to side.	• Speed higher than Anguilliform or Subcarangiform locomotion. • Low maneuverability.
Thunniform 		• Undulation of peduncle and caudal fin. • Streamlined body. • Rigid lunate tail fin.	• Speed higher than Carangiform. • Maneuverability lower than Carangiform locomotion.
Ostraciiform 		• Stiff body with pendulum-like oscillation of caudal fin. • Narrow peduncle.	• Low hydrodynamic efficiency. • Low speed but high maneuverability.

2.1.1. Anguilliform

Entire body of an Anguilliform swimmer generates a large amplitude undulation. To achieve this, the body of the robot should be continuously deformed to get the required undulation.

Anguilliform robots posses relatively high maneuverability because of their hyper-redundant design comprising of multiple serially connected links controlled by chain of coupled oscillators which increases the degree of freedom of the robot. NEF- II [15, 16], AmphiBot II [17], Biorobotic Lamprey [18, 19], Amphibious Snake-like Robot [20], Salamandra Robotica II [21] had five, seven, ten, eighteen and twenty degrees of freedom respectively. However, due to the pseudo-rigid nature of the links the maneuverability of the robots does not match with that of their biological counterparts. One of the possible techniques for enhancing the maneuverability further is the use of soft actuators [22] made up of smart materials like shape memory alloy (SMA) and electroactive polymers (EAP) [23, 24]. Use of smart material based soft actuators, however, present the problem of lower thrust compared to that of servomotors and therefore require further research. Snake-like swimming robot [25] developed by Kamamichi et al., was made up of three links which were actuated by means of ionic polymer metal composites (IPMC) film. Anguilliform robots have longer undulating bodies which leads to dissipation of energy during locomotion and that causes relatively lower speeds. Due to the presence of a large number of actuators the control effort is relatively more in the case of Anguilliform robots.

Snake-like robot also show full body undulation as Anguilliform and hence has been added in this section. We have also added some amphibious robots which include Salamandra Robotica II [21] developed by Crespi et al., AmphiBot II developed by Crespi and Ijspeert [17], and amphibious snake-like robot developed by Yu et al., [20] as they also perform Anguilliform locomotion. Salamandra Robotica II [21] has four additional limbs which helps it in walking on land and undulatory body for swimming in water. While moving from water to land the body continues to undulate but the legs help in walking and the body wave changes from an undulatory to a standing wave. The motion of a real lamprey which follows Anguilliform locomotion is controlled by a neural element (Central Pattern Generator) located in the spinal cord which actuates the muscles of the lamprey to accomplish the required motion [26].

2.1.2. Subcarangiform and Carangiform robots

Major part of the anterior portion of Carangiform and Subcarangiform robots is maintained rigid during the locomotion and therefore the body undulation is localized in the posterior portion. This causes an enhanced propulsive force. Therefore, robots inspired by Carangiform and Subcarangiform locomotion are more likely to have higher speeds compared to their Anguilliform counterparts.

On the other hand, the degree of freedom of Subcarangiform and Carangiform robots ranges from one to nine which is lower as compared to Anguilliform robots in which the degree of freedom ranges from three to twenty, hence have low maneuverability compared to Anguilliform robots. Some robots [23, 24] have been reported to be using soft material based actuators to improve the maneuverability, however, thrust produced is very small in those robots.

Subcarangiform locomotion requires undulation of posterior half of the body of the swimmers which provides the thrust required for forward locomotion. Various mechanisms have been used to get such undulation in robot which includes, use of flexible tail, which is connected by servomotor to main body [27, 28, 27], wires passing through vertebrae module, pulled and released via servomotor to get required undulation of two-third portion of the body [29], compliant links connected by means of servomotor [1, 30], and use of SMA [31] and Macro Fiber Composites (MFC) [32] which forms the posterior half of the body and actuated by means of application of voltage across these smart actuators.

Carangiform locomotion requires undulation of last one-third portion of the fish body. Due to relatively small difference between these two locomotion it becomes somewhat difficult to differentiate between robotic systems performing Carangiform and Subcarangiform locomotion. Hence, we are describing both types of locomotion together in this section.

Though dolphins and sharks in general follow Thunniform locomotion, multilink dolphin-inspired robot developed by Shen et al., Slider-crank centered robotic dolphin developed by Wei and Yu [33] and Bionic robotic dolphin developed by Guang et al., [34] used the concept of undulation of half of its body and is thus categorized here as Subcarangiform locomotion based robot [35]. Wire-Driven Robot Shark [36] and Wire-driven robot [37] were driven by wires which were actuated by means of a servomotor.

To achieve this kind of undulation, in most of the robots, the actuated one-third part of the body was made up of multiple compliant links which were connected via means of motors [2, 3, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57] and were also covered by flexible membrane in some cases [2, 3, 40, 41, 42, 44, 47, 51, 55, 58]. In Po-tuna [59] and UC-Ika 1 [60] tail portion were actuated via motor connected to a peduncle mechanism, Nanyang Arowana-like fish (NAF) [61] made use of a single motor which was used to actuate a coupling which was further used to actuate two joints, Fisho used two servos placed side by side in rigid head and was used to actuate two joints [62], use of flexible tail connected via servomotor to main body [63], Essex MT1 robotic fish [64] consisted tail actuated via metal shaft passing through each link and were actuated by a single motor, Soft robotic fish [65] had a soft fish tail made up of fluidic elastomer actuators and was continuously bent via fluidic actuation of two lateral cavity structures on each side, Torpedo-shaped robot fish developed by Chen and Tan [66] made use of actuation of a center shaft via DC torque motor, at end of which a disc with eccentric shafts were attached, these shafts were further used to actuate tail mechanism of the robot. *iSplash*-II was capable of obtaining a high speed of 11.6 BL/s with help of a power-train which made use of a continuously rotating motor [67]. Belts were used to transmit motion to shafts used in the links in robot developed by Wen et al., [68, 69, 70, 71].

Smart actuator based robots include motor-less and gear-less bio-mimetic robotic fish developed by Rossi et al., [23, 24], robot developed by Suleman and Crawford, [72], which made use of SMA, IPMC-propelled robotic fish developed by Chen et al., in 2013 [73], robot developed by Guo et al., [74] and robot developed by Liu et al., [75] made use of IPMC actuators, Biomimetic fish robot developed by Ngyuyen et al., [76] consisted of actuation system based on piezoceramic unimorph actuator.

2.1.3. Thunniform

Thunniform - In Thunniform locomotion only the posterior 10% [7] of the body oscillates which includes the narrow peduncle and the tail fin. The body of fishes have a streamlined structure that reduces drag; they also have a rigid crescent shaped lunate tail fin (e.g., Dolphin inspired robot developed by Hu et al., [77]).

2.1.4. Ostraciiform

Fishes performing Ostraciiform locomotion have rigid body and an oscillating rigid caudal fin that provides the required propulsive force. Ostraciiform robots make use of fewer number of actuators as only the tail fin needs to be oscillated unlike Carangiform robots wherein posterior one-third of the body need to be undulated. For example Microautonomous Robotic Ostraciiform (MARCO) [78], Boxybot [79], Boxfish-like Robot [80] and Box-fish like Robot [81] makes use of three actuators, Osctaciiform Fish Robot [82] makes use of one actuator, and Robotic Fish [56] fish makes use of six actuators while Carangiform and Subcarangiform robots can make use of upto nine actuators [35], and Anguilliform robots can make use of upto twenty actuators. This results in a higher ease of control in Ostraciiform robots.

