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REVIEW PAPER

Designs of the Biomimetic Robotic Fishes Performing Body and/or Caudal Fin (BCF) Swimming Locomotion: A Review

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Abstract

The excellent swimming performances of live fish motivate scientists and engineers around the world to study its swimming mechanism and develop fish-like underwater robots, namely, the biomimetic robotic fishes. This paper compares different designs of biomimetic robotic fishes performing Body and/or Caudal Fin (BCF) swimming locomotion, and stresses how the designs evolve. The general trend is to utilize a simpler and more robust mechanism to make biomimetic robotic fishes mimic their counterparts in nature better, at the same time, to exhibit better swimming performances. Representative studies are given and discussed. Challenges of current studies are summarized and future research directions are presented. With state-of-the-art engineering and biological technologies, the biomimetic robotic fishes have great potentials in some areas where the conventional screw propellers are not applicable, like narrow space navigation and eco-friendly environment monitoring.

Keywords Biomimetic robotic fish · Actuation methods · Designs · BCF swimming locomotion

1 Introduction

With millions of years of evolution, fish has developed excellent swimming performances in water. For example, most fishes have an efficiency of 90% or higher [1]. A swordfish can reach a speed up to 110 km/h. A pike has an acceleration as large as 249 m/s^2 [2]. This motivates scientists and engineers around the world to study its swimming mechanism and develop fish-like underwater robots, namely, the biomimetic robotic fishes.

According to the ways of propulsion in the periodic movements, fish locomotion can be roughly classified into two categories, i.e., the Body and/or Caudal Fin (BCF) swimming locomotion as well as the Median and/or Paired Fin (MPF) swimming locomotion, which is as shown in Fig. 1. On one hand, BCF swimmers perform steady rectilinear locomotion by coordinately flapping their bodies to generate a traveling wave of increasing amplitude passing from head toward tail. The speed of the traveling wave is higher than the swimming speed of the fish. This category covers about 85% of the fish species. On the other hand, MPF swimmers rely on their median and/or paired fins to swim. Those fins involve the pectoral fin, the dorsal fin, and the anal fin. Moreover, a further distinction is made for both the BCF and MPF swimmers—the undulatory motion (S-shape deformation) and the oscillatory motion (C-shape deformation). These two types of motions should be considered as a continuum.

In terms of the fractions of the body used in flapping, BCF swimming locomotion can be further divided into anguilliform (such as eels and lamprey) [5], subcarangiform (such as trout), carangiform, thunniform (such as tunas and sharks) [4], and ostraciiform. Most part of the anguilliform swimmer's body participates in flapping, and at least one complete wavelength of the traveling wave is present. The anguilliform swimmer has excellent body flexibility and maneuverability. Most of them can perform backward swimming by making the traveling wave passing from tail to head [6]. The subcarangiform swimmer shows similar movements, while flapping motion is limited at the posterior half of the fish's body. As for the carangiform swimmer,

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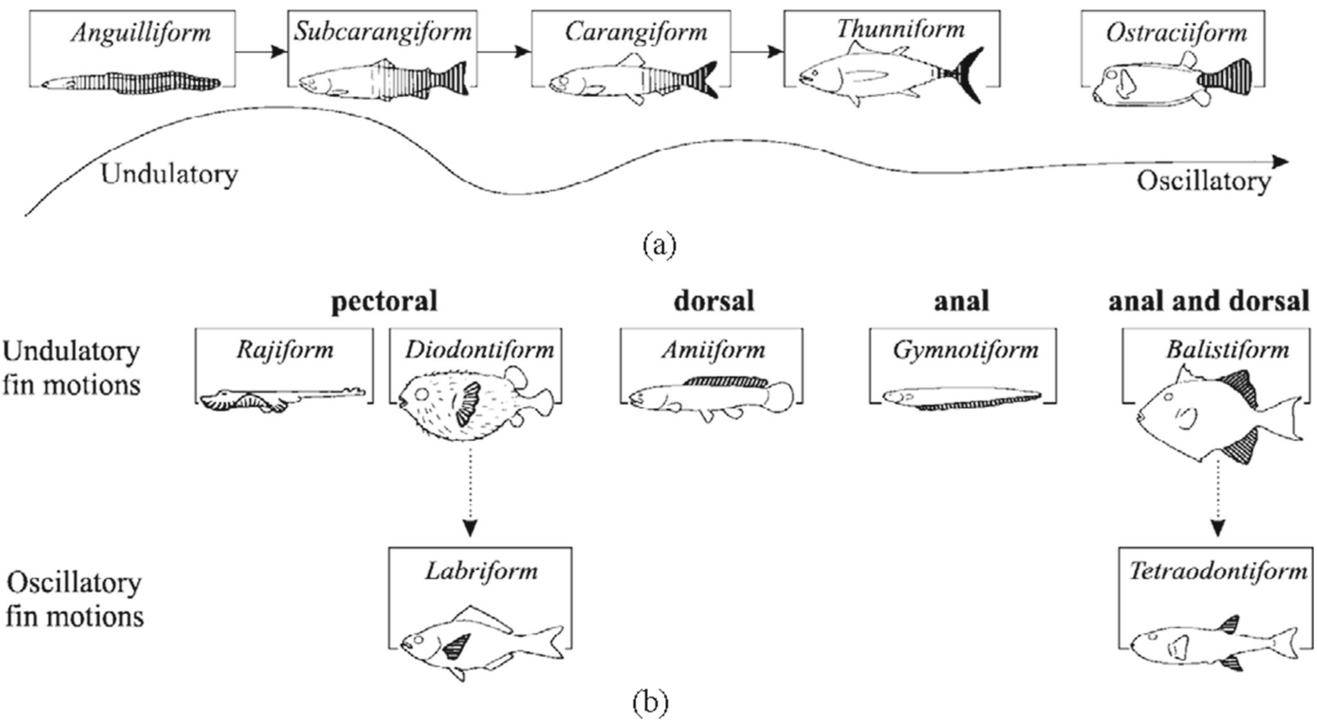


Fig. 1 Swimming locomotion: **a** BCF, **b** MPF. Shaded areas indicate the fractions involved in thrust generation. (Modified from [3, 4])

the flapping motion is further confined at the last third of the fish's body. The body is stiffer compared with the anguilliform swimmer and the subcarangiform swimmer, which results in a faster swimming speed. However, the recoil of its head (known as headshaking) is usually larger since the lateral force concentrates at the posterior part. As for the thunniform swimmer, the flapping motion is mainly conducted by the caudal fin which is rather stiff. It is the most efficient locomotion, and capable of maintaining a fast swimming speed for a long duration. Yet, its maneuverability and acceleration are compromised. An interesting finding is that the thunniform swimmer has very small recoil, which is attributed to the streamline body shape and proper mass distribution. The ostraciiform is superficially similar with the thunniform, having a stiff body and a stiff caudal fin. However, the ostraciiform swimmer mainly relies on its median and/or paired fins to generate thrust, and the caudal fin works as a supplementary propulsion method. Thus, the ostraciiform is sometimes excluded from BCF swimming locomotion [7]. The driving mechanisms vary for different kinds of BCF swimming locomotion, but they fall into three main categories—the single-joint/multi-joint design (usually driven by motors), the design using smart materials and the compliant design (driven by pneumatic, hydraulic or cables).

The midline body curve of a BCF swimmer can be described by a traveling wave model with different characteristic parameters, which is firstly proposed by Lighthill and Barrett [8, 9]. This traveling wave model is shown as:

$$y(x,t) = (c_1 x + c_2 x^2)\sin(kx + \omega t) \tag{1}$$

where, $y(x,t)$ is the lateral deflection, x is the displacement along the main axis of the fish's body, c_1 and c_2 are the linear and quadratic wave amplitude envelopes, ω is the body wave frequency, k is the body wave number. This model is subsequently adopted as the norm for fish swimming and robotic fish control. However, due to the inability to precisely control the individual characteristic parameters (such as the flapping amplitude, the flapping frequency, the shape of flapping pattern, and the phase lag along the body curve) and the difficulty to measure locomotor characteristics of live fish (such as the thrust, the speed, and the efficiency), there still remains some unanswered questions before the fish swimming mechanism is fully understood. Among those studies about flapping patterns, the fish's body is usually modeled as a rigid/flexible foil [10–17]. One general conclusion is that the thrust rises with the increase of the flapping amplitude and the flapping frequency. When the thrust becomes larger, an inverse von Karman wake can be found behind the rear of the tail, which is believed to be the cause of this improvement. Xie et al. used an untethered biomimetic robotic fish platform and experimentally proved that the traveling wave model of Eq. 1 offered a good balance among the thrust, the recoil, and the swimming speed, which resulted in a high swimming efficiency [18].

The median and paired fins are essential for maneuverability and motion stabilization. Whereas, they can also serve as the main propeller to generate thrust. According to which fins are used, MPF swimming locomotion can be divided into rajiform, diodontiform, labriform, amiiform, gymnotiform, balistiform, and tetraodontiform. The rajiform swimmers, such as rays and mantas, swim by flapping their pectoral fins upwards and downwards, just like bird's flying. Their pectoral fins are large, triangular in shape and flexible. As for diodontiform and labriform, propulsion is achieved by passing undulation down broad pectoral fins. In addition, the amiiform, gymnotiform, balistiform, and tetraodontiform depend on the dorsal fins, the anal fins, anal&dorsal fins to generate thrust. There are other kinds of swimming locomotion besides BCF and MPF, such as the jet propulsion (used by jellyfish), walking and crawling (used by shrimp and lobster), but these species are limited.

Ref. [3, 7, 19–23] are reviews or books on the development of biomimetic robotic fishes, most of which are published four years ago. A more recent one only focuses on motion control [20]. In these years, together with the single-joint/multi-joint mechanism, smart materials and the compliant mechanism are increasingly employed in the designs of biomimetic robotic fishes, enriching study of this field and pushing the boundary on robotic fish's performances. The framework of this paper is given in Fig. 2, where three objectives are defined. First, it emphasizes and provides a more comprehensive survey on various designs of biomimetic robotic fishes performing BCF swimming locomotion. Representative robotic fishes are studies and comparisons among them are made. Second, based on the survey, current major challenges in this field are concluded. Finally, promising and inspirational future research directions are given.

The rest of this paper is organized as follows. Section 2 presents designs of the single-joint/multi-joint robotic fishes. Section 3 introduces robotic fishes using smart materials. Section 4 provides designs of the compliant robotic fishes. Section 5 briefly reviews the modeling and control methods. Finally, Section 6, the concluding remarks, contains current challenges and potential research directions.

2 Single-joint/Multi-joint Robotic Fishes

The single-joint/multi-joint mechanism is the most popular in robotic fish design. This kind of robotic fishes uses the serial-link mechanism to fit the midline body curve of live fish in swimming. Each joint is usually driven by one motor. The fitting accuracy depends on the number of links. When there are more links, the midline body curve of the robotic fish can match that of the live fish better. However, the mechanical complexity and the difficulty in control increase. As a result, 3 to 5 links are mostly employed in the multi-joint robotic fish design. Moreover, the miniaturization of this design is difficult due to the size limitation from the actuators.

The first attempt to create a freely swimming robotic fish was made by MIT and Draper Laboratory accompanied by 3 projects [20], i.e., RoboTuna [1], Vorticity Control Unmanned Undersea Vehicle (VCUUV) [24, 25], and RoboPike [26, 27] (refer to Fig. 3).

RoboTuna is known as the first robotic fish in the world. The purpose of this project is to explore the fish swimming mechanisms. In order to mimic its counterpart in nature as vivid as possible, RoboTuna has its shape taken from a casting of a real blue-fin tuna, which is 1.2 m in length. However, this robot is tethered and can not swim freely. A number of force sensors are employed to measure the torques of motors, drag forces on the supporting pillar and pressures on the caudal fin. Moreover, Barrett et al. [9] determined seven key parameters affecting the swimming performances, and used Genetic Algorithm (GA) to obtain the optimal parameters.

Following RoboTuna, another robotic fish, VCUUV is co-developed by MIT and Draper Laboratory. It is designed to control the vorticity to generate thrust. The VCUUV is much larger than RoboTuna, up to 2.4 m in length and 173 kg in weight. It is a four-joint robotic fish, and all the joints are driven by a closed-loop hydraulic system. It is untethered, which enables it to swim freely. The maximum swimming speed is 0.61 Body Length/Second (BL/s) at the frequency of 1 Hz, and the maximum turning rate is 75 °/s. Its swimming speed is less than design due to the saturation of the actuator system.

Inspired by the excellent maneuverability of pike, the RoboPike project was launched around 2000. Compared with RoboTuna and VCUUV, it is simple in mechanical structure, which has three joints and is 80 cm in length. Each joint is driven by a waterproof brushless DC servomotor. Harper et al. reported that it could save up to 30% energy of RoboPike by using harmonically turned springs to recapture the inertial energy [27]. However, it had not been verified by experiments. Without parameter optimization, its maximum cruising speed was about 0.3 BL/s at the frequency of 1 Hz.

The Human Centred Robotics (HCR) research group at the University of Essex has been working on robotic fishes since 2003. Two interesting robotic fishes they have built are G9 and iSplash [30–32], which are shown in Fig. 4. The ascending/descending performance of G9 was the best in the world at that time. The maximum ascending and descending speeds are about 1.5 cm/s and 2 cm/s,

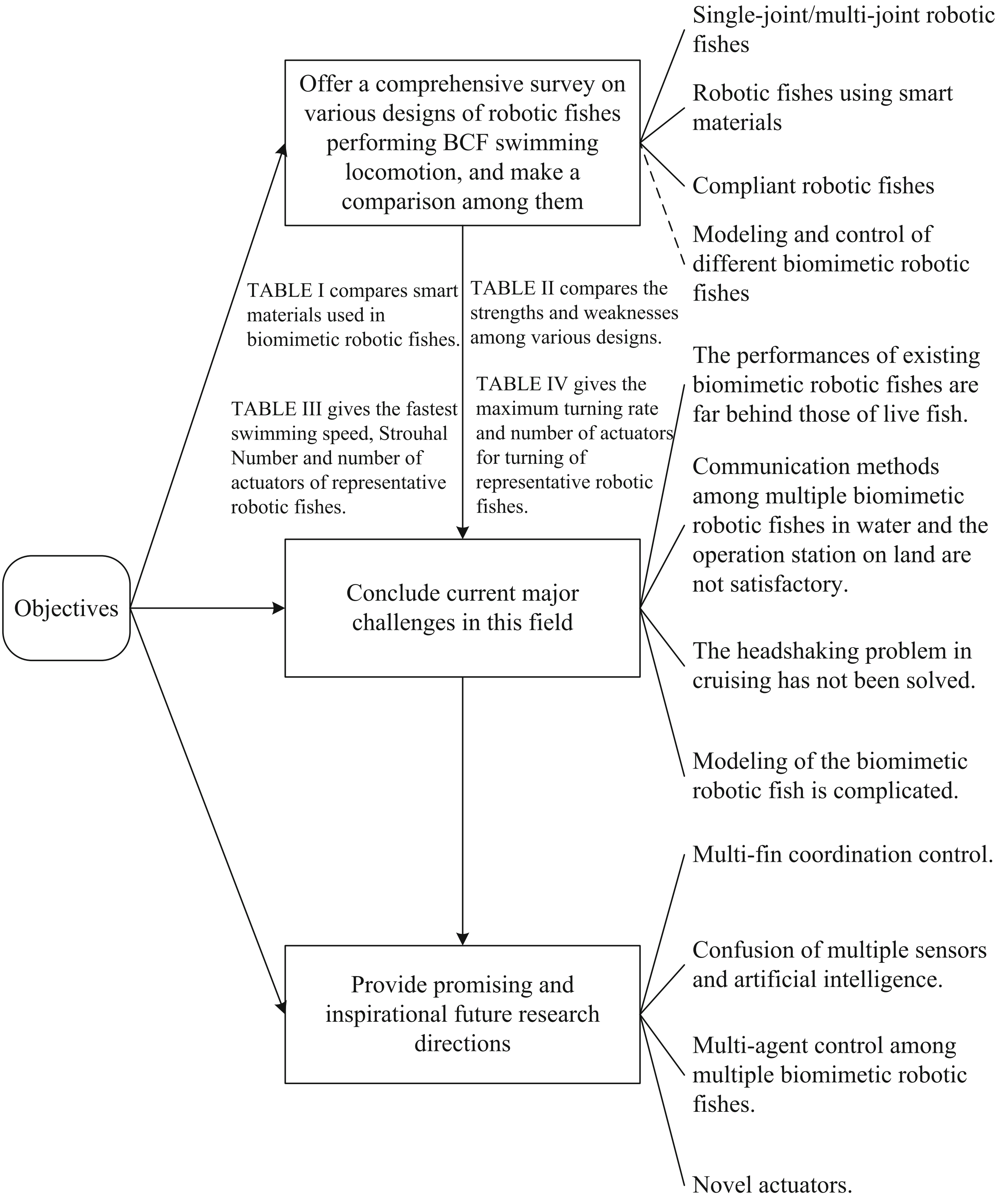


Fig. 2 The framework

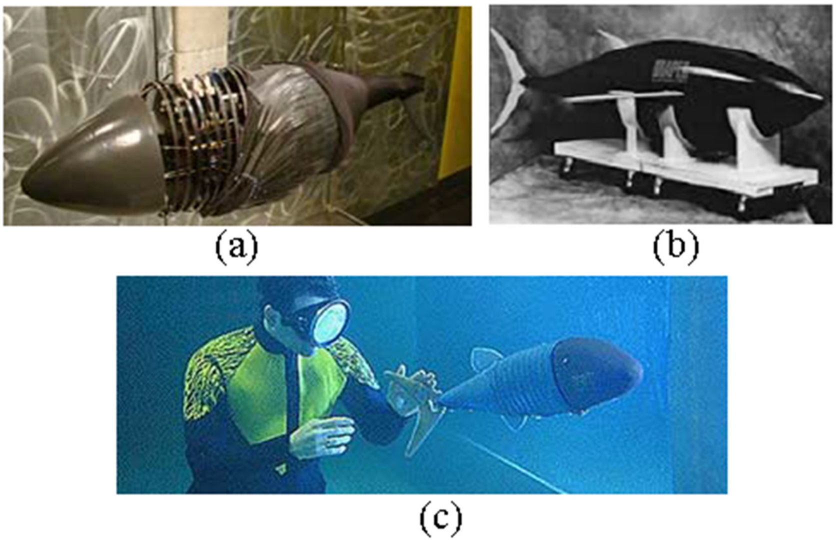

(a) (b) (c)

Fig. 3 **a** RoboTuna [28], **b** VCUUV [24], **c** RoboPike [29]

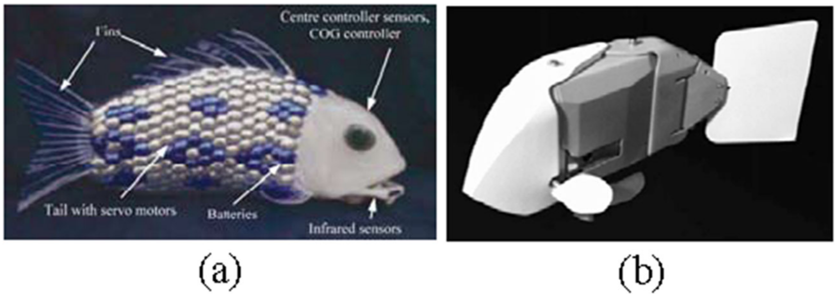
respectively. In addition, its fastest swimming speed is 1.02 BL/s. Another project, iSplash, is well-known for its swimming speed, up to 11.6 BL/s, which is far beyond others even today. However, one limitation of this project is that iSplash can only swim in a straight line. In other words, it can not perform multimodal swimming, like turning, ascending/descending.

In the past two decades, the State Key Laboratory of Management and Control for Complex Systems in the Institute of Automation, Chinese Academy of Sciences (IACAS) is one of the most active groups in robotic fish research [20, 33–54]. The designs of their robotic fishes mainly adopt the single-joint/multi-joint mechanism, and their representative is the robotic dolphin (refer to Fig. 5), which was reported the first time to succeed one single leap in 2016 [38], and three continuous back-to-back leaps in 2019 [45]. In this project, they aim to emulate the high-speed and short duration locomotion of a dolphin. To realize this, an integrative model of both kinematics and dynamics is formulated. Meanwhile, an angle of attack theory-based control strategy is proposed to modulate the orientation. The robotic dolphin's fastest swimming speed is up to 2.3 BL/s. Its Strouhal Number (SN), an index to qualitatively describe the swimming efficiency, is 0.32. The Strouhal Number is defined as below:

$$SN = \frac{f A_{p-p}}{U} \tag{2}$$

where f is the frequency, A_{p-p} is the peak-to-peak amplitude at the tail end, U is the cruising speed. In nature, most of the aquatic animals have their Strouhal Numbers falling into the narrow range between 0.2 and 0.4, and the efficiency is high within this range [55, 56].

The double-caudal-fin robotic fish (refer to Fig. 6), created by the University of Science and Technology of China (USTC), aims to improve the agility, stability and efficiency by taking the advantages of both insect wings and fish fins [57]. Two caudal fins are installed parallelly at the tail end as the main propeller. During cruising, two caudal fins flap in the opposite directions. Thus, a water jet is produced to enhance the thrust generation, and the lateral forces are canceled out. By the aid of it, this robotic fish has better stability (the amplitude of headshaking is lower than 2 °) and a faster swimming speed (1.2 BL/s).



(a) (b)

Fig. 4 Robotic fishes from University of Essex: **a** G9 [30], **b** iSplash [31]

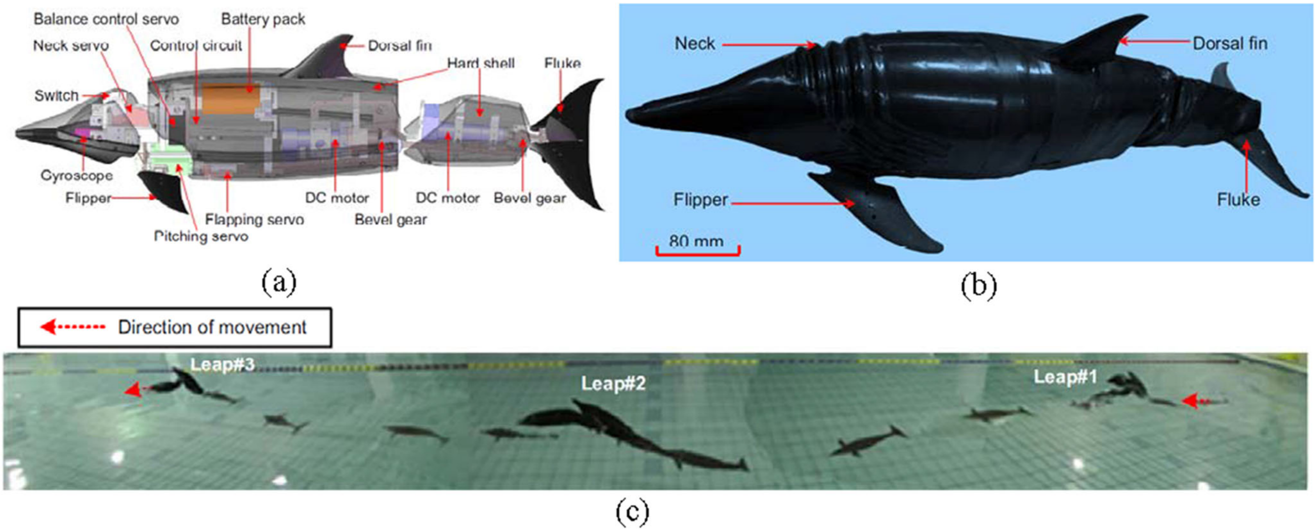


Fig. 5 Robotic dolphin from IACAS: **a** The CAD model, **b** The prototype, **c** Three continuous back-to-back leaps [45]

Overall, in these nearly three decades (since RoboTuna was created in around 1995), the designs of conventional robotic fishes based on single-joint/multi-joint mechanism evolved. It starts from the traditional one that rigid links are connected serially and flap horizontally to a big diversity, like the one that rigid links are also connected serially but flaps vertically [45], or the one that only a motor is used to drive the main axis defining the flapping patterns [31], or the one that using two independent flapping links [57]. Each design has its own advantages as well as disadvantages, but the general trend is to utilize a simpler and more robust mechanism to generate a better swimming performance.

3 Robotic Fishes Using Smart Materials

Smart materials, such as Shape Memory Alloy (SMA), Ionic Polymer Metal Composite (IPMC), and Piezoelectric material (PZT), are widely used in the designs of biomimetic robotic fishes. The use of them makes the robotic fish simple and compact. Strengths and weaknesses of those smart materials are summarized in Table 1 [58, 59]. Compared to robotic fishes with conventional actuators, this kind of robotic fish has better dynamic response characteristics and noiseless operation. However, its power efficiency and swimming performances are compromised.

When temperature changes, SMA goes through a material phase shift between the Austenite and Martensite, leading to the deformation. SMA continuously attracts attentions from researchers due to its high chemical corrosion resistance, exception from cyclic fatigue, deformation with low voltages, etc. There are different kinds of SMAs, but the most widely used one is Nickel-Titanium (Ni-Ti) alloy. Because of the good flexibility, it is a suitable alternative to the biological muscle. SMA has been adopted to construct several robotic fish systems. For example, Wang et al. built a micro robotic fish using SMA, whose fastest cruising speed, minimum turning radius and Strouhal Number

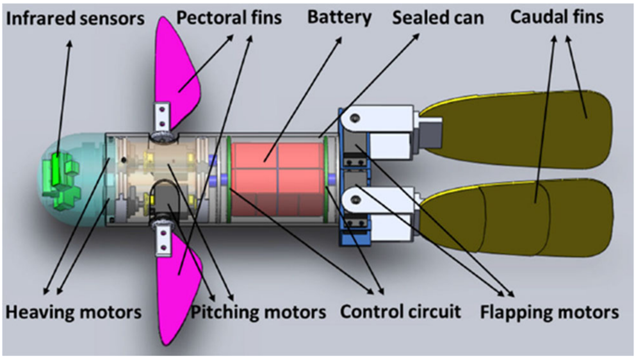


Fig. 6 The double-caudal-fin robotic fish [57]

Table 1 Smart Materials Used in Biomimetic Robotic Fishes

Smart materials	Strengths	Weaknesses
SMA	Chemical corrosion resistance	
	Free from cyclic fatigue	High nonlinearity
	Low working voltage	Low efficiency
	High power density	
	High stress	
IPMC	Low working voltage	Low power density
	Low power consumption	Low stress (0.3 MPa)
	Excellent flexibility	
	Ease to use in fluid	
PZT	High bandwidth	Low strain (1%)
	High efficiency (75%)	Low power density

were 0.75 BL/s, 0.93 BL, and 0.58, respectively. Each fin of the SMA-based robotic fish included elastic substrate, skin and the transverse SMA wires. Elastic energy storage and exchange mechanism were employed to improve the efficiency. Thermal analysis was carried out to find the proper actuation strategy [60]. Suleman et al. developed a 4-joint robotic tuna tail, each joint of which was driven by two SMA wires. Remarkably, they investigated the power consumption, thrust generation, issues of adopting SMA in robotic fish design like cooling time [61]. Zhang et al. studied the motions of pectoral fins of a live carp, and extracted four patterns from them. Then, a two degrees of freedom fin ray was proposed, which was formed by two SMA plates connected serially with their cross sections perpendicular to each other. Each SMA plate had two SMA wires embedded on two sides of a plastic plate. Five fin rays and an elastic membrane formed one pectoral fin. The simulations and experiments showed that the SMA-based pectoral fin was lightweight, capable of generating motions as the four patterns of the live carp [62].

IPMC deforms in the condition of various stimulus, such as voltage, chemicals, light, and even the magnetic field. Normally, an IPMC consists of a polyelectrolyte membrane in between two metal electrodes. When an electrical field is applied, the cations move to the negative electrode, leading to the deformation. IPMC is becoming a very promising actuator type due to the low working voltage, low power consumption, noiseless, excellent flexibility, etc. Chen et al. [63] developed a robotic fish using an IPMC beam with a passive plastic fin. They developed a model including both dynamics of the IPMC actuator and hydrodynamics, which was capable of predicting the steady cruising speed. Though, their robotic fish only achieved a maximum swimming speed of 0.58 BL/s. Guo et al. [64] developed a double-caudal-fin robotic fish based on IPMC actuators, which was 45 mm in length, 10 mm in width, and 4 mm in height. There were a buoyancy adjuster and a body posture adjuster for realizing swimming motion with three degrees of freedom. Experiments were conducted to measure the propulsive force, the cruising speed as well as the maximum lateral displacement of the tail under various voltages (frequency: 0.1-0.5 Hz, amplitude: 0.5-10 V). It was found that the propulsive force and the maximum lateral displacement would decrease with the increase of frequency of the input voltage. The direction of cruising could be modulated by controlling the frequency difference between two IPMC actuators. The maximum cruising speed of this robot was about 0.12 BL/s. To increase thrust, the undulatory locomotion (S-shape flapping) was investigated on an IPMC-driven tadpole robot, whose maximum cruising speed was 23.6 mm/s (equivalent to 0.25 BL/s) [65].

The PZT can produce voltage when subject to mechanical strain, which enables it for sensing. This is the direction piezoelectric effect. On the other hand, it can induce strain when an electric field is applied, which enables it for actuation. This is the converse piezoelectric effect. Typical PZT can produce stress in the order of 40 MPa, while its strain is much smaller, only 1%. As a result, when the PZTs are used as actuators in robotic fishes, an amplifying mechanism is usually utilized. Deng et al. [66] designed, fabricated, modeled and measured the force exerted by a centimeter scale boxfish, in which the PZT bimorph actuators drove a four-bar mechanism for motion amplification. Cen et al. [67] developed an untethered PZT driven robotic fish. It was noiseless, capable of working in a wide range of frequencies and simple in mechanical structure. To predict the thrust, a distributed-parameter electro-elastic model coupled with Lighthill's Elongated Body Theory (EBT) [68] was proposed. Experiments showed that thrust in still water was in the order of 10 mN, and the maximum swimming speed was 0.3 BL/s in the frequency of 5 Hz.

4 Compliant Robotic Fishes

Biomimetic robotic fishes based on compliant mechanisms have simple mechanical structures, ease to realize continuous motion and good mimicry of fish's body. They are made of soft materials, like silicon and elastomer, or/and driven in soft ways, like wire-driven, hydraulic or pneumatic.

Alvarado and Youcel-Toumi from MIT pioneered the usage of compliant mechanisms in robotic fish design [69–71]. Their soft robotic fishes are as shown in Fig. 7, which are made of soft polymers. Each of them employs one servomotor to generate torques for flapping. Based on the beam theory and EBT, a dynamic model is formulated to estimate the swimming locomotion in water. This robotic fish works at the dominant mode of vibration. Its maximum cruising speed is about 1.1 BL/s and Strouhal Number

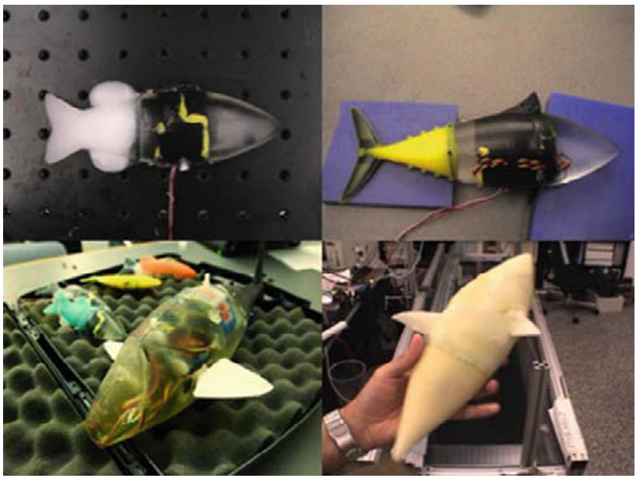


Fig. 7 Soft robotic fish driven by a servomotor [22]

is 0.86. Similar robotic fish was created in the FILOSE (Robotic Fish LOcomotion and SEnsing) project, which aimed to study how the fish sensed surrounding flow and how it reacted to the flow change [72, 73]. The tail propeller of this robotic fish was modeled as a cantilever beam and driven by a time-varying momentum.

Another soft robotic fish, also from MIT (Rus's team), adopts fluidic elastomer actuators. The earlier version (refer to Fig. 8a) aims at emulating the rapid escape response of live fish. This locomotion requires a large acceleration and continuum-body motion [74]. The robotic fish is untethered, having all the necessary components inside, such as power, actuators and a control board. After that, a latter version (refer to Fig. 8b) is built to provide a new method for close-up exploration of underwater life [75]. It differs from the earlier version in three aspects. First, a miniaturized acoustic communication module is designed and fabricated. Second, it is capable to dive deeper, up to 18 m. Third, this robotic fish is equipped with an onboard camera, enabling it to provide a close-up observation of the aquatic environment. Its maximum swimming speed is 0.5 BL/s.

One team from Chinese University of Hong Kong employs the wire-driven mechanism to mimic the skeleton structure and the muscle arrangement of live fish [76, 77]. It is one kind of underactuated mechanisms, while making the structure compact.

In the earlier version, the robotic fishes are totally rigid, neglecting the elasticity of wires [22, 78–83]. Several prototypes are as shown in Fig. 9, including the serpentine version, the continuum version, the double-segment version, the vector version and the two degrees of freedom pectoral fin version. Notably, the vector version is capable of performing not only the fish-like swimming locomotion (flapping in the horizontal plane), but also the dolphin-like swimming locomotion (flapping in the vertical plane). The double-segment version can conduct the oscillatory motion (C-shape) as well as the undulatory motion (S-shape). This robotic fish has the maximum cruising speed of 0.67 BL/s, the minimum turning radius of 0.24 BL, and the maximum turning rate of 51.4 °/s.

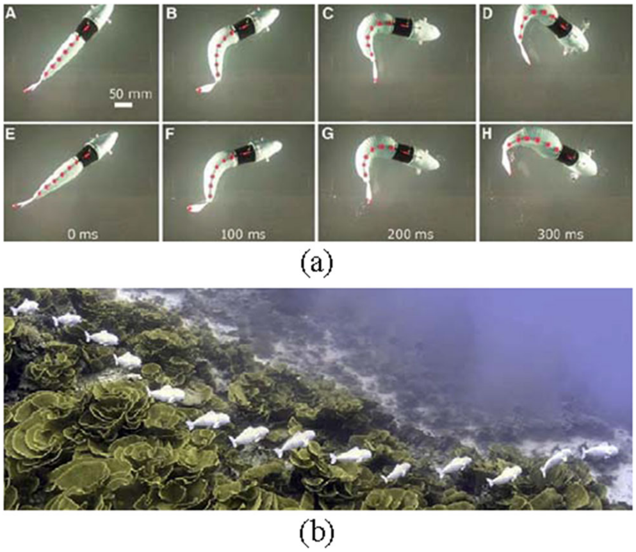


Fig. 8 Soft robotic fish driven by fluidic elastomer actuators [74, 75]

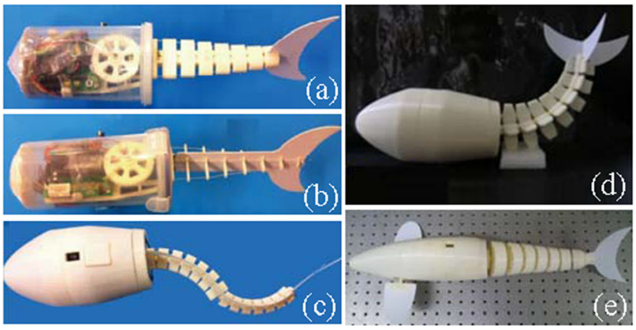


Fig. 9 The wire-driven robotic fishes [22]

In the latter version, the robotic fish is rigid-flexible coupled. Based on the thrust generation and torque distribution of live fish, a compliant tail is introduced [84, 85], which is shown in Fig. 10. By the aid of this compliant tail, the performances of the robotic fish can be significantly improved, with the maximum cruising speed of 2.15 BL/s and the peak turning rate of 457 °/s. In addition, its Strouhal Number is 0.28. The midline body curve of the robotic fish in cruising is similar with that of the live fish, especially in the posterior part where most of thrust is generated. Field experiments were carried out in Shing Mun River, Shatin, Hong Kong SAR. The robotic fish swam nearly 700 m in 40 minutes with a 500 mAh Ni-H battery.

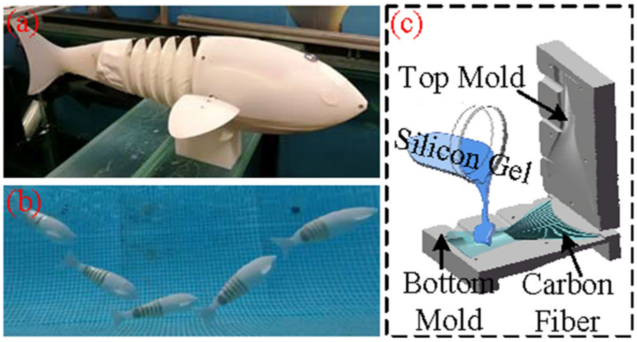


Fig. 10 The wire-driven robotic fish with compliant tail: **a** The prototype, **b** Ascending and descending, **c** Fabrication of the compliant tail [18, 85]

5 Modeling and Control of Biomimetic Robotic Fishes

The unique BCF swimming locomotion involves ever-changing interactions between the fish's body and its surrounding fluid environment, which makes modeling of the system extremely difficult. Approaches to model behaviors of fish swimming can be divided into two categories: the analytical approach and the numerical approach. The analytical approach is feasible for controller design and motion control. The first analytical model of fish swimming is the resistive force theory [86], in which viscosity plays a dominant role, and the inertial force is not considered. After that, a more pragmatic approach is Lighthill's Elongated Body Theory (EBT) and its extension, the Large Amplitude Elongated Body Theory (LAEBT) [8, 68, 87, 88]. In EBT, the force exerted on the fish's body is equal to the force exerted on the liquid by the fish's body from a reactive nature. It is based on the Momentum Conservation Law. However, EBT is only applicable to the slender fish undergoing small lateral deformation. LAEBT extends its applications to the scenario of large lateral deformation. In addition, the quasi-steady lift and drag model from airfoil theory is also widely used in modeling of the fish's body or the assistant fins [89]. For example, Mason et al. [90, 91] formulated a quasi-steady flow model for predicting the thrust of a tethered three-link robotic fish conducting planar motion. Wang et al. [92] established a three-dimensional model for their robotic fish, which had a single-joint mechanism as the main propeller and two pectoral fins for assistant adjustment. The forces, including the quasi-steady lift and drag, gravity, buoyancy, and waterjet strike force, were considered. The numerical approach, like Computational Fluid Dynamics (CFD), involves solving the Navier-Stokes equation. This approach has accurate results and can deal with complicated situations. However, it is really time-consuming and needs powerful computational capacity. Moreover, the calculation results can not be used for real-time motion control.

Motion control is another important part of biomimetic robotic fishes. Roughly, fish locomotion can be divided into two types: cruising and maneuvering [3]. In cruising, fish swims in a straight line with a constant speed, while in maneuvering, fish changes its direction and speed, resulting in motions like turning, quick start, accelerating, decelerating, ascending and descending.

Normally, the density of the robotic fish is designed the same with the density of water, so the robotic fish will not go up or down when its tail does not flap. Moreover, the center of gravity (CG) and the center of buoyancy (CB) should be in a vertical line, which is as shown in Fig. 11. The CB is at the top and the CG is at the bottom. As a result, when any disturbance in the rolling motion occurs, there will be a torque formed by the gravity and the buoyancy, which overcomes this disturbance and keep the robotic fish stable.

The robotic fishes usually utilize the pectoral fins or buoyancy-adjusting systems to realize spatial motion, like ascending and descending. In the first method [38, 85, 93, 94], assume the robotic fish cruises with velocity $\boldsymbol{U}$, and the angle between the cruising speed, $\boldsymbol{U}$, and the pectoral fin is θ. The force exerted on one pectoral fin, $\boldsymbol{F}$, is proportional to the square of the pectoral fin's velocity with respect to water [90, 91]. When θ does not equal to 0, $\boldsymbol{F}$ has a non-zero vertical component $\boldsymbol{F_y}$, followed by a torque $\boldsymbol{M}$ to change the robotic fish's pitch angle. Figure 12a and b demonstrates the robotic fish ascends and descends, respectively.

Inspired by gliders [95, 96], Fig. 13 shows a robotic dolphin with a buoyancy-adjusting system and a movable mass to realize motions of ascending and descending [52, 97]. In comparison to pectoral fins, the robot utilizing this method can surface or dive even the tail propeller does not flap. As shown in Fig. 13a, there are two oil bladders, including one outside the hull and one inside the hull. When oil is pumped between them, buoyancy of the robot changes, thus, net force between gravity and buoyancy drives the robot to move vertically. Moreover, the movable mass can change the position of CB. Correspondingly, the pitch angle of the robot is modulated. In coordination of the buoyancy-adjusting system, the robotic dolphin is capable to glide.

In practical applications, sensors are incorporated into the robotic fishes to perceive surroundings. For example, the Inertial Measurement Unit (IMU) is used to obtain orientations. Pressure sensors are employed to detect the depth. An onboard camera can provide a close-up look of the aquatic environment [75]. Currently, there are mainly two control methods of biomimetic robotic fishes, i.e., the

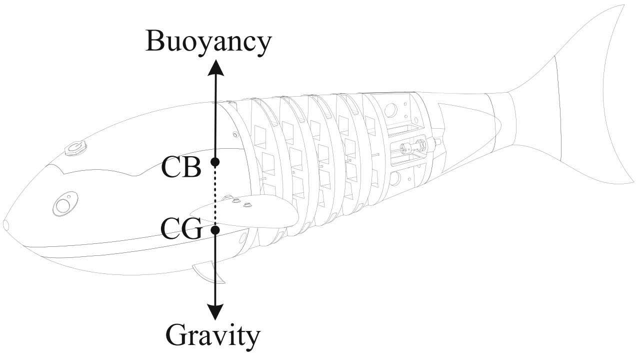


Fig. 11 The CG and CB

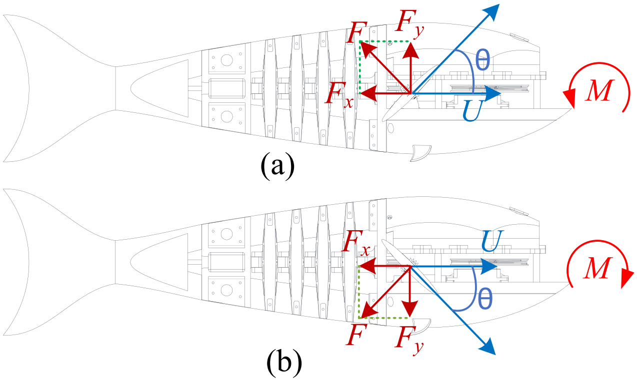


Fig. 12 Ascending and descending with the aid of pectoral fins: **a** Ascending, **b** Descending

trajectory approximation method and the Central Pattern Generator (CPG) control method [32].

The trajectory approximation method is often called the sinusoidal-based approach. That is because in nature the kinematical model of fish cruising follows a sinusoidal pattern, and the trajectory approximation method utilizes a serial-link mechanism to fit this kinematical model. The major advantage of this approach is the accurate mimicry results, both in cruising and maneuvering, since in principle it is based on live fish swimming. For example, Yu et al. [37] developed a four-link biomimetic robotic fish, which was controlled by using the trajectory approximation method. The robotic fish was designed to follow the traveling wave model of Eq. 1. The joint angles were pre-calculated and stored at a lookup table. The maximum flapping frequency and the maximum cruising speed were 2 Hz and 0.8 BL/s, respectively. Liu et al. [32, 98] proposed a kinematical model of C-shape turning, and applied it onto a three-joint robotic fish named G9, resulting in a maximum turning rate of 120 °/s. However, one major limitation of this method is that the control parameters can not be modulated online.

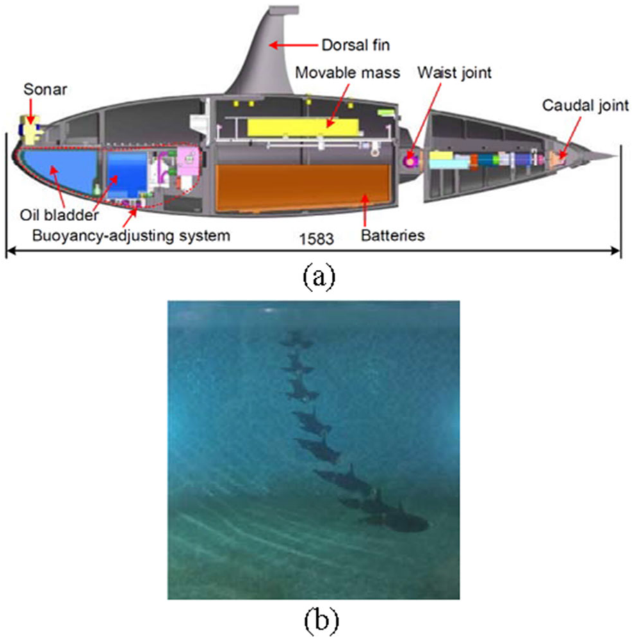


Fig. 13 Ascending and descending with the aid of buoyancy-adjusting systems: **a** Robotic dolphin with a buoyancy-adjusting system and a movable mass [52], **b** Snapshot sequence in gliding motion [97]

In contrast, CPG control method can solve this limitation very well. It is known that fish swimming is one kind of rhythmic motion, like animal walking and bird flying. Biological research reveals that in nature, the rhythmic motion may be produced by CPGs, which are neuronal circuits capable of producing rhythmic motor patterns in the absence of sensory or high-level inputs carrying specific timing information [99]. CPG has been employed in many biomimetic robots including the robotic fish. Crespi et al. [93] developed a CPG controlled amphibious robotic fish called BoxyBot, which could perform various motions, like swimming forward, swimming backwards, turning, rolling, ascending/descending and crawling. Its CPG model consisted of three coupled amplitude-controlled phase oscillators. Wang et al. [46] formulated a CPG model for a multi-joint robotic fish with a pair of flexible pectoral fins. In particular, the parameter sensitivity of the CPG network was analyzed and the stability was proved. Westphal et al. developed a robotic Sea Lamprey, which was driven by SMA and controlled by CPG. Various sensors, including a compass, accelerometers, inclinometers and a short baseline sonar array (SBA), were mounted on the robot and providing feedback data to the CPG network [100]. Recently, Yu et al. [42] developed a real-time energy measurement system compatible with a CPG based controller, and deployed them on an untethered two-joint robotic fish. They tried different sets of CPG parameters and studied how these parameters would affect the energy consumption.

6 Concluding Remarks

This paper provides a general survey on the designs of biomimetic robotic fishes, which starts from the single-joint/multi-joint design, to the design utilizing smart materials, and the design based on compliant mechanism. The evolution direction is to utilize a simpler and more robust mechanism to enable the biomimetic robotic fishes to mimic their counterparts in nature better, and obtain better swimming performances. Table 2 summarizes strengths and weaknesses of different kinds of biomimetic robotic fishes. The single-joint/multi-joint robotic fish is well developed, representing state-of-the-art in terms of swimming performances. However, it has a complex mechanical structure and is rather

Table 2 Designs of biomimetic robotic fishes

Mechanism	Strengths	Weaknesses
Single-joint/ Multi-joint robotic fish	1. Well developed 2. Great swimming performances	1. Complex mechanical structure 2. Noisy
Robotic fish using smart materials	1. Simple mechanical structure 2. Good dynamic response characteristics 3. Noiseless 4. Cost is relatively low	1. Low power efficiency 2. Low swimming performances
Compliant robotic fish	1. Good mimicry of live fish 2. Simple mechanical structure 3. Continuous motion 4. Good swimming performances 5. Cost is relatively low	1. Complex modeling method 2. Precise control of the fish's body is difficult

noisy. Normally, this kind of robotic fish may work as a mobile platform, just like ROV (Remotely Operated Vehicle) or AUV (Autonomous Underwater Vehicle). Different features are realized by being equipped with different functional modules, e.g., sonar, Doppler Velocity Log (DVL), underwater acoustic communication module, which makes the cost vary significantly. The robotic fish based on smart materials has a simple mechanical structure, good dynamic response, and noiseless operation, while its power efficiency and swimming performances are unsatisfactory in comparison with the single-joint/multi-joint robotic fish. The compliant robotic fish offers a balance between them, which has a simple mechanical structure and good swimming performances. In addition, it can better resemble behaviors of live fish and is capable of conducting continuous motion, but modeling and precise control of it are difficult. The cost of the robotic fish based on smart materials and the compliant robotic fish is relatively low, usually within hundreds of U.S. dollars. In conclusion, major challenges of current research in this field include but are not limited to the followings:

(1) **The performances of existing biomimetic robotic fishes are far behind those of live fish.** Table 3 summarized the fastest swimming speed, the Strouhal Number and the number of actuators for flapping of representative biomimetic robotic fishes in selected literature. First, it is seen that iSplash II is in the top of this list, whose fastest swimming speed is up to 11.6 BL/s, far beyond others. However, it is not capable of multimodal swimming, like turning, ascending or descending. Second, the robotic fishes whose swimming speeds are above 3 BL/s are all driven by motors. This type of robotic fishes still represents state-of-the-art in terms of swimming speed. Third, most of the swimming speeds are in the range between 0.06 BL/s and 2 BL/s, which are far behind that of live fish. Fourth, most of Strouhal Numbers are in or close to the narrow range between 0.2 to 0.4, indicating that locomotion of the biomimetic robotic fishes is efficient. Table 4 shows the maximum turning rates of typical robotic fishes, which sees that the turning rates distribute between 30 °/s and 670 °/s. In contrast, a live fish can easily swim up to 8 BL/s and turn as quick as 4000 °/s [101]. The factors of this situation are various, including the energy density of actuators, efficiencies of the design and control methods, number of actuators, etc.

(2) **Communication methods among multiple biomimetic robotic fishes in water and the operation station on land are not satisfactory.** Currently, there are two kinds of communication methods—the wired communication method and the wireless communication method. On one hand, the wired communication involves an electrical cable supplying power and transmitting signals. In this situation, the robotic fish is tethered, and the operating distance is subject to the length of the cable. One the other hand, the wireless communication includes the electromagnetic wave communication and the underwater acoustic communication. The electromagnetic wave communication has a faster transmission rate, whereas it attenuates quickly in water. Currently, the most commonly used frequency of the electromagnetic wave in robotic fish

Table 3 The fastest swimming speed, strouhal number and number of actuators

Robotic fish	Highest swimming speed (BL/s)	Strouhal Number	Number of actuators
iSplash II [31]	11.6	0.34	1
ICHTHUS V5.7 [102]	4.0	–	3
iSplash I [103]	3.4	0.41	1
Single-joint robotic fish from CAS [49]	3.07	–	1
Robotic fish driven by PZT [104]	2.9	–	1
Robotic dolphin [38]	2.3	0.32	2
Wire-diven robotic fish from CUHK [84, 85, 105, 106]	2.15	0.28	1
The double-caudal-fin robotic fish [57]	1.21	–	2
Multi-joint robotic fish from CAS [35, 44]	1.15	–	4
Soft robotic fish from MIT (Youcef-Toumi’s team) [70, 71]	1.1	0.86	1
G9 from University of Essex [32]	1.02	–	3 or 4
Robotic fish from Beihang University [107, 108]	0.98	0.375	–
i-RoF [109]	0.85	–	2
RoboTuna [110]	0.80	0.18	6
Robotic fish powered by SMA [111]	0.75	0.58	1
Multimodal swimming robotic fish [46]	0.66	–	4
Amphibious robotic fish from CAS [33]	0.64	–	4
VCUUV [24, 25]	0.61	–	–
Soft robotic fish from MIT (Rus’s Team) [75]	0.5	–	1
Tensegrity robotic fish [112]	0.7	0.45	1
RoboPike [26, 27]	0.3	–	3
Robotic fish powered by PZT [67]	0.3	–	1
Tadpole robot driven by IPMC [65]	0.25	–	1
Micro robotic fish driven by IPMC [64]	0.12	–	2
Continuous robotic fish driven by SMA [113]	0.10	1.32	1
Robotic fish from BUAA driven by IPMC [114]	0.075	–	1
Robotic fish from NYU driven by IPMC [89]	0.06	–	1

is 433 MHz. Even though, the signal disappears when the robotic fish works in tens of meters of depth. In contrast, the underwater acoustic communication method has better penetration capability, up to tens of kilometers. However, its transmission rate is low in comparison with other communication methods.

(3) **The headshaking problem in cruising has not been solved.** When the robotic fish flaps, due to the reactive force from water, there will be a periodic torque in the yaw motion. As a result, the head of the robotic fish swings from side to side, leading to the increase of drag and decrease of cruising performances. In contrast, the live fish is capable of coordinating all the muscles along its body, and making the reactive force in the sway direction cancel each other out. Limited by current robotic technologies,

Table 4 The maximum turning rate and number of actuators for turning in selected literature

Robotic fish	Maximum turning rate	Number of actuators for turning
Multi-joint robotic fish from CAS [43]	670	4
Wire-driven robotic fish from CUHK [85]	457	1
G9 from University of Essex [32]	120	3 or 4
VCUUV [24]	75	–
Robotic fish from BUAA [115]	60	2
Robotic fish from LZJTU [116]	34	5 (3 of the tail propeller 2 of the pectoral fins)
Robotic fish enabled by motor and water electrolyser [117]	30	2

such as actuator's properties, sensor's properties and computational capacity, it is difficult to address this problem for the robotic fish in the same way as live fish. Even though Lighthill [8] theoretically introduces three methods to mitigate this problem, and subsequent researchers make efforts through optimization of the body shape [118], mass distribution [119] as well as body flapping pattern [120], no existing robotic fish can completely overcome this problem so far.

(4) **Modeling of the biomimetic robotic fish is complicated.** As for kinematics, the midline body curve of a BCF swimmer can be described by a traveling wave model of Eq. 1, which is only applicable for cruising. To address this problem, an interesting methodology proposed by Liu et al. considered the relative movements of the tail propeller to the fish's head, and an integral swimming pattern was presented to describe both cruising and C-shape turning [121]. In comparison to kinematics, dynamic modeling of biomimetic robotic fish is much more complex. At present, the most commonly used and most pragmatic method to model the biomimetic robotic fish is Lighthill's EBT and LAEBT [68, 88]. Yet, they were proposed nearly 50 years ago. The development of modern computational technologies provides a more precise way to model the robotic fish and its surrounding fluid environment. