A review study on bio-inspired robotic fish

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Abstract: The paper presents a comprehensive review of design, modelling and performance parameters of robotic fish. Bio-robotics capitalises on the natural behaviours of biological systems to facilitate new designs for robots. The propulsion mechanism employed by natural fishes is imitated for designing of robotic fishes. Fishes have two locomotion modes, body and/or caudal fin (BCF) mode and median and/or paired fin (MPF) mode. These modes have been studied in this paper, so as to facilitate easy selection of a specific mode according to the application. A robotic fish system includes different subsystems (such as mechanical unit, control unit and actuation unit). These along with various materials and components used in these subsystems have been overviewed. Further study has been carried out to understand the dynamic characteristics of a robotic fish model. Performance parameters of the robotic fish are discussed in this paper. Various innovative approaches towards designing of robotic fish and the issues that need to be resolved are also discussed.

Keywords: BCF; bio-mimetics; bio-robotics; MPF; robotic fish; strouhal number.

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1 Introduction

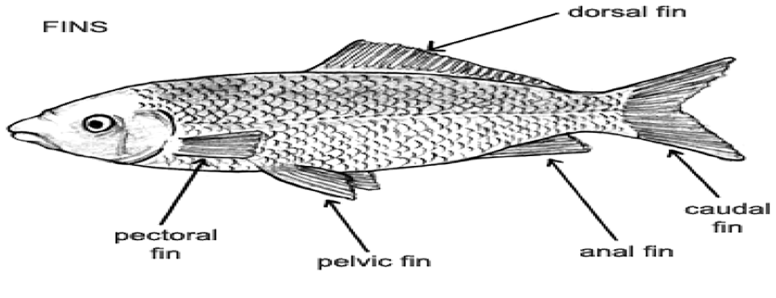
Bio-inspired robotics is a branch of robotics, which employs biological mechanisms as a knowledge base to develop new designs of robots. This can be applied to perform tasks that are either too complex to be performed by human or the tasks to be performed under a complex and dynamic environment.

In essential, in bio-inspired robotics, the functional mechanism of a biological system or species is studied, and the core elements which make the functioning possible are figured out. Efforts have been made to develop robotic systems that are capable of imitating some of these features/functions. Consequently, sometimes the term 'biomimetics' is used in bio-inspired robotic systems. Although it is impossible to imitate a biological system completely, inculcating a couple of features of a biological system also proves to be extremely efficient in various applications.

Of the many bio-inspired robotic systems that have been developed over the years, robotic fish has also gained significance in the area of underwater robotics. Propulsion in a live fish occurs through coordinated motion of fins, body and tail of the fish. A live fish has magnificent manoeuvrability as compared with traditional marine vehicles with equal power consumption. Propulsive efficacy offered by a live fish is tremendously high. Propulsion of a live fish is, therefore, a power efficient biological mechanism. It is infeasible to completely replicate functioning of a live fish. However, while designing a robotic fish, the aim is to extract some of the basic principles of live fish and replicate them in the robotic fish design so as to fulfil the needs of targeted area of application.

A live fish body consists of seven different types of fins (viz. Pectoral, Pelvic, Dorsal, Anal, Caudal, Adipose fins and Caudal peduncle (Figure 1)). Various fishes employ different fins to perform different functions that collectively make locomotion of fish possible.

Figure 1 Fins of a fish



As stated in Zhang et al. (2008), two types of swimming locomotion that are generally adopted by fish are:

1 BCF: It is body and/or caudal fin locomotion. Mostly, BCF mode is utilised for forward propulsion (Zhang et al., 2008).

2 BCF locomotion mode comes into picture when either body undulation or caudal fin oscillations or both are used in varying degrees for generation of thrust (Kodati et al., 2008).

3 MPF: It stands for median and/or paired fin locomotion. This mode does not contribute much in propulsion. Thus, mostly, it is used for stabilisation as well as manoeuvring by fishes (Zhang et al., 2008).

4 MPF locomotion mode includes the type of locomotion in which paired fins are employed for thrust generation (Kodati et al., 2008). For example, utilisation of left and right pectoral fins for thrust generation.

The above-stated locomotion modes are essentially derived from two characteristic movements; they are undulatory and oscillatory motions. As oscillatory motions can be created by gradually increasing undulation wavelength; therefore, it can be concluded that the mechanisms for generation of undulatory and oscillatory motion are similar. These motions can be generated by coupling oscillations generated by elements such as muscles, as they are generated by fins of a fish for propulsion (Zhang et al., 2008).

Biologically, on the basis of different undulation wavelengths, BCF swimming modes for fishes are classified into five categories (Zhang et al., 2008), which are

1 anguilliform

2 ostraciiform

3 carangiform

4 subcarangiform

5 thunniform.

Large amplitude undulations are generated by the whole body of the fishes with anguilliform swimming mode. An example of fish with anguilliform mode is Lamprey (Yu et al., 2004). Anguilliform mode is known to have the highest undulatory motion; characterisation of this mode can be done as a traversing of a transverse wave through the entire body length (Kodati et al., 2008).

In carangiform mode, the posterior part (last one-third part of the body) is responsible for generation of body's undulations; and a rigid caudal fin is the means for thrust production (Kodati et al., 2008; Yu et al., 2004).

Earlier, in ostraciiform swimming mode, it was considered that propulsion is caused by oscillations in tail fin. However, this concept is now obsolete, as now it is known that ostraciiforms (fishes with ostraciiform swimming mode) have a multifin structure. This is not only responsible for propulsion but it also facilitates ostraciiform to behave in a way which enables crucial functions such as minimisation of recoiling (undesired deviation) and self-correcting mechanism (immunity to water disturbances) (Kodati et al., 2008).

The most efficient swimming mode is the thunniform mode. Only the region close to the peduncle and the tail fin is the source of occurrence for lateral movements. This swimming mode is best suited for high-speed sail in calm water (Zhang et al., 2008). Thrust production in this mode happens through lifts during lateral movements. An example of thunniform is Shark.

Subcarangiform swimming mode is similar to anguilliform swimming. This mode is known to offer higher speed, but manoeuvrability is reduced. Increment in wave amplitude across body length is noticed. Most of the thrust production occurs at the rear end of the body. In this mode, adduction of pelvic and pectoral fins against the body occurs. Also partial erection of dorsal and anal fins happens. The family of fishes, 'trout', is known to have this swimming mode.

All the five swimming modes are being explored to be replicated in robotic fishes to achieve versatile use of exploitation of functional concept of these modes. Although carangiform swimmers attain higher speeds but they are less agile due to rigidity in their structure as compared with anguilliform swimmers. However, it is more convenient to realise carangiform mode according to the engineering point of view (Yu et al., 2004).

MPF swimming modes are categorised into seven classes, which are given as follows:

1 Rajiform: It causes undulatory movements. Vertical undulations along sizeable pectoral fins are responsible for thrust production.

2 Diodontiform: Propulsion is possible due to undulatory movements along large pectoral fins.

3 Amiiform: Undulatory movements occur along dorsal fins; body axis is carried stable and straight.

4 Gymnotiform: Effectively, it is up-side-down amiiform gait. Propulsion (undulations) is caused by anal fin.

5 Balisitiform: Propulsion is caused by both anal and dorsal fins. Undulatory movements are produced.

6 Tetraodontiiform: This type of locomotion is executed by generation of oscillatory movements by flapping of anal and dorsal fins and flapped either in phase or absolutely in opposite phase.

7 Labriform: It is a kind of locomotion in which propulsion is either drag based or lift based. It occurs by generation of oscillations in pectoral fins.

Many aspects of robotic fish have been under research such as use of different materials and actuators that can be employed, trajectory planning, control strategies, and coordinated motion of multiple robotic fishes. In this paper, the basic design of a robotic fish and its characterisation is discussed. Also, different designs that have been proposed by researchers are discussed. Variation in these designs is essentially based on the factors such as different swimming modes that are employed in the biomimietic system, different actuators employed to cause movements in the robotic fish. According to the area of application being addressed, efficacy and suitability of a particular robotic fish design can be assessed.

The designing, hydrodynamics and dynamic modelling of an ostraciiform are carried out in Kodati et al. (2008) and Kopman et al. (2015). The robotic fish considered in Kopman et al. (2015) is actuated electrically by a servomotor actuator. The characterisation of an ostraciiform is done by employing modular compliant tail fin. The material used in the modular tail fin is Mylar sheets that are sandwiched together to form the fin. Dynamic modelling, crucial parameters and control of this robotic fish are discussed in Kopman et al. (2015).

Functional capabilities of boxfish (a typical ostraciiform swimmer) are considered to design a microautonomous biomimetic robotic fish in Kodati et al. (2008). Robotic flapper mechanism is employed to realise movements and control similar to boxfish, which has a self-correcting behaviour towards water turbulence.

The design and performance analysis of an ostraciiform-based biomimetic robotic fish similar to that in Kopman et al. (2015) is performed in Kopman and Porfiri (2013). The material used to construct modular tail fin considered here is acrylonitrile butadiene plastic. The design also offers wireless control of the robotic fish.

Realisation and control of functions similar to thunniform swimming mode using only one actuator are discussed in Zhang et al. (2008). An electrostatic film motor (made of FPC(Flexible Printed Circuit) films) is used as actuator. Insight from functionality of carangiform swimming mode is drawn to model a biomimetic fish in Yu et al. (2004). Control strategies for parameters such as speed and orientation of the robotic fish are also developed.

Realisation of rajiform locomotion found in cownose ray fish is done by modular bionic flapping foil, and spatial parallel mechanism is used for control purpose in Niu et al. (2013). An important judgment drawn from the analysis of biomimetic robotic fish developed is that larger phase difference between the two fins flapped together does not affect the swimming speed; to attain maximum swimming speed, deformation of bionic fins must be optimised.

Implementation of various conventional actuators to achieve fish such as movements has been practiced so far. However, these actuators have some limitations when used in robotic fish. Thus, it has been a subject of interest to employ innovative approaches to design actuation module for a biomimetic robotic fish design. Such an approach has been developed in Hubbard et al. (2014), where artificial muscle (made of ionic polymer-metal composite) which is electrically driven is proposed to work as an efficient actuator in designing of a robotic fish. It provides high DOF(Degree of Freedom) with elimination of requirement of more number of actuators to attain high DOF.

The desirable performance of a robotic fish cannot be attained without identifying crucial parameters, which may vary according to the application and subject for which the fish is being designed. Establishing control over these parameters is of vital importance. Another essential consideration that has to be given while developing a design for biomimetic fish is the interdependence of these parameters. Some of the chief parameters which are mostly kept in consideration are swimming speed control, orientation control and turning control.

A couple of parameters associated with turning control are discussed in Yu et al. (2008). Some analytical techniques along with fuzzy logic control are employed in Wen et al. (2012) to establish swimming control for a robotic fish that is developed on the knowledge base of the live fish ‘Scomber scombrus’. Control strategies to replicate special functioning of MPF mode- and BCF mode-based robotic fishes are established in Hu et al. (2014) and Su et al. (2014), respectively. Along with modelling, design and control strategies for biomimetic robotic fishes, this paper will also discuss localisation and coordinated transport of robotic fishes. Also, hybrid or cross-disciplinary designs for robotic fishes, which are still in a premature developing stage, are also discussed in this paper.

2 Design features of robotic fish

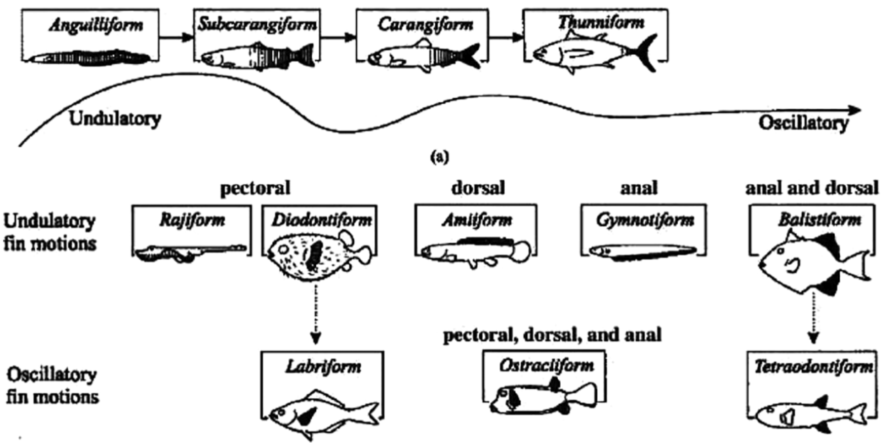
2.1 Selection of fin motion

The locomotion of a fish results from interactions between body of the fish and the fluid environment. The first step for designing of a robotic fish is the selection of a swimming mode, for locomotion of the robotic fish as per the intended area of application for which the robotic system is being designed. As stated earlier, different swimming modes employ different fins to exhibit movements. To replicate a particular swimming mode in the robotic system, only those fins which are known to cause motions in live fish, are actuated, and they are called active fins, and rest of the fins are called passive fins.

Another important deciding factor in the selection of a swimming mode is the kind of motion that is desired. Both BCF mode and MPF mode offer two types of motions such as undulatory and oscillatory motions.

Different modes which offer oscillatory and undulatory fin motions are shown in Figure 2.

Figure 2 Different modes which offer undulatory and oscillatory motions



Source: Kodati et al., 2008

2.2 General configuration of a fish shaped robot

The basic configuration of a robotic fish (Yu et al., 2004) consists of the following components:

1 mechanical structure and its support

2 actuation unit

3 control unit

4 communication unit.

2.2.1 Mechanical structure and its support

It comprises a rigid body of an appropriate material such as acrylonitrile butadiene strylene is used in Kopman and Porfiri (2013), active fins section (such as tail fin section is required to realise ostraciiform swimming mode) and waterproofed skin. The body of the system is an assembly of exoskeleton, head and fore body.

2.2.2 Actuation unit

Mobility, swimming and manoeuvring potential of underwater animals are far better than man-made underwater robotic systems. Underwater animals can perform highly complex movements which are infeasible to be exactly replicated in a robotic system. However, to achieve motions close to the actual complex motion, the robotic system is required to offer multiple degrees of freedom. Thus, the actuation scheme utilised in the robotic fish system holds crucial importance.

Standard actuating schemes, such as electrical and pneumatic, generally offer 1-DOF for one actuator. For example, one servomotor if employed as an actuator, it will offer only one degree of freedom. If conventional actuating scheme is used in the design of a robotic fish, then to achieve multiple degrees-of-freedom, complex actuating mechanism with multiple actuators will be required (Hubbard et al., 2014). This leads to heavy- and large-sized robotic systems that are certainly not desirable. Although robotic fish systems delivering good performance using conventional actuators have been designed yet their bulkiness troublesome.

Simpler actuation techniques to achieve higher degrees of freedom have been a subject of research. For streamlining the existing robotic fish systems, new techniques to actuate the robotic fish have been in consideration. These actuating schemes involve ‘smart actuators’.

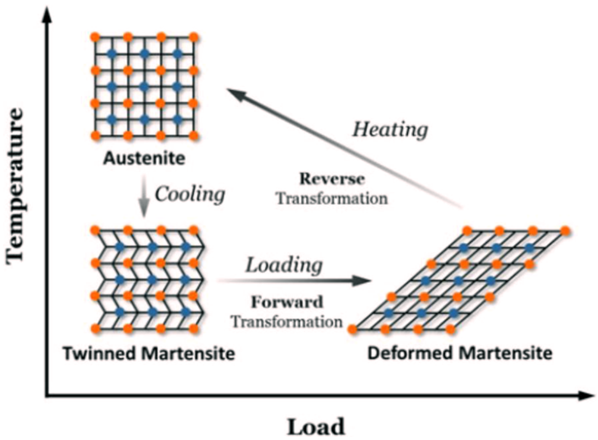
Smart actuators not only provide high degree of freedom, they also provide compact actuating unit that does not make noise, unlike conventional actuators. As mentioned in Chu et al. (2012), essentially three ‘smart actuators’ have been used in the design of robotic fish. These are listed as follows:

1. shape memory alloy (SMA)
2. ionic polymer metal composite (IPMC)
3. lead zirconate titanate (PZT).

2.2.2.1 Shape memory alloy

It exhibits thermomechanical characteristics. The factors related to these characteristics are temperature, SME(Shape Memory Effect), and internal stresses. SME is the shape memory effect, in this effect, if a stress is applied at a specific temperature between austensite and martensite phases, the transformation of austensite phase into deformed martensite phase takes place (forward transformation), though it will have residual stresses. If stress is applied at austensite phase at this point, then reverse transformation will take place that means the deformation which occurred earlier will be destroyed (See Figure 3). The entire process effectively leads to generation of high amount of stress, which is the reason that SMA is being used as an actuator.

Figure 3 Shape memory effect (see online version for colours)



Source: Chu et al., 2012

SMA actuator was used to develop a robotic fish at Harbin Institute of Technology (Chu et al., 2012). The fish robot was designed to deliver a BCF mode with oscillatory motion (ostraciiform swimming mode). Its design specifications are given in Table 1.

Table 1 Specifications of the fish robot developed at Harbin Institute of Technology

Length of the robot fish	146 mm
Diameter of SMA wire	0.089 mm
Deformation angle	108° (at 7.2 V)
Maximum speed	112 mm/s (at 2.78 Hz)

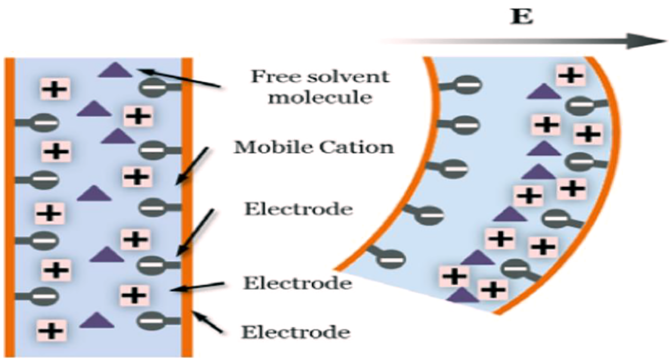
Source: Chu et al., 2012

2.2.2.2 Ionic polymer metal composite

It is highly suitable material to be employed as an actuator in biomimetic underwater robotic systems. It consists of the polymer, Nafion, and electrodes (Chu et al., 2012). Neutralised ionic membrane of the polymer is inserted between electrodes that are made of noble metals (e.g. platinum) (Hubbard et al., 2014).

An electric field is generated on application of voltage to electrodes, due to which a bending effect occurs as the distribution of volume of water molecules becomes uneven (Figure 4). This uneven distribution is caused due to fixed SO_3-ions and transit of sodium ions and water molecules to the cathode (Chu et al., 2012). This bending effect in IPMC is capitalised on, which leads to application of IPMC as a smart actuator.

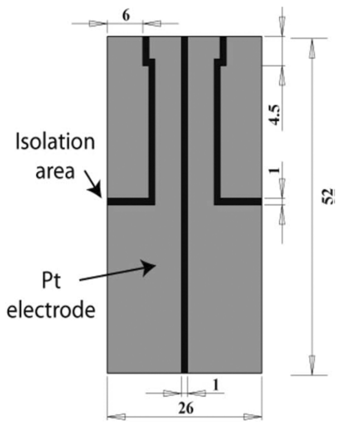
Figure 4 Principle of IPMC actuator (see online version for colours)



Source: Chu et al., 2012

An artificial muscle fin using IPMC is designed to be employed as an actuator for the robotic fish in Hubbard et al. (2014). High flexibility of the artificial muscle fin so designed is attained by sectoring of the surface electrode material into separate regions that are electrically isolated (Figure 5). Such a configuration leads to generation of complicated twisting and bending motions. On cautious designing of patterned electrode, specific sections can be used to generate complex deformations whereas other sections of electrode can be utilised for tasks such as sensing. The robotic system so designed in Hubbard et al. (2014) has an actuating mechanism that has integrated capabilities of monolithic control surface and sensing. The analysis of designed robotic fish showed that any increment in the thrust attained from increasing voltage input causes increase in power consumed. The increase in power consumed is proportional to increment in thrust.

Figure 5 A patterned IPMC (units in mm)



Source: Hubbard et al., 2014

The advantageous characteristics of IPMC actuator are

1 Operation of IPMC actuators is flexible.

2 It delivers large displacement with a low driving voltage.

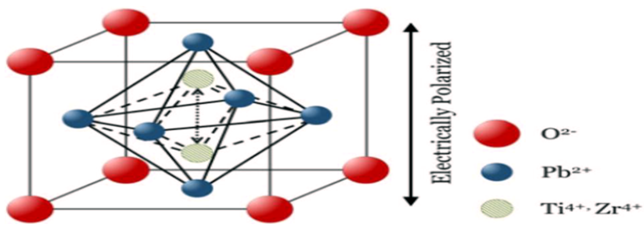
3 Repeatability.

4 The response time of IPMC actuators is quite short.

2.2.2.3 Lead zirconate titanate

It is an inorganic compound with the formula $Pb[Zr_xTi_{1-x}]O_3$ where 'x' can vary from 0 to 1. It works as an actuator on the basis of piezoelectric effect. An electric field is generated when pressure is applied on the surfaces of PZT (Figure 6). The electric field so generated is proportional to the pressure applied on surfaces of PZT. Generation of electric field further leads to production of voltage, which causes deformation of PZT. This deformation is the basis for employing PZT as an actuator.

Figure 6 Principle of PZT (see online version for colours)



Source: Chu et al., 2012

As the principle of functioning for the three smart actuators are nonidentical, thus, the characteristics defining their performance are different. The dissimilar performance characteristics for these smart actuators are given in Table 2.

Table 2 Characteristics of smart actuators

Characteristics	*SMA*	*IPMC*	*PZT*
Voltage (V)	Low (>2)	Low	High
Strain (%)	Medium (>5)	Large	Small
Stress (MPa)	Large (>200)	Low	Large
Actuation frequency (Hz)	Slow (~1)	Fast (<100)	Very fast (~10,000)

Source: Chu et al., 2012

Smart actuators can be collectively used to develop a hybrid actuator that leads to synergy of the characteristics of the actuators involved in making the hybrid actuator. A robotic replica of jelly-fish was developed, in which the actuating unit comprised four similar actuators. The actuator used was made using a combination of SMA and ionic conducting polymer film (ICPF).

As compared with conventional actuators, smart actuators are much more compact and make less noise. Also, it is known that smart conductors such as SMA and IPMC work more efficiently in fluid environment (Chu et al., 2012). Smart actuators provide faster swimming speed (in body length per second) than provided by conventional actuators in robotic fish systems of same size and weight.

2.3 Control unit

The control architecture of a robotic fish comprises an embedded system with three major components: the processing module, the sensor module and the control module. These three functional components collectively operate to manoeuvre the robotic fish in the desired manner, based on various predefined control parameters.

The control parameters associated to a particular biomimetic fish design can be determined by dependence of output parameters on certain input parameters. The input parameters on which the output parameter to be controlled depends are the control parameters. The nature of dependence of output on the control parameters defines the relationship that can be utilised to vary control parameters accordingly.

Consider a robotic fish designed to provide oscillatory motions for locomotion, then the angular position of the control surface in consideration will be given as

$$\theta(t) = V + A\sin(2\pi ft + \varphi) \tag{1}$$

where V is the angular bias, A and f are the oscillatory amplitude and frequency, respectively; and φ is the phase difference.

The speed for straight motion of the fish is known to depend only on joint's oscillatory frequency and oscillatory amplitude. Orientation of a robotic fish can be controlled by controlling various joint angles (or deflections). The direction of propulsion is governed by the angular bias.

A particular swimming mode employs one or more control surfaces to execute the locomotion. The movement of a specific control surface is governed by one or more fins. To attain a particular gait of the fish under BCF, MPF or hybrid mode, a couple of control surfaces may be involved. Behaviour of these control surfaces is determined by the associated control parameters.

There are various parameters that are desirable to be controlled other than the basic speed and orientation control, for example, turning control. Different control strategies can be employed to dominate these parameters. Control issues associated with robotic fish include trajectory planning and tracking and high manoeuvrability.

Strategy for swimming control along with turning and diving control strategies, biomimetic fish mimicking behaviour of thunniform is given in Zhang et al. (2008). Analytical techniques and fuzzy logic control are employed for turning control for a robotic fish designed to propel through oscillating tail fin (Wen et al., 2012). The fuzzy control is also established for controlling orientation of biomimetic fish robot designed in Yu et al. (2004). However, for speed control, proportional-integral-derivative controller is employed. Fuzzy control facilitates higher acceleration and lower steady-state error as compared with open-loop proportional integral derivative (PID) controller (Wen et al., 2012).

Kinematic and dynamic modelling of fin ray undulation are carried out in Hu et al. (2014) so as to develop a control strategy for tracking of fin ray undulations. Implementation of certain complex turning and bending maneuvers require development of specific control strategy. Such an approach is employed in Su et al. (2014); it intends to establish a control on a BCF mode mimicking robotic fish, to implement C-fast starts (high-speed and high-energy swimming bursts are known as fast starts) (Su et al., 2014).

2.4 Communication unit

The communication unit of a underwater robotic system such as fish-shaped robot, consists of a wireless receiver.

3 Modelling of a robotic fish

Different modelling techniques have been established to develop designs of robotic fishes with varying degree of performance capabilities, size and complexity. The degree to which influence of inspiration drawn from natural fish affects the actual robot design establishes difference between various designs available.

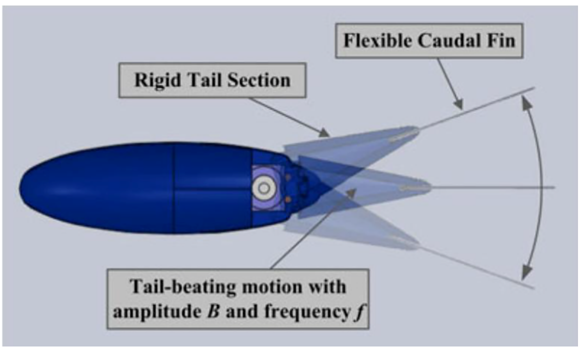
Although a wide range of prototypes have been proposed for robotic fish, limited extent of autonomy is facilitated to the robot in these designs. A robotic system can be made highly autonomous only be enhancing its control. By intensifying degree of autonomy of the system, the area of applications it can cater to, broadens. Such a proposition of robotic fish with enhanced autonomy is given in Kopman et al. (2015). Two-link mechanism has been considered, with a frontal link and a tail link (right caudal peduncle and flexible tail fin). Thrust production results from vibrations generated by the compliant tail fin.

The concept behind developing enhanced autonomy biomimetic fish prototype is to develop a model in which locomotion of the fish can be tracked by a single input (steering angle) (Kopman et al., 2015).

3.1 Structure

The structure of the robotic fish consists of two-link mechanism with the first rigid link that represents the frontal link or part of the fish body, and the second link represents tail fin (caudal fin) and caudal peduncle collectively(refer Figure 7). The rear link itself comprises a rigid part that fulfils the function of caudal peduncle and a flexible part which is designed to work as the caudal fin. Mylar sheets are sandwiched to form the caudal fin.

Figure 7 Structure of robotic fish with flexible caudal fin (see online version for colours)



Source: Kopman and Porfiri, 2013

Some distinctive features employed while structuring the robotic fish to inculcate certain desirable characteristics are given as follows:

1 The compactness of robot prototype is achieved by housing all the components in both body and caudal peduncle.

2 Servomotor is used as an actuator in the system. It is cost efficient and light. Servomotor is positioned at caudal peduncle.

3 Waterproof connectors and cover are employed to keep the electronic components intact.

4 Components are strategically located in the structure to have a control over mass distribution of the system.

5 Control of ON/OFF state and charging connection are established at the side of the body.

6 A void for small weight is created in internal structure to attain stability in the system.

7 Thrust production is much higher if the tail fin is of trapezoidal geometry; thus, caudal fin is constructed to have a trapezoidal shape.

Oscillations generated by robotic fish's tail lead to thrust production. Thus, for establishing a control over thrust vector, axis along which tail fin oscillates is varied. The speed of the robot can be varied by varying frequency or amplitude of the oscillating tail (Liu et al., 2012). Various structural specifications of the robot prototype developed in Kopman et al. (2015) are presented in Table 3.

Table 3 Characteristics of prototype designed in Kopman et al. (2015)

Characteristics	*Values*
Body length (L_r)	0.150 m
Width (W_r)	0.026 m
Height (H_r)	0.046 m
Dry mass (m_r)	0.06 kg
Wetted surface area (A_r)	145×10^{-4} m^2

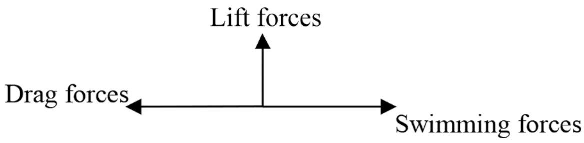
3.2 Dynamic modelling

The mechanism designed for the prototype consists of two links connected through an actuated joint. Kirchhoff's equations of motion for rigid body in static fluid and Euler Bernoulli beam theory are used to develop dynamic models of the frontal link and caudal fin vibrations, respectively. The external environment, which is of the surrounding fluid is modelled by employing Morison equation and hydrodynamic derivatives for body.

The robot is designed to have three DOFs; this restricts the motion of the body to surge, sway, and yaw. Surge and sway correspond to linear motions whereas yaw is a rotational motion. Surge refers to longitudinal front/back type of motion whereas sway refers to lateral top/down type of motion. Yaw corresponds to rotational motion about the vertical axis. Robotic fish in Kopman et al. (2015) is so designed that it can execute only these three movements. These movements are characterised by their respective velocities: $u(t)$, $v(t)$ and $r(t)$ velocities for surge, sway, and yaw, respectively.

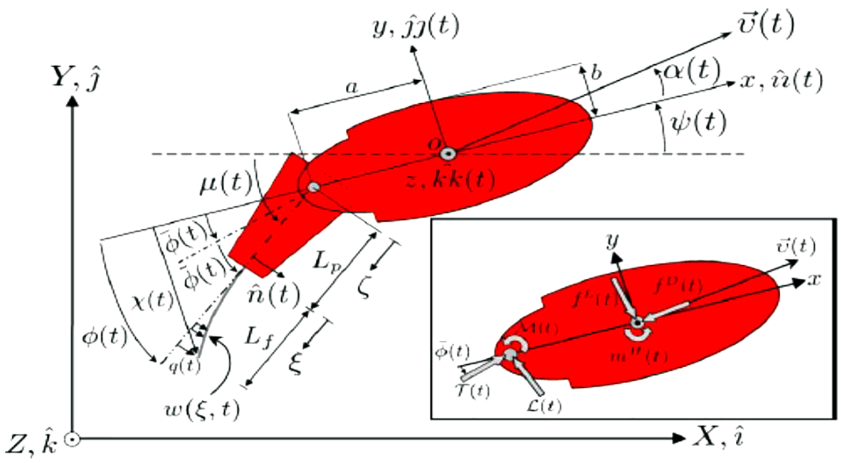
Hydrodynamic effects of quiescent fluid are taken into account by considering lift and drag forces and hydrodynamic moment. The drag forces act against swimming direction of the robot where lift forces act in the direction normal to the swimming direction.

Figure 8 Directions of hydrodynamic forces



Hydrodynamic moment acts at centre of buoyancy (COB) of the body. Caudal peduncle motion and hydrodynamic moment collectively lead to bending of fin in water. The former reason for bending of fin is modelled through developing a modal model that is based on the Euler-Bernoulli beam theory; whereas the latter is taken into consideration Morison equation (Kopman and Porfiri, 2013). To elucidate motion of this robotic fish prototype, higher order non-linear model is required. Various parameters needed to characterise robot's orientation are presented in Figure 9.

Figure 9 Diagram depicting swimming robotic fish with notations for associated parameters (see online version for colours)



Source: Kopman et al., 2015

Coherent description of the crucial parameters, which governs the orientation of the robot, holds significance. This can be done by assigning coordinate frames to in-plane swimming robotic fish prototype. The two coordinate frames essentially required for this purpose are universal coordinate frame $\{X, Y, Z\}$ and body fixed coordinate frame $\{x, y, z\}$. The unit vectors for Universal Cartesian coordinate system are $\hat{\imath}$, $\hat{\jmath}$, and $\hat{k}$. For body-fixed coordinate frame, unit vectors are represented as $\hat{\imath}\,i$, $\hat{\jmath}\,j$, and $\hat{k}\,k$. The origin 'o' for body fixed coordinate frame is considered to be the COB of the robot.

As a result of strategic mass distribution as stated in 3.1, centre of mass (COM) of robot is located 0.010 m below the COB (o), on the *z*-axis. The salient features of this model are as follows:

i Robot's body is symmetric about *x-z* plane. The semiwidth of the robot's body on either side of *x-z* plane is 0.013 m.

ii Along *x*-axis, the distance from the origin to the front and distance from the origin to the hinge are equal. And this length is equal to $a = 0.033$ m as shown in Figure 8.

iii Length of the tail is given as $L_t = L_p + L_f = 0.085$ m

where

L_p (length of the peduncle) = 0.035 m

and L_f (fin length) = 0.050 m.

iv Robot's heading is the angle between *x*-axis and *X*-axis. It is denoted by $\psi(t)$.

v The angle formed by velocity $\vec{v}\,(t)$ of the body with the positive *x*-axis is the angle of attack $\alpha(t)$.

The studies of dynamics of body and tail and evaluation of thrust production have been used collectively to establish the dynamic model of the robotic fish in Kopman et al. (2015).

3.2.1 Dynamics of the robot fish's body

The robot's plane motion can be considered to be similar to motion of vessels near surface of the water. Thus, it can be modelled as Kopman et al. (2015):

$$(m_b - X\dot{u})\dot{u}(t) = (m_b - Y\dot{v})v(t)r(t) + F_x(t) \tag{2}$$

$$(m_b - Y\dot{v})\dot{v}(t) = -(m_b - X\dot{u})u(t)r(t) + F_y(t) \tag{3}$$

$$(J_{bz} - N\dot{r})\dot{r}(t) = (Y_u - X\dot{u})u(t)v(t) + M_z(t) \tag{4}$$

Here,

m_b: body mass

J_{bz}: mass moment of inertia about *z*-axis

$X\dot{u}$, $Y\dot{v}$, and $N\dot{r}$: constant hydrodynamic derivatives depicting effects of additional mass due to the fluid.

The force components along *x*-axis and *y*-axis ($F_x(t)$ and $F_y(t)$), moment of inertia about *z*-axis ($M_z(t)$) (Kopman et al., 2015) are given as

$$F_x(t) = -f^D(t)\cos\alpha(t) + f^L(t)\sin\alpha(t) + T(t)\cos(t) - L(t)\sin(t) \tag{5}$$

$$F_y(t) = -f^D(t)\sin\alpha(t) - f^L(t)\cos\alpha(t) + T(t)\sin(t) - L(t)\cos(t) \tag{6}$$

$$M_z(t) = m^H(t) + M(t) - T(t)\,a\sin(t) - L(t)\,a\cos(t) \tag{7}$$

Here, f^D (t) and $f^L(t)$ are hydrodynamic drag and lift forces, while $m^H(t)$ is the moment acting on the body. $\bar{\varphi}(t)$, the angle between peduncle's neutral axis and x-axis is the steering angle. The undulations of the tail result in generation of thrust, lift and moment on the hinge. These are represented as $T(t)$, $L(t)$ and $M(t)$, respectively.

The drag force, lift force and moment acting on the body are formulated as (Kopman et al., 2015)

$$f^D(t) = \frac{1}{2}\rho V^2(t)\, A_r C_D \tag{8}$$

$$f^L(t) = \frac{1}{2}\rho V^2(t)\, A_r C_L \alpha(t) \tag{9}$$

$$m^H(t) = \frac{1}{2}\rho V^2(t) A_r(2a)\left[C_{M\alpha}\alpha(t) + \frac{2a}{V(t)} C_{Mr} r(t)\right] \tag{10}$$

Here, the mass density of water is represented as ρ (1000 kg m^{-3}). The coefficients of drag and lift forces are represented as C_D and C_L, respectively. And the coefficients for restoring and viscous moments are $C_{M\alpha}$ and C_{Mr}, respectively. These coefficients are scaled according to the wetted surface area of the body.

3.2.2 Dynamics of caudal fin and peduncle

The joint between body and tail of the fish robot is an active joint. It corresponds to the servomotor shaft that is located at the caudal peduncle. The joint is at a distance a from the origin (COB) in the direction of negative x-axis. The angle φ, is the angle between the caudal peduncle and the x-axis. It acts as the only input parameter that is necessary to define the locomotion of the robot. It is given as

$$\varphi(t) = B\sin(2\pi ft + \delta) + \bar{\varphi}(t) \tag{11}$$

The angle $\varphi(t)$ is influenced by the following parameters:

1 angular amplitude B

2 frequency f

3 phase lag δ

4 steering angle $\bar{\varphi}(t)$.

To accomplish complex trajectories, steering angle can be made to vary with a small rate of change; otherwise, it can be held constant. The caudal peduncle (rigid beam) is connected to the hinge which translates, whereas the tail fin (flexible beam) is cantilevered to the hinge.

The bending stiffness of the tail fin is given as

$$K_M(\xi) = \frac{1}{12}Eh^3 \tag{12}$$

where

E: Young's modulus of the material

h: thickness of the fin

$d_f(\xi)$: width of the fin

ξ: material abscissa along the fin axis. Its range is $0 < \xi < L_f$.

The width of the fin, $d_f(\xi)$, is length dependent and is given by the formula

$$d_f(\xi) = (2/5)\xi + 0.024 \tag{13}$$

The characteristic parameters of the tail fin of the robot are as follows:

The area of the tail fin is given as

$$A_f = \int_0^{Lf} df(\xi)\, d(\xi)$$

Mass per unit length is given as

$$\rho(\xi) = m_f d_f(\xi) / A_f$$

where m_f is the total mass of the fin, $m_f = 0.496 \times 10^{-3}$ kg.

The modal model equation for the tail vibration as derived in Kopman et al. (2015) is given as

$$\begin{aligned} &M\ddot{q}(t) + P\sin\varphi(t)\dot{u}(t) - P\cos\varphi(t)\dot{u}(t) + [Pa\cos\varphi(t) + G]\dot{r}(t) \\ &= [M\dot{\mu}^2(t) - K]\, q(t) - G\ddot{\varphi}(t) + R(t) \\ &+ P[u(t)r(t)\cos\varphi(t) + v(t)r(t)\sin\varphi(t) - ar^2(t)\sin\varphi(t)] \end{aligned} \tag{14}$$

where

K: modal stiffness of the fin that acts as a torsional spring

M: modal mass (fin dry mass + added mass)

P, G: parameters associated with inertial effects (affected by rigid body motion of the fin)

$R(t)$: parameter associated with hydrodynamic damping, which is related to overall motion in static fluid

$q(t)$: fin tip displacement.

3.3 Integrated dynamic model

The equations developed for modelling of body, caudal fin and caudal peduncle in Sections 3.1 and 3.2 are collaborated to establish a set of equations that depict robotic fish's motion. This is accomplished by combining the equations of dynamic model of body, caudal fin and caudal peduncle in a compact matrix form. These are given as

$$\mathbf{x} = [u\ v\ r\ \psi\ q\ \dot{q}] \tag{15}$$

$$[\mathbf{x}\ \mathbf{x}] = \left[u^2\ v^2\ r^2\ uv\ ur\ vr\right] \tag{16}$$

The equations defining motion of the robot are given in matrix form as

$$A(\varphi)\dot{x} = B(x,\varphi)[xx] + F(x,\varphi) + C(\varphi)\ddot{\varphi} \tag{17}$$

The details associated with the matrices $A(\varphi)$ and $B(x, \varphi)$ and vectors $F(x, \varphi)$ and $C(\varphi)$ can be referred from Kopman et al. (2015). The robotic fish in this study is modelled such that the locomotion of the robot can be governed by only using one parameter, $\varphi(t)$.

3.4 Assessment of thrust production

Many studies have estimated that the thrust produced by the tail of fish-like swimmer is mainly because of the inertia of surrounding fluid (Kopman et al., 2015). This concept has been generally accepted, and it can be approximately formulated as

$$T(t) = \frac{1}{2} C_T\, \rho A_t \dot{\chi}^2(t) \tag{18}$$

where

C_T: nondimensional coefficient of thrust

$\chi(t)$: lateral fin tip excursion

A_t: area of the tail.

The lateral fin tip excursion $\chi(t)$ is perpendicular to the x-axis, and it can be defined as

$$\chi(t) = q(t)\cos\varphi(t) + L_t \sin\varphi(t) \tag{19}$$

The area of the robot's tail can be approximately formulated as $A_t = L_t\, d_{f\,\max}$. $d_{f\,\max}$ is the maximum width of the tail fin. There are many ways to obtain the value of thrust coefficient (C_T). In Kopman et al. (2015), for evaluation of C_T, the fin tip vibration is considered to be of the form: $\chi(t) = \chi_{peak} \sin(2\pi f t)$. The thrust coefficient in Kopman et al. (2015), is formulated as

$$C_T = 4\bar{T}L_t / \rho v^2 d_{f\,\max} \left(\mathrm{Re}_f\right)^2 \tag{20}$$

where

$\bar{T}$: mean thrust

v: Kinematic viscosity of water at room temperature ($v = 10^{-6}$ m^2 s^{-1})

Re_f: oscillatory Reynolds number given as, $\mathrm{Re}_f = 2\pi f \chi_{peak} L_t / v$.

The optimal range of Reynolds number is experimentally evaluated by simulation results of computational fluid dynamics (CFD). The optimal range of Reynolds number is evaluated on the basis of suitable factors. For example, to attain a certain value of the ratio of peak fin excursion to propulsion length, a certain range of values of Reynolds number would lead to that specific value.

The biomimetic fish robot designed in Kopman et al. (2015) presents a unique feature in which steering angle is the only parameter which defines the locomotion state of the robotic fish. However, this study does not include the effect of turbulent fluid environment. The environment of the robot is considered to be quiescent fluid. In practice, the environment of an underwater robot is not static. Thus, for practical implementation of this design, a study of the designed robot's behaviour in turbulent fluid environment and its control is necessary.

The controlling unit of the designed robotic fish constitutes of PID controller. The control of the robotic fish can be made more efficient and accurate by employing adaptive control.

4 Performance parameters for fish shaped robots

The performance of a robotic fish can be assessed by different approaches. Numerical analysis, simulations and monitoring working prototype of robotic fish in artificially created environment are the techniques generally employed to assess performance of robotic fish designs.

Numerical analyses such as CFD are commonly used to verify performance of a particular robot design, by drawing judgments from the simulation results of the CFD analysis. Such an approach has been used in Liu et al. (2012). Many technically advanced softwares facilitate an artificial environment in which the model's behaviour can be monitored easily. The results so obtained are close to real-time execution of the robotic fish. Performance verification, of robotic fish designed to be controlled by PID controller and Fuzzy logic, has been done by simulation that is done in Wen et al. (2012).

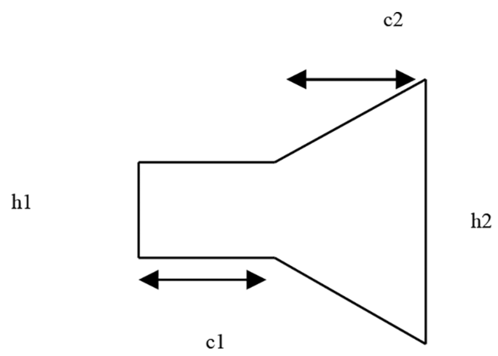
Performance of a robotic fish design can be done in real time by monitoring the behaviour of the prototype in an artificially created underwater environment, such as a pond with still water. Similar approaches have been employed in Yu et al. (2008), Hu et al. (2014) and Su et al. (2014), to assess the performance of the design for a robotic fish.

The parameters which explicate the performance of a robotic fish design vary from design to design. However, some performance defining parameters are basic, and these are crucial for every robotic fish design. These include factors such as flexibility, degree of freedom, efficiency and stability. Depending upon the application for which the robot is required characteristics of a design may be assessed as suitable or unsuitable. For example, low speed might be a drawback in reference of one application but low speed capabilities might be suitable for some other application.

Flexibility is the most important performance defining characteristic of a robotic fish design. The accuracy of the robotic fish is directly dependent on flexibility of the robot. The cause of flexibility and degree of flexibility in the robot design are different for different swimming modes. To increase flexibility, designs with hybrid swimming modes can be considered. It means that, movements corresponding to different swimming modes can be employed in collaboration in one robot design. This would lead to higher flexibility.

In the design of biomimetic ostraciiform (Kodati et al., 2008), it has been shown that flexibility can be varied by varying geometry of the caudal fin. A boxfish-like template has been used as the shape template for the caudal fin. It has been studied that, flexibility can be varied on changing the dimensions while keeping the aspect ratio and total fin area constant (Figure 10).

Figure 10 Shape template for caudal fin



Source: Kodati et al., 2008

The degree of freedom offered by a robotic fish is essentially the deciding factor for flexibility. DOFs provided by a specific design depend on the permitted motions for that design. For example, linear movements along two axes and rotational movement along one axis are provided by robotic fish designed in Kopman et al. (2015); this implies that the degree of freedom offered by that robot design is three. Although flexibility and higher DOFs offered by live fishes are infeasible to be imitated exactly, but the higher the degree to which the behaviour of the live fish is mimicked, the greater will be the efficiency.

Buoyancy is yet another significant factor to determine the performance of a robotic fish. It is determined by the volume of fluid displaced by the solid model (Kodati et al., 2008). A robotic fish should be either neutrally buoyant or slightly positively/negatively buoyant. For neutral buoyancy of robot, the force of the weight and buoyancy force must be equal (Kodati et al., 2008). A slightly positively buoyant designed robot will tend to float on the fluid surface. On the contrary, if a robot is designed to exhibit slightly negative buoyancy, then drag and lift mechanism have to be designed for such systems (similar to live fishes); otherwise, the robot will sink.

One of the most dominating characteristics in determination of performance of any system is its efficiency. In case of biomimetic fish robots, efficiency can be broadly defined using any of the following three methods.

The conventional method of determining the efficiency can be employed. Such an approach has been used in Kodati et al. (2008) to define efficiency as a ratio, given as, the ratio of output power delivered by fin/input torsional power required to drive the fin. Second, efficiency can be expressed as thrust efficiency as evaluated in Wen et al. (2012). Last, efficiency can be determined by evaluating lift and drag forces generated by movement of the biomimetic robot's body as in Liu et al. (2012).

A robotic fish design should have strategically uniform mass distribution to attain stability. The locations for COM and COB should also be predetermined as they also play a vital role in stability of the robot's body.

The swimming speed is the most significant aspect in determining the performance of a biomimetic fish robot. 'Strouhal number' is a very important parameter that is used to determine the maximum swimming speed possible. The maximum swimming speed corresponds to a specific range of strouhal number. It can be defined as a non-dimensional number that establishes an interrelationship between forward velocity and flapping frequency (Kodati et al., 2008)

$$St = fw / U \quad (21)$$

Here, *w* corresponds to the wake width, or it can be considered to be width of a single stroke as done in Kodati et al. (2008). As stated in Hubbard et al. (2014), for efficient swimming modes, optimal range of *St* has been found to be 0.25–0.35.

5 Recent expansions

The technology behind designing biomimetic fish robots have been continually evolving. New innovative approaches are being introduced to make these robots highly autonomous and smart. Combinations of different sensors are being employed to make the robot more efficient and accurate and intelligent.

The monte carlo localisation approach has been used in Wang and Xie (2015), for probabilistic localisation of robotic fish with high precision. An onboard camera is employed to attain visual cues, and an underwater image processing algorithm is also utilised to enhance the quality of visual cues. Inertial cues are attained from inertial measurement unit, which has decimetre-level precision with 5 Hz refreshing rate. This unit gathers two pieces of information: first being accurate orientation of the robot and second it attains rough odometery of the robot.

The technology developed for localisation in Wang and Xie (2015) is not only very advance, but it is also computationally cost efficient. It provides with high precision global positioning of the robot. It is best suited for the miniature UWRs with limited computational capabilities (Wang and Xie, 2015).

Innovative collaborations of different biological mechanisms to develop more efficient and versatile designs have also emerged in the recent time. Such an approach has been utilised in the design of miniature underwater glider (Zhang et al., 2014). In the design of this underwater glider, two mechanisms have been collectively realised. The two mechanisms utilised for this purpose are gliding mechanism and fin actuation mechanism.

Similar approaches involving combination of different mechanisms such as of a fish and a bird are also under research. Although such designs are in a premature stage, they will certainly prove to work efficiently in future of underwater robotics.

6 Conclusion

In this paper, basic design features of a biomimetic fish robot have been studied. Different swimming modes have been discussed, and consideration is given to dynamic modelling of a biomimetic fish robot propelled by flexible caudal fin. The design of a robotic fish propelled by flexible caudal fin (Kopman et al., 2015) has been studied. Although the existing design is highly efficient and exhibits an extraordinary feature of controlling the locomotion of the robot, by varying only one state parameter, the fluid environment considered while designing the robot was static fluid; however, practically the environment in which robotic fish has to work is turbulent fluid. Thus, it is desirable to carry out analysis of the system for turbulent fluid environment. Designing of biomimetic fish robots is still in evolving stage in the area of underwater robotics. There are many issues which need to be addressed, such as stability issues, failure diagnosis and tolerant issues, and environment perception issues. The continual refinement of the biomimetic fish robot designs will lead to resolution of these issues and development of intelligent and more efficient underwater robotic systems.

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