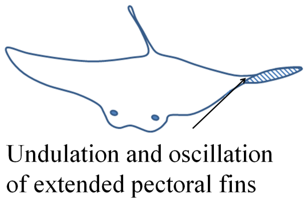
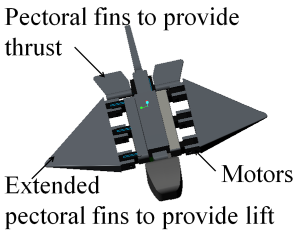
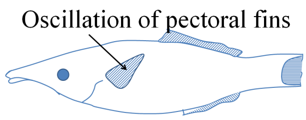
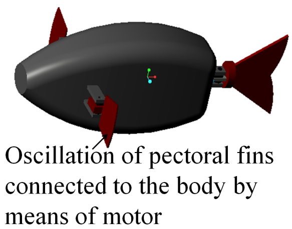
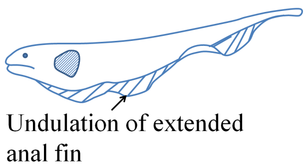
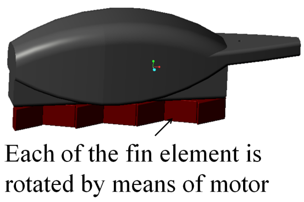
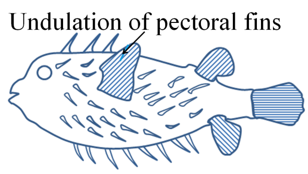
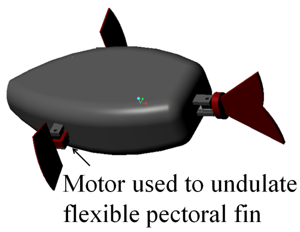
The Ostraciiform fishes are capable of turning at their own place and similar quality is seen in its robotic counterpart. Hence, these robots have high maneuverability. As the bodies of these robots are in form of boxes, they are very easy to fabricate but this makes the robots less streamlined. Though in real fishes performing Ostraciiform locomotion the speeds are lower as compared to the fishes performing other kinds of BCF locomotion but due to the use of high torque actuators, some of the Ostraciiform robots may have higher speeds compared to that of the other kinds of BCF robots [56].

Ostraciiform robot mainly have a rigid body. The caudal fins in some cases are connected to the rigid body [56, 78, 79, 82, 83, 84, 80, 85] via a revolute joint actuated by a motor. Robotic Fish developed by Qian [86] made use of coils, magnets (which forms the caudal fin), and a swing rod for actuation. Power supply around the coil generates a magnetic field which actuates the magnetic caudal fin and hence results in locomotion of the robot. Box-fish like robot [81] developed by Kim et al., made use of tail made up of magnetic material actuation via means of a rotating magnetic field generated by a three-axis Helmholtz coil and robot developed by Liu et al., [87] made use of bimorph giant magnetostrictive thin film (GMF) caudal fin and fin was actuated via an external magnetic field generated by Helmholtz coil.

2.2. Robots Based on MPF Locomotion

MPF swimmers can mainly be categorized into undulatory, oscillatory or a combination of both the motions. Undulatory locomotion can be classified into Diodontiform, Gymnotiform, Amiiform and Balistiform locomotion. Oscillatory motion can be classified into Tetraodontiform and Labriform locomotion. Rajiform locomotion is a combination of undulation and oscillation. Robots have been designed based on some of the above locomotion categories (see Table 2) and are described in this section.

Table 2: Robot design schema inspired by MPF locomotion

Diagram of Fish	Representative CAD model	Typical mimicked features	Remarks on performance
Rajiform 		• Large flexible triangular shaped pectoral fins. • Increase in undulation amplitude from anterior portion to fin apex. • Decrease in undulation amplitude from fin apex to the posterior portion. • Up and down flapping of fins. • Sharp angle of attack in pectoral fins.	• Low speed. • Low to medium level of maneuverability.
Labriform 		• Oscillating narrow-based pectoral fins. • Fan-like and rounded pectoral fins. • Fins brought far forward and then forced back broadside in rowing mode. • Up and down flapping fins in flapping mode.	• Low speed and maneuverability.
Gymnotiform 		• Hyper-redundancy of undulating anal fin. • Rigidity of the body.	• High maneuverability. • Speed higher than Labriform locomotion.
Diodontiform 		• Broad undulating pectoral fin. • Placement of fin base in variable planes. • Changeable pectoral fin angle.	• Speed higher than Labriform locomotion. • High but slow maneuverability.

2.2.1. Rajiform

Rajiform fishes have high maneuverability but in case of the robots inspired by Rajiform locomotion the maneuverability varies from low to medium. The degree of freedom varies from two in Micro Biomimetic Manta Ray Robot Fish [88] to twenty in Robotic Stingray [16, 89, 90]. This is because the broad fins used in the robots are not as flexible as the fins of the fishes resulting in lower degrees of freedom. Use of a large number of actuators to get the required undulation in the fins result in lesser ease of control [16, 89, 90]. The speeds of these robots are relatively low due to the bulky nature of the fins and the body and ranges from

0.038 BL/s [91] to 1 BL/s [16, 89, 90].

In some of the robots pectoral fins were made up of multiple fin rays, each of these rays were actuated by servomotor in such a way that a wave-like motion was created in the fin. These rays were then covered by flexible membrane like polypropylene, latex and rubber [92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102]. The extended fin of Raybot 3.3 [103] was actuated by means of fin-shear actuation mechanism consisting of rays actuated by means of servomotors. Punning et al., [91] developed a biologically inspired ray-like underwater robot in which the pectoral fins comprised of rays made up of IPMC sheets covered with platinum coating and were in shape of a bottle and each of the rays were connected by means of latex foil. The skeletal structure of pectoral fin in Robo-ray III [104, 105] was made by 'cartilage calcification' and 'cross-bracing' which stiffens the leading-medial area of pectoral fins with carbon fiber board at leading edge and root of the biomimetic pectoral fin to provide rigidity. The robotic pectoral fin was then actuated via servomotors. Additional vertical and horizontal oscillating tails were attached for depth control. The fins of BHRay was made up of flexible silicone rubber; the base of the fins were actuated actively by a motor while the distal end was oscillated passively by fluid flow [106].

Manta ray robotic fish developed by Wang et al., [88] consisted of two pectoral fins which was made up of a biomimetic fin (which had SMA wire running though it) at the leading edge and a latex membrane on the surface such that only the leading edge undulated creating a wave in the fin.

2.2.2. Robots based on other types of MPF Locomotion

The robots performing other MPF motions (such as Labriform, Gymnotiform, and Diodontiform) are smaller in number and therefore we present all those robots under this sub-section. Labriform locomotion is based on the oscillation of pectoral fins. The fishes swim in two modes, namely, (a) rowing mode (drag based motion) which is more effective at a lower speed and (b) flapping action (lift based motion) which is more effective at a higher speed [7]. Labriform robots perform locomotion at a lower speed and the maneuverability is also low as compared to the Rajiform robot. The small size of the fins generates lower thrust and therefore relatively lower speed. The number of actuators used in these robots is also low resulting in lower maneuverability and design complexity but higher ease of control.

Sitorus et al., [107] developed a Labriform based robot which was capable of rowing, flapping and hovering and each of its fins were actuated by two servomotors together to drive a single fin which provided flapping, feathering and rowing motion to the robot.

Due to longer anal fin in Gymnotiform robots they possess higher speed compared to Labriform robot [107] which has smaller pectoral fins. The other factors affecting the robot speed include overall dimensions of the robots, number of actuators involved, and overall inertia of the robots. Due to the undulating fin capability similar to the Anguilliform locomotion, the maneuverability of these robots is higher. However, because of the presence of larger number of actuators the control effort required is higher.

Gymnotiform based fishes have an extended anal fin. The undulation of the anal fin provides the required propulsion. The anal fins in robot were made up of a number if fin ray elements. Knifefish-inspired NKF-II [90, 108, 16] robot's fins were made up of a combination of fin-ray linkage, consisting of slider connected in series. Another robotic Knifefish developed by Curet et al., [109] used a stackable fish steak based design to realize the extended anal fin. Radio-controlled robotic fish [110, 111] developed by Liu et al., used two rods which were connected by flexible membrane as the anal fin. The anal rods used slider crank mechanism to generate oscillations.

Diodontiform robots have higher speed as compared to Labriform robots as the fins of these robots are broader as compared to the Labriform robots resulting in higher thrust generation. The fins of these robots can be placed in variable planes which help in achieving higher maneuverability. Use of smaller number of actuators result in higher ease of control. Fishes performing Diodontiform locomotion have pectoral fins of moderate length which can be placed in different planes. The two pectoral fins may lie at a certain angle with each other (complementary), which can also be altered.

Free swimming fin actuated underwater vehicles [112] and Robotic fish with flexible pectoral fins [113] consisted of pectoral fins actuated by servomotors. The only characteristic which makes them follow Diodontiform is the small fin size compared to the body. Free swimming fin actuated underwater vehicle [112] was also capable of placing fins in variable planes.

In addition to the above robots we also present some of the fins developed for robots in this section. Robotic ribbon fin [114] developed by Epstein et al., and biomimetic undulating fin, RoboGnilos [115] developed by Hu et al., could be used in robots based on Gymnotiform locomotion. The fin developed by Hu et al., was actuated by means of multiple servomotors. Pectoral fin based on Bluegill Sunfish [116] developed by Tangorra et al., and robotic fish caudal fin [117] developed by Esposito et al., also used servomotors to actuate the fin. Batoid-inspired oscillating fin [118] developed by Clark and Smits used DC motors to drive the fins.

2.3. Miscellaneous

In this section we review the robots which cannot be classified into a unique locomotion category. Vector propelled robot fish developed by Liu et al., in 2013 [119] used vector propulsor which was capable of flapping in both vertical and horizontal planes. Wires passing through vertebrae module were pulled and released via servomotor to get the required undulation.

Multimodal robotic fish developed by Wu et al., in 2013 [120] was made up of multiple compliant links which were connected via means of motors. It had a pair of additional pectoral fin actuated by motor.

Autonomous underwater robotic fish developed by Yu et al., [121] was capable of following both Carangiform and Anguilliform locomotion. Aluminum skeleton consisting of joints actuated by means of DC control actuators were added to the robot which provided the required motion. Biomimetic robotic fish SPC-III developed by Wang et al., [122] was capable of rotating and moving in transverse direction and was actuated via servomotors. A robotic fish using a flexible joint [123] developed by Yun et al., and CyberFish developed by Malec et al., [124] were also actuated by servomotors.

Untethered robotic fish [125] had a tail made up of Macro Fiber Composite (MFC) bimorph propulsor which was actuated by means of a PWM signal. Galatea [126] shape was based on Wortmann FX 71-L-150/20 airfoil. Manual control was used to vary oscillation frequencies (both symmetrically and asymmetrically) and thereby the thrust and moment to get the required motion. Underwater vehicles actuated by ionic polymer metal composites developed by Aureli et al., [127] had a caudal fin made up of IPMC.

The robot developed by Shen et al., [128] was made up of IPMC muscles and a plastic fin which acted as a tail fin. The robot developed by Ye et al., [129] had a rigid body and a pair of tail fins actuated by means of ionic conducting polymer film (ICPF) actuators. The robot used classical feedback control for obstacle avoidance.

NEMO (novel electromaterial muscle oscillator) [130] developed by McGovern et al., consisted of a rigid body and a caudal fin attached to the body by means of PPy tri-layer actuators. The robot developed by Ye et al., [131] consisted of a rigid head and a flexible tail portion made up of IPMC actuator. Hubbard et al., [132] developed bbioinspired underwater vehicle in which the pectoral fin was made up of IPMC plate connected by webbing of Kapton film.

3. Design Aspects

This section presents a general discussion on the choice of sensors, actuators and autonomy/control used for the design of fish-inspired robots.

3.1. Sensors

The first appearance of fish-like creatures based on fossil records was about 530 million years ago [133]. Since then, the fishes have evolved themselves and are capable of surviving underwater environment with a lot of ease, some owing to their ability to perform a variety of locomotion and some due to their ability to sense the environment successfully. We have already presented the details of the locomotion aspect of the fishes used in robot design in Section 2; in this section we focus on the sensory function of the fishes. Different kinds of sensory functions found in fishes include, (1) vision, (2) hearing, (3) flow and pressure detection, (4) chemoreception and (5) electroreception.

To carry out these sensory functions, fishes have a variety of sensory organs which are described below.

- Rod and cone cells - Rod and cone cells are used to provide proper vision in fishes. Rod cells help in vision at low light intensity (scotopic vision) and cone cells are the ones which are active at higher light intensity (photopic vision) [134]. This helps the fishes to see its surrounding environments in low and high light intensity and helps the fishes in localization and detecting unwanted obstacles.
- Otoliths and Weberian organ - Hearing sensors found in fishes includes otoliths and weberian organ. Otoliths are found in the inner ear of the fishes. Bending of the ciliary bundles due to relative motion between sensory epithelium and the otolith in ear of fishes results in hearing [135, 136]. Weberian organ transfer vibrations in the swim bladder to the inner ear [137]. The sense of hearing is used by fishes for escaping from danger and to find prey.

- Lateral line - Current flow and pressure change in fishes are detected by means of lateral line. Lateral line consists of neuromasts made up of a number of hairy cells and a cupula. The cupula connects the hairy cells to the surrounding water masses [138, 139, 140].
- Olfactory sensors - Chemoreception in fishes are done by means of olfactory sensors. These sensors are capable of detecting many substances like steroids, bile acid, amino acid, nucleotides and steroids. The odorant substance and olfactory receptor (OR) present in the olfactory epithelium combine with each other and an information is sent to the central nervous system and hence the fishes react accordingly [141].
- Ampullary electroreceptors and Tuberous electroreceptors - The fishes are also capable of sensing natural electrical stimuli which is known as electroreception. The electroreception in fishes is performed by Ampullary electroreceptors and Tuberous electroreceptors. Ampullary electroreceptors help the fishes in detecting weak bioelectric fields which are generated by other animals while Tuberous electroreceptors senses the distortion in electric field generated by the fish itself [142].

Taking inspiration from the different sensory functions (and to some extent the related sensory organs) the roboticists have made attempts incorporate them into fish-inspired robots. Table 3 provides a glimpse into different kinds of sensors corresponding to various sensory functions in the fishes and has been described in the following paragraphs.

- In robots, the sense of vision is provided by means of cameras. A camera is equipped with photo-sensitive sensors such as charge-coupled device (CCD) and focusing lenses and is capable of forming the image of the surrounding environment. This information in then processed by on-board or off-board computer to form a map of the environment around the robot which helps the robot in performing various operations like, navigation [2, 3], detecting threats or obstacles [18], avoiding obstacles, localizing, goal recognition [44] etc.
- Sense of hearing in robots is usually implemented using ultrasonic wave detection which has been incorporated using sensors like SONAR, ultrasound range sensors and ultrasonic proximity sensor. These sensors are based on time-of-flight principle and are capable of generating ultrasonic waves, which are further reflected from the obstacle and then received by the receiver present on the sensors and hence helps in detecting the obstacles [34, 48] and performing navigation [143]. Forward speed of robot can also be directly measured by Doppler SONAR signals [45].
- Flow and pressure sensing in robots are incorporated by means of sensors such depth meter, water sensor, pressure sensor and leak sensor. Depth sensors measure the depth at which the robot is operating by detecting the hydrostatic pressure due to liquid column above it [62, 44, 45, 64, 83]. Leak sensor and water sensor detects the presence of water [2, 3, 21, 41, 48, 49, 56, 92, 103, 104]. When the water level in the water separator reaches the warning level the leak and water sensors get activated [103]. Online data obtained from pressure sensors can be used to control ascent or descent motion of the fish [38].
- To the best of our knowledge chemoreception has not been implemented in fish-inspired robots so far.
- Electrosensing in robots is performed by means of an array of electrodes. Active electrodes create an electric field around the robot. The distortion in electric field due to the surroundings obstacles is detected by means of passive electrodes [114].

Table 3 also incorporates some of the sensory functions which are limited only to the robots which include odometry and localization. The sensors shown in localization category are only those sensors for which there are no biological counterparts. To identify the properties of the robots and to determine its parameters, sensors such as spectrophotometer [144], camera [21, 145, 32, 39, 68, 63, 52, 54, 55, 72, 76, 78, 97, 98, 99, 100, 102, 127, 128, 131, 146], infrared LED [40], torque sensor [122, 123], force sensor [58, 78, 109, 128, 132, 128], light sensors [79] and displacement sensor [74] are used.

Table 3: Sensors for Mimicking Biological Sensory Functions

Sensing Capability	Biological Sensors	Robotic Implementation	Sensor Applications
Vision	Rod cells and Cone cells [134, 147]	CMOS Camera [2, 3, 18] and CCD Camera [44]	Obstacle detection and Localization
Hearing	Otoliths [135, 136] and Weberian Organ[137]	SONAR [45, 103], Ultrasonic Proximity sensor [48, 34] and Ultrasound Range Sensors [49]	Obstacle Detection

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Sensing Capability	Biological Sensors	Robotic Implementation	Sensor Applications
Current Detection and Pressure Detection	Lateral Line [138, 139, 140]	Water Sensor [21, 56], Pressure Sensor [148, 33, 38, 40, 83], Depth Meter [62, 44, 45, 64, 48, 49, 104, 92, 103, 112, 122] and Leak Sensor [103]	Pressure and Flow Sensing
Chemoreception	Olfactory Sensors [141]	Not found in fish-inspired robots	Not found in fish-inspired robots
Electroreception	Ampullary Electroreceptor and Tuberous Electroreceptor [142]	Array of electrosensing electrodes [114]	Localization and Obstacle Detection
Odometry	Not found in fishes	• Stretch Sensor [18] • SMA [23] • IPMC [25] • Inclinometer [38, 64] • Gyroscope [38, 47, 48, 53, 80, 113, 120, 121, 122] • Accelerometer [2, 3, 33, 41, 48, 53, 79, 80, 86, 113] • CCD Camera [42, 51] • Heading Sensor [45] • Compass [64, 53, 80, 112, 113, 122] • Proximity Sensor [66] • Joint Position Sensor [1, 30] • Potentiometer [77] • IMU [82, 83, 84, 121] • Laser triangulation sensor [87] • Camera [124]	Odometry
Localization	Not found in fishes	Infrared Sensor [2, 3, 83, 84, 129, 131], GPS [35, 49, 121], Position Sensor [38] and Navigation Sensor [61]	Localization

Table 4 gives the specifications and limitations associated with sensors used in the robots. Besides the limitations mentioned, the sensors should be enclosed in such a way that their is no water seepage into sensor circuits.

Table 4: Sensors for Mimicking Biological Sensory Functions

Sensors	Specifications	Sensor Model	Limitation
Camera	Frame rate [2, 3, 18] and Field of view [18]	MO-S3588-2G-N [18]	• Cannot detect distant objects due to turbidity in water • Problems with maintaining undisturbed signal via wireless communication system from the onboard video camera at the greater depths
Accelerometer and INS	Measurement Range (Typically- ±1.7, ±5, ±18 g) [48, 79, 113] and Output Voltage [86]	ADXL345 [48], ADXL203 [79], ADXL335 [86] and MinIMU-9 v2 [113]	Odometry noise increases due to damping
Infrared Sensor	Response time: (Typical value- 39 ms) [64]	GP2D12 [64]	Atmospheric attenuation of IR energy

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Sensors	Specifications	Sensor Model	Limitation
Pressure Sensor and Depth Sensor	Maximum Pressure [48], Depth Resolution and Scale span/linearity [148]	MS5407 [148]	Temperature change leads to expansion or contraction of the metal used in sensor and affects the compensating techniques used in depth sensors
SONAR, Ultrasonic Proximity sensor and Ultrasound Range Sensors	Bandwidth [48] and Detectable Range	MA40B8R and MA40B8S	Atmospheric attenuation of ultrasonic waves
Gyroscope	Sensitivity [47, 48, 113]	LPY5150AL [47] and IMU-3000 [48]	Repetitive calibration of sensor is required
GPS	Acquisition time	LS20030	Underwater operation is not possible
Inclinometer	Sensitivity accuracy [64]	ADXL202 [64]	Rolling may result in error of measurement
IPMC and SMA	Response Time	Nitinol [23]	Sensing capability affected due to change in temperature
Current Sensor	Maximum Bandwidth	ACS712	Difficulty operating under strong external magnetic fields
Compass	Degrees of accuracy [64]	CMPS03 [64] and HMR3300 [112]	Difficulty operating under strong external magnetic fields
Potentiometer	Sensitivity	Various	Reading may be affected due to change in temperature
Laser triangulation sensor	Measuring rate and Linearity	optoNCDT	Received waveform may be offset or disrupted due to atmospheric attenuation

3.2. Actuators

Actuators are the physical devices that transform electrical, chemical or thermal energy into mechanical energy. Swimming robots make use of mainly five kinds of actuators, namely, servomotors, SMA, EAP, piezo-based actuators and magnetic actuators. Servomotors are modified conventional DC motors which consist of motor coupled to a sensor for position feedback. Shape Memory Alloy (SMA) is an alloy that memorises its original shape which is acquired by heating (baking) at a very high temperature. After baking, SMA can be deformed to any shape and can regain its predeformed shape when heated at a relatively low temperature as compared to the baking temperature [149].

Electroactive Polymer (EAP) gets strained under the effect of electrical stimulus. They are classified on the basis of mechanism responsible for actuation into two types, namely, electronic EAPs (which are driven by electric field or Coulomb forces) and ionic EAPs (which change their shape due to the mobility or diffusion of ions and their conjugated substances) [150].

Piezo-based actuators are mainly of two types, namely, piezoceramic actuators and Macro Fiber Composites (MFC). Piezoceramic actuators are actuated due to piezoelectric effect which is the capability to generate an electric charge on application of mechanical stress and expand in same direction as the electrical field.

Macro Fiber Composite (MFC) was developed by NASA [151]. The material consists of rectangular piezoceramic fibers and interdigitated electrode pattern on the polyimide film which helps in yielding better flexibility and impact response, and provides higher level of strain than conventional piezoelectric actuators. It is capable of straining in direction of the fibers on application of AC voltage [151]. In case of magnetic actuation, magnets were used to actuate the robot motion as in [81] and Helmholtz coil as in case of [87].

Various types of actuators used by fish-inspired robots and their corresponding performance measures such as speed, maneuverability, and specific power/specific energy consumption has been presented in Table 5. In this table, we have used normalized measures of speed (robot speed per unit body length, BL/s), maneuverability (turning radius per unit body length, BL), specific mass (mass of the robot per unit number of actuators, kg per actuator, kgpa), and specific power consumption (energy dissipated per actuator used in the robot, W or Wh per actuator, Wpa or Whpa). Here BL refers to unit body length of the robot. To differentiate between different kind of locomotion - A is used for Anguilliform, S for Subcarangiform, C for Carangiform, O for Ostraciiform, R for Rajiform, G for Gymnotiform, D for Diodontiform and M for miscellaneous robots. The observations we have drawn from this study are listed below.

- By using servomotors as actuators, a wide range of robot swimming speed can be obtained as shown in Table 5. However, fish-inspired robots utilizing servomotors as actuators have higher specific mass; it may be upto 100 kgpa [45], whereas the lightest one in this category has a specific mass of 0.0015 kgpa [74]. In contrast to higher mass of servomotors, the smart actuators are relatively lightweight; the specific mass of fish-inspired robots utilizing smart actuators ranges from 0.0007 kgpa to 0.7 kgpa. The robot swimming speed obtained by using smart actuators such as SMA, EAP, piezo-based actuators is lower as compared to the servomotors. Magnetic actuation has also been reported to be used for fish-inspired robots. In the case of external magnetic actuation the speed obtained is higher and the robot is lightweight (as the actuating magnet is outside the robot body) however, the limitation is that the actuation is confined to a limited range. In the case of internal magnetic actuation the speed obtained is lower and the specific mass of the actuators is increased as the actuating magnets are contained by the robot body.

- The specific mass of the robots using servomotors depends on the type of locomotion followed by the robots. For example, to attain a given body speed in the case of Anguilliform locomotion based robot, the number of servomotors used is relatively higher in order to provide the undulation to the full body in comparison to other BCF locomotion based robots. This results in higher specific mass of Anguilliform robots. Table 5 shows that the specific mass of Anguilliform based robot is highest. An exception to this observation is BAUV robot [45] which follows Carangiform locomotion and has a very high specific mass 100 kgpa in comparison to Anguilliform based robots. A likely reason for the higher mass in BAUV may be due to the use of heavy motors and mechanisms to support and propel the bulky body of length 2.4 m.

- The number of publications reporting maneuverability in terms of turning radius is very less (14 papers out of total 98 papers reported) and therefore determining a trend in terms of locomotion patterns is relatively difficult. In general, we observed that the maneuverability obtained by the use of servomotors is highest in the case of Ostraciiform, followed by Anguilliform robots and lowest in the case of the Subcarangiform robots. The Ostraciiform fishes can turn at their own place and therefore have highest maneuverability and the same is observed in their robotic counterparts [78]. In case of the Anguilliform robots the number of actuators per unit length is higher than other BCF locomotion except Ostraciiform which results in higher maneuverability.

- To obtain higher maneuverability the length of the robot should be less and/or the number of degrees of freedom of the robot should be high. Smart actuators may be tuned in both the ways to provide higher maneuverability. If the desired length of a robot is small then smart actuators are a better choice compared to DC servomotors. For example, the servomotor based robot with a maneuverability of 0.7 BL has a length of 0.459 m [29] whereas similar smart actuator based robot with a maneuverability of 0.6 BL has a length of 0.053 m [129].

  A downside, however of using smart actuators is the low torque produced. In some designs like Carangiform based robot it has been observed that the maneuverability of smart actuator based robot is poorer because of low torque. For example, motor-less and gear-less robot showing Carangiform locomotion using SMA has relatively poor maneuverability of 2.8 BL [23, 24] in comparison to servomotor based Carangiform robot with a maneuverability of 0.8 BL [42].

- Specific power (or energy) is the ratio of power (or energy) required by the entire robot operation with respect to the number of actuators. It should be noted that here the power (or energy) comprises of both actuator as well as other medium (like sensing and control) of dissipation during the robot operation. The power consumed by servomotors far exceeds the power consumed by smart actuators. Also, major part of power is consumed for actuation while a small part is spent in sensing and control. Therefore, the specific power consumption of fish-inspired robots actuated by smart actuators is relatively lesser compared to that actuated by servomotors. The range of specific power in the case of servomotor based robots is between 0.8 Wpa - 28 Wpa while the minimum specific power for smart actuator based robots can be as low as 4.3×10^{-6} Wpa [130]. Therefore, smart actuators can be helpful in designing energy efficient fish-inspired robots.

Table 5: Variety of actuators used by fish-inspired robots (A: Anguilliform, S: Subcarangiform, C: Carangiform, O: Ostraciiform, R: Rajiform and M: Miscellaneous)

Actuators	Speed (BL/s)	Maneuverability (BL)	Specific Mass (kgpa)	Specific power/Specific energy
Servomotor	0.1-0.288 (A) 0.11-0.7 (S) 0.1-11.6 (C) 0.08-3.65(O) 0.04-0.3 (R)	0.008-0.5 (A) 0.7 (S) 0.18-0.8 (C) 0-1.1 (O)	0.2-1 (A) 0.03-0.6 (S) 0.17-100 (C) 0.007-0.5 (O) 0.004-1.2 (R) 0.7 (G) [16, 108] 0.2 (D) [113]	0.8 Wpa [18, 19] (A) 6.48 Wpa [15, 16] (A) 3.4 Wpa-28 Wpa (C) 24.3 Whpa [43] (C) 120 Wh [61] (C) 80 Wpa [99] (R) 0.0004 Wpa [101] (R)
SMA	0.1 [23, 24] (C) 0.2 [31] (S) 0.12 [88] (R)	0.03 [23, 24] (C) 0.03 [31] (S)	0.7 [23, 24] (C) 0.2 [31] (S) 0.5 [88] (R)	0.4 Wpa [23, 24] (C) 8.3 Whpa [88] (S)
EAP	0.00145 [74] 0.17 [75] (C) 0.0038 [91] (R) 0.085 [127] (M) 0.00505 [128] (M) 0.015 [129] (M) 0.0162 [130] (M) 0.003 [131] (M)	0.6 [129] (M) 1.1 [130] (M) 0.8 [131] (M)	0.03 [74] (C) 0.7 [127] (M) 0.1 [128] (M) 0.06 [129] (M) 0.1 [130] (M) 0.2 [131] (M) 0.4 [132] (M)	0.5 Wpa [75] (C) 1.3 Wpa [91] (R) 1 Wpa [127] (M) 1.3×10^{-4}Wpa [128] (M) 0.3 Wpa [129] (M) 4.3×10^{-6} Wpa [130] (M) 2×10^{-4} Wpa [131] (M) 4.6×10^{-4} Wpa [132] (M)
Piezo-based Actuator	2.9 [32] (S) 0.08 [76] (O) 2.2 [125] (M)	-	0.015 [32] (S) 0.085 [76] (O) 0.3 [125] (M)	0.1 Wpa [32] (S) 4.1×10^{-5} Wpa [76] (O)
Magnetic Actuation	3.65 [81] 0.09 (O) 0.03 [86] (R) [87] (O)	-	0.0007 [81] (O) 0.006 [86] (R)	-

3.3. Level of Autonomy

Underwater environment pose various challenges in imparting autonomy to fish inspired robots, namely (1) uncertainty in localization due to sensor noise caused by turbid aquatic medium, (2) motion uncertainty due to environmental disturbances like currents, (3) presence of dynamic obstacles with complex underwater dynamics, and (4) limited onboard power. Fishes have evolved an ability to deal with such challenges and to a great extent are capable of performing actions under the constraints like imperfect perceptive information, tight time constraints, limited availability of information about the world, cognitive limitations, physical capabilities, and very limited information about the intended motion of other organisms. Imitation of such autonomous behavior in fish-inspired robots can be very useful. The fish-inspired robots reported till date have very limited autonomy capabilities and a huge scope of research lie in this area. Various research advances in imparting autonomy to robots via learning from demonstration [152], evolutionary approaches [153, 154], dynamic programming [155], and coverage planning [156] may be employed for handling environmental disturbances [157, 158].

In the reported fish-inspired robots, autonomy is implemented at two levels, namely, task level and joint level. In task level autonomy, a robot determines and executes actions in order to accomplish certain assigned tasks. The actuator level actions are automatically determined to complete the assigned task. In the joint level autonomy, in contrast, certain joint level commands are executed without any consideration of a higher level task. In the area of fish-inspired robots, following specific tasks have been reported.

- Goal recognition by the robot - Goal recognition is the task in which the robot needs to recognize its target location. Biorobotic Lamprey [18, 19] detects the position (in terms of pixels) and mass (intensity in terms of number of pixels) of the target light source using image-processing and maneuvers itself to the detected target location. In case of robot developed by Guan et al., [44] the camera placed on the robot sends the video captured by it to an upper console which further extracts the goal based on color recognition algorithm. The robot developed by Lachat et al., [79] was capable of reaching a static bright light and was able to follow a slowly moving light source as well. Goal position was determined using image processing and was then used for controlling the turning rate. CyberFish [124] was capable of detecting red round object based on video obtained from on-board wireless video camera.

- Waypoint following - In the case of waypoint following, the robot needs to maneuvers itself autonomously via several predetermined intermediate target locations known as waypoints. The robot developed by [45] was capable of tracking three waypoints that were arranged to allow the robot to take wide turns.
- Course tracking - In course tracking, the robot is required to autonomously track its motion along a stated heading direction. The robot developed by Liu et al., [64] performed course tracking.
- Environment recognition - In the case of environment recognition, the robot autonomously determines the environmental condition by comparing online sensor information and offline training data. The robot developed by Liu et al., [56] was capable of determining suitable gait by measuring and comparing pressure and flow while following a predetermined path with stored training data.
- Cooperative tasking - In cooperative tasking, a team of robots accomplish a task cooperatively in an autonomous fashion. In this category the robots developed by Shao et al., [51] was capable of cooperatively pushing a disk. The autonomous cooperative behavior of a team of three robots was tested by competing the team against a manually controlled robot. Here the autonomous team of robots had to reach the goal while preventing the manually controlled robot.
- Obstacle Avoidance and 3-D swimming - In this, the robot need to autonomously avoid obstacles while swimming in 3D water space [2, 3, 38, 40, 41].
- Robots for behavioural work on fish - Polverino et al., studied the possibility of development of robotic fish which could affect the behavior of live zebrafish [52].
- Station Keeping - Station keeping is the task in which the robot is required to maintain its position under the influence of flow. Robot developed by Salumae et al., was tested for station keeping under effect of currents (flow) in water [28].
- Robot navigation under flow - Flow relative control via a PID controller for closed loop control was used in FILOSE fish-like and was implemented via pressure-driven controller for achieving rheotaxis behaviour to swim up gradients [28, 159].
- Piston-based buoyancy control - Robotic Stingray was capable of buoyancy control. The robot consisted of a buoyancy control module which controled the volume of water present inside the water tank of the robot and hence was capable of adjusting the total weight of the body [16, 89, 90].

Joint level control is implemented via various means like layered control architecture consisting of three layers, namely, (1) cognitive layer, (2) behavior layer and (3) swim pattern layer [38], remote control [31, 32, 75, 76, 88, 108], CPG control [2, 3, 17, 18, 19, 21, 40, 41, 46, 54, 55, 56, 79, 80, 92, 120], serial communication [125], H_∞ control method [73, 160], Computed Torque Method (CTM) [30, 145], radio-control [110], speed controller [118], fuzzy logic control method [53, 122], Bio-inspired distributed control [1, 30], sinusoidal motion control [33, 77, 112, 62, 68, 69, 70, 71], pitch control mechanism [48], PID based controller to control the robot speed by varying the frequency of link oscillation [39, 161], simplified wave control method [109], hierarchical control algorithm, approximate control algorithm [124] and open loop control of links [1, 4, 77, 35, 44, 39, 49, 52, 57, 59, 61, 63, 66, 68, 69, 72, 89, 90, 91, 94, 95, 96, 97, 98, 107, 108, 109, 123, 127, 148, 162]. Nanyang Arowana-like fish (NAF) [61] consisted of a master controller which controlled different local controller which was used for controlling the actuators.

Based on the extent of the planning horizon, there are two levels of autonomous behaviours, namely, deliberative and reactive [163]. In the highest level of autonomous control, known as deliberative control, the robot uses entire sensory information available in addition to the internally stored knowledge and based upon that it determines what actions to perform next. The lower level autonomous control, known as reactive control, tightly couples the sensory inputs and the actuator outputs using very simple rules (while avoiding complex deliberative logic used in the deliberative controller) in order to enable the robot to respond very quickly to dynamic and unstructured environments.

In the biological world, reactive control in the form of stimulus-response or *nociception* is very common and has been extensively studied [164, 165]. One of the advantages of reactive control is that it does not require the acquisition or maintenance of world models, as it does not rely on the types of complex reasoning processes utilized in deliberative control. Real-time performance is easily achieved using such a reactive control. To the best of our knowledge, almost all the reported research work in the area of fish-inspired robotics utilizes reactive control based architecture. There is a need to develop fish-inspired robotic systems with deliberative planning in order to accomplish long term missions.

3.4. Sealing and Waterproofing

One of the major issues of robots traveling under water is sealing and waterproofing. Sealing and waterproofing is required to prevent seepage of water into the robot causing three problems, namely,

- water seepage may destroy the electronics present in the robot,
- weight of the robot may increase resulting in reduced maneuverability of the robot, and
- water seepage may result in corrosion.

Various mechanisms have been reported in the literature which can be classified into following categories.

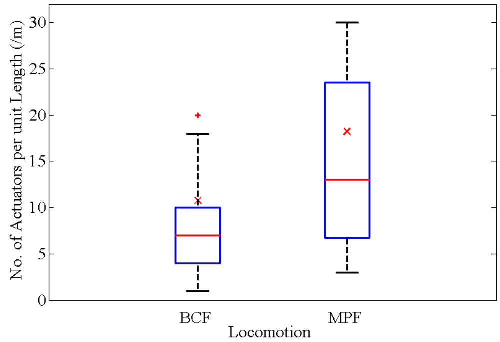
- Water-proof servomotors and O-ring for waterproofing - Waterproof servos have O-rings at case splits, on all screws that hold the case together and on the output shaft and may even use grease on the O-rings. This prevents the internal elements of the servomotors from getting destroyed. O-ring is a loop shaped flexible gasket made up of elastomer with a round cross-section. It creates sealing at interface when placed in a groove which is compressed during assembly between two or more parts. Waterproof servomotors have been used by Chan et al., [82] and Behbahani et al., [113]. Such O-rings have also been used at the joints to links so as to prevent the flow of water inside the robot [21, 17, 20, 77, 78, 79, 80, 125]. Some bellows [20] and static sealing [42] have also been used along with the O-rings to provide better waterproofing.
- Water-proof skin - To prevent leakage of water, the robot body is covered by means of flexible skin [18, 44]. Many types of flexible skin has been reported in the literature. Some of them include use of layers of very soft and thin silicone separated by means of hydrophobic lubricant, which repels water which may seep into the layers [18], use of a plastic film covering made up of multiple layers of materials like antistatic polyethylene terephthalate (PET), a low-density polyethylene (LD), and an antistatic linear low-density polyethylene (LLD) [57]. Some of the robots also made use of rubber based skin like rippled rubber tube which provides waterproofing as well as proper flexibility [39], rubberised plastic [52], rubber coating [77] and latex sheet [78]. Some of the other flexible skin materials include silica based skin [71], flexible waterproof PVC tube [64], compliant waterproof skin [47], silica gel coating [35] and emulsion cover [120].
- Shell for enclosing the electronics and servomotors - Some of the robots made use of rigid covering in the form of shells to cover robot electronics and servomotors. Different types of shells reported in the literature are Acrylonitrile Butadiene Styrene plastic shell created in fused deposition modelling machine [125], body shell printed on a Dimension SST^{TM} rapid prototyping machine [127], waterproof box [94, 95, 108, 166] and sealed compartment made up of aluminium and wrapped with heat molded semitransparent acrylic [112].
- Other sealing mechanisms - Some of the other methods of sealing described in the literature are, use of dynamic sealing mechanism [41, 42] in which a film of fluid is generated by hydrodynamic effect and is maintained without developing a leak, quick release fasteners or toggle latches for tight enclosure [43] and gravity based pitching mechanism to prevent the inflow of water [110].

4. Discussion

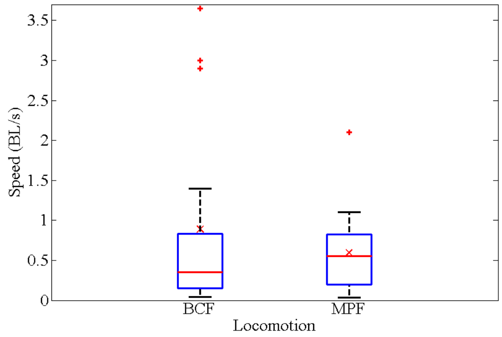
Figure 1 shows a comparison between different design features, namely, number of actuators, speed, mass, turning radius and thrust generated based on BCF and MPF locomotion. Each of the design features has been normalized with respect to the corresponding robot length. The data for this figure has been collected from 98 different research papers; 75 fall in BCF category and 23 in MPF category. Henceforth, in this section, we refer to the robots based on BCF locomotion as BCF robots while the robots based on MPF locomotion as MPF robots. The data has been represented in the form of box plot except for the turning radius and thrust per unit mass of MPF robots only one and three data were available respectively.

In each figure red '×' represents the mean of the data collected. The main observations and analysis of Figure 1 are explained below.

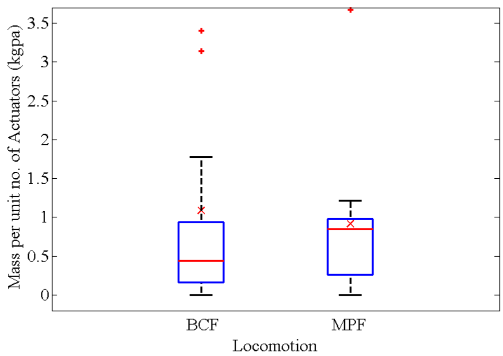
- The average number of actuators used per unit length of MPF robots is higher compared to that of BCF robots (see Figure 1(a)). This is because a larger number of actuators are packed laterally to allow for the body undulation as well as fin oscillation resulting in a larger value of the number of actuators per unit length in the case of MPF robots. In BCF robots, on the other hand, all the actuators are lined up along the medial direction, as only body undulation is needed for the locomotion and therefore results in a relatively smaller value of number of actuators per unit length of the robot.



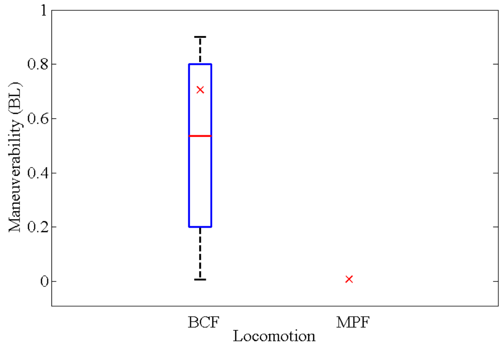
(a) Number of actuators per unit Length versus Locomotion



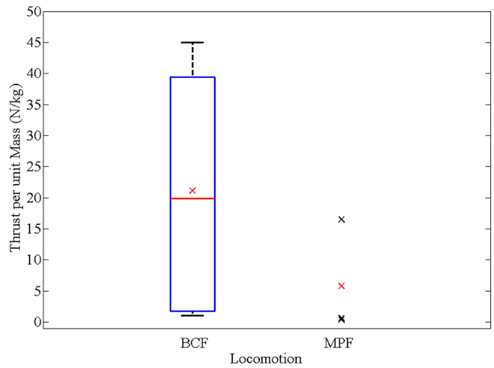
(b) Speed of the robots versus Locomotion



(c) Specific mass versus versus Locomotion



(d) Turning Radius versus Locomotion



(e) Thrust per unit mass versus Locomotion

Figure 1: Comparison of BCF and MPF locomotion based on different design features

- Mean speed in the case of BCF robots is higher compared to that of MPF robots (see Figure 1(b)). One of the main reasons for a higher speed in the case of BCF robots is that a larger thrust gets generated due to body undulation and oscillation as compared to that in MPF robots wherein the thrust is predominantly generated via fin oscillation. However it is to be noted that the median speed of BCF robots is lesser compared to that of MPF robots. This is mainly because, about 62% of the reported BCF robot speeds are lesser than 0.5 BL/s in comparison to the MPF robots for which only about 38% of reported speeds are lesser than 0.5 BL/s. The number of data points reported for BCF robots is 34 while the number of data points reported for MPF swimmers is 13 during the period 2004–2015. The maximum speed obtained in MPF robots is 2.1 BL/s [110] while in BCF robots it is 11.6 BL/s [4]. For the sake of clarity of the figure we have not shown the point representing maximum speed of BCF robot. The next highest speed obtained in BCF robots is 3.65 BL/s. Therefore, the BCF locomotion based robot design has a potential for obtaining higher speeds. However, the design complexity of BCF based robots may be more due to the requirement of body undulation leading to a poorer design and thereby overall lesser speeds.

- Though the number of actuators per unit length in case of BCF robots is lesser compared to that of MPF robots the specific mass in the case of BCF robots is more compared to that of MPF robots (see Figure 1(c)). This is because, the type of actuators used in case of the BCF robot are such that they have more torque and are bulkier compared to the MPF based actuators. As a result, the mechanical parts required to support the actuators need to be strong and thereby bulky. The additional weight of the support results in increase in the overall mass of the BCF robots. For example, the mass of the BUAV robot [45] is 200 kg while number of actuators used is two and hence specific mass is equal to 100 kgpa, in spite of only two actuators being used.
- Turning radius is used as a measure for maneuverability by many robots. Smaller the turning radius better is the maneuverability and vice versa. Another reported measure for maneuverability is the robot's turning rate. The maneuverability in the case of BCF robots is poorer compared to that of MPF robots, as the turning radius of the BCF robots is larger compared to that of MPF robots (see Figure 1(d)). In case of MPF robots, turning radius is reported in only one reference [113]. Majority of the research papers reporting MPF robots describe the details of their design but have not provided the turning radius or any other quantitative measure of maneuverability.
- Figure 1(e) shows the thrust per unit mass for BCF and MPF robots. For MPF we had only three data points and hence are represented by black '×'. Two of the data points are almost equal and hence are coincident in the plot. Undulation of BCF robots generates higher thrust as compared to the thrust generated by the fins of MPF robots. This is because the actuators used in case of BCF robots have higher power as compared to the MPF robot. Hence the mean value of thrust per unit mass is higher for the BCF as compared to MPF. This shows that the BCF robot has a better performance as compared to MPF robots. It is to be noted that the cases were thrust were not given directly, we made use of power and speed to calculate the thrust such that power divided by speed gives the thrust.

In order to study the research activity happening in the area of fish-inspired robotics we compiled the information about publications during the period 2004–2015. The number of publications was sampled bi-annually during 2004–2015 (see Figure 2). We took both journal as well as conference papers into account while plotting. Publications in the area of BCF robots as well as MPF robots have been shown separately. The red bar shows the number of papers published in case of the BCF robots and the blue bar shows the number of papers published in the field of MPF robots. The black '+' represents the total number of papers publishes biannually. From the figure following can be concluded.

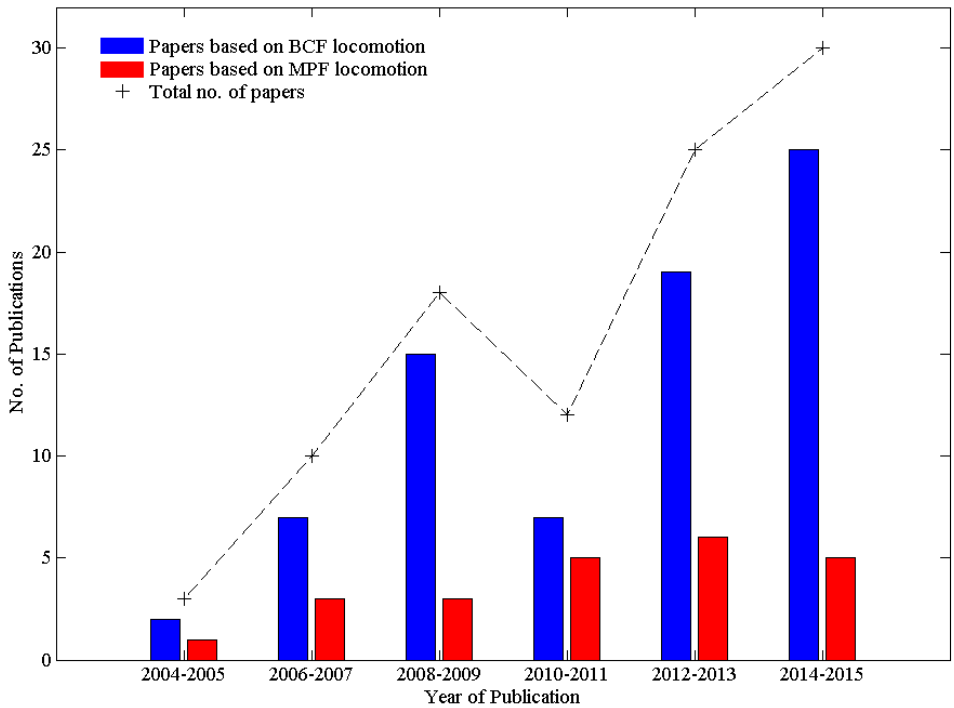


Figure 2: Number of Publication versus Year of Publication

- In general, we observed that the publications in the area of BCF robots is larger than MPF robots, an indicative of higher activity in the development of BCF robots compared to MPF robots.
- There is a consistent increase in the research activity in field of BCF robot development except for a dip in 2010-2011.
- The research in field of MPF robots is also improving but at a slower pace compared to BCF robots.
- Overall, the research in the field of fish-inspired robotics has been increasing consistently in the last decade as the total number of papers published is increasing every year except for a dip in 2010-2011. It is expected that the research activity in this field will grow in future too.

5. Conclusion

This paper presents a detailed survey of fish-inspired robots developed during past one decade and focuses primarily on the aspects related to design, sensing, actuation, and autonomy. This review reveals following open research areas.

i. Improvements in functional capabilities - We describe the research opportunities in the area of improvement in functional capabilities of fish-inspired robots in terms of speed, maneuverability and depth of operation.

   - Speed and maneuverability - Most of the robots discussed in this paper utilize electro-mechanical actuators, such as motors. In spite of wide acceptance of electric motors as actuators, there are problems related to the lack of flexibility or softness [167], bulkiness, and high power requirements that limits their applicability in fish-inspired robotics.

     To improve the speed and maneuverability of fish-inspired robots, more flexible and smart actuators should be incorporated. A lot of advancement has taken place in the area of smart materials [167], however, their application in fish-inspired robotics is still a topic of ongoing research [168, 65]. The open research issues include: (1) optimal design of smart actuator based robot structure that can strike a trade-off between the competing design objectives namely dexterity and load capacity [22, 169], (2) compliant mechanism design for the soft robot structures utilizing smart actuators, (3) development of novel techniques that can integrate the smart actuators with the robot structure both mechanically and electrically, and (4) development of control algorithms to impart functionality to the entire robot actuated by smart actuators.

   - Depth of operation - One of the most interesting applications of fish-inspired robots is in deep ocean exploration which is fraught with the problems caused by hydrostatic pressure like high stresses in robot body and leakage. Thus, an open research issue is the development of leak proof designs of robot structures and joints [21].

     Another related issue is to control the depth of operation, for which artificial swim bladder [170] can be incorporated. Some of the robots have incorporated such kind of features to control their operating depth by using a bladder and a pump mechanism [48, 16, 89, 90]. Major limitations of this mechanism include large overall weight of the robot and the high noise of operation. Two open research problems include, (1) design of lightweight and less bulky swim bladders to maintain robot stability and (2) design of noise-free swim bladders for stealth [171, 172].

   - Improving energy efficiency - A need exists for research in the area of development of energy efficient compliant body structures for fish-inspired robots. In addition, to improve its energy efficiency during performing low-level locomotion, a robot should be capable of efficient trajectory planning and obstacle avoidance and thereby minimize wasteful movements during performing high-level longer term missions. During operation, underwater robots come across static obstacles such as rocks, coral reefs etc. and dynamic obstacles such as different fishes and animals moving inside the water masses. Many motion planning algorithms for negotiating optimal path amid dynamic and static obstacles have been developed [173]. The critical challenge faced in the case of motion planning for fish-inspired robots is the disturbance caused by the aquatic environment. Environmental disturbances such as the ones caused due to current and drag affect the motion of the robots in spite of using feedback controllers. This necessitates development of intelligent motion planning algorithms that can generate obstacle free trajectories taking into account the environmental disturbances [155]. In addition to high level planning algorithms, new feedback control algorithms need to be developed for minimizing energy consumption due to motion under environmental factors like currents and fluid induced drag [160].

ii. Enhancing the accuracy of bio-mimicry using soft robotics - Though, various fish-inspired robots have been developed, they are not capable of exactly mimicking the locomotion pattern of a real fish. The main reason can be attributed to the use of discrete and rigid links in robots compared to the flexible bodies of fishes made up of muscles and tendons. Rigid structural components of robots, unlike fishes, impede natural continuous body motions. To alleviate this problem use of soft materials for fabricating compliant robot links are being explored in order to achieve fish-like continuous motion [167]. Use of soft materials in robots can impart improved flexibility and a continuous structure and thereby can allow infinite degrees of freedom to the robot resulting in high maneuverability.

    Open research issues in the area of application of soft materials in fish-inspired robotics include (1) bottom-up design of robot bodies using functional materials so that actuators and sensors are embedded in the robot bodies [174], (2) design of onboard compact electrical systems for adequately powering and controlling smart and soft actuators (e.g., on-board high actuation voltages for EAPs), (3) design of proper insulation of the robot from the surrounding water (4) design of mechanical systems to manage actuation heat in case of SMA, PAMs, etc., and (5) motion modeling and simulation of smart material and controller design for bio-mimicry (also see (i.)).

iii. Increasing the level of autonomy - To increase the autonomy of the robot, planning algorithms need to be developed. In order for the development of a planning system, research in two areas are needed, namely, (1) development of novel path planning algorithms suitable for fish-inspired robots and (2) development of dynamics simulators. Motion planning for fish-inspired robots face distinct challenges in terms of higher dimensional state space due to hyper-redundancy, environmental noise, and sensor noise. Motion planning algorithms dealing with such factors need to be developed.

    In addition to motion planning algorithms, high fidelity [175] as well as high performance dynamics simulators need to be developed. A dynamics simulator helps in determining the feasibility of the plan before actually using it. The governing equations used for developing the simulator should take rigid body motion [176] as well as rigid - fluid interaction [155] into consideration. Achieving high fidelity may cause impaired performance due to increase in computation. Hence, model simplification to achieve high simulation performance and fidelity is an open research area [177].

iv. Better fish-inspired robot design tools - Various design tools have been developed like CAD modelling, multibody motion simulation and various electrical/electronic circuit design tools. The need is to integrate all these and develop a unified fish-inspired robot development software platform. The design platform should accommodate suitable imaging and analysis modules for acquiring live video footage of fish movement and inferring various nuances of morphological details and locomotion patterns. Information extracted from imaging and analysis module can be incorporated into CAD tools directly. Such an integrated development environment can help in experimenting and iterating over the robot designs to optimize them for various objectives like motion accuracy, energy efficiency, speed and maneuverability.

v. Research in manufacturing - Manufacturing technologies are required both for the prototyping and the mass manufacturing in the area of robotics. Additive manufacturing (AM) technologies, also called as "rapid prototyping" and "3D printing" as well as novel subtractive techniques like laser and water jet based cutting have been developed and are used for prototyping to develop new designs abundantly in robotics. Although, these processes are capable of rapid fabrication of components with sufficiently complicated geometries, they have certain limitations such as small choice of materials used in these processes, low strength of fabricated parts, and being capable of producing only monolithic components.

    Robotic mechanisms consist of large number of moving parts with sophisticated kinematics and require the embodiment of sensors, actuators, power sources, electronic and electrical interconnects, and control electronics. This necessitates research in the development of novel manufacturing processes to deal with the above requirements. A need exists for the development of manufacturing processes to overcome the heterogeneity of present day manufacturing methods, wherein many subcomponents are manufactured independently and then assembled together to develop the complete robot [178]. Consequently, the fabricated systems after assembling independent subcomponents are generally more bulky, costly, inefficient, and less reliable. Therefore, manufacturing systems need to be developed that can handle multipart and multimaterial jobs.

    Embodiment of sensors and actuators need to be accomplished during manufacturing stage itself in order to improve the overall reliability and to reduce the manufacturing cycle time. Research in the area of shape deposition manufacturing [179] and origami-inspired folding processes [180, 181] using laser cutting machine [182, 183] have begun and require further efforts to apply them effectively in fish-inspired robotics. Novel manufacturing processes need to be developed for efficient fabrication of complex geometries made of elastomeric materials realizing compliant mechanism.

With an obvious advantage of low operational noise, further research in the area of fish-inspired underwater robots can be used in defence related applications like surveillance, rescue, and recovery. Industrial applications of fish-inspired robots include in-situ inspection and possibly maintenance of large machinery and equipment such as turbines, pressure vessels, boilers, mixers, etc. These swimming robots can be very useful in deep sea exploration related to oil and mineral expedition. These robots can also be used in environmental monitoring by collecting samples from rivers and seas to determine the level. Due to the versatility of motion, fish-inspired robots can also be used to recover missing items from the wreckage of ships or missing airplanes. An interesting zoology application of fish-inspired robots is in the study of social behavior of fishes.

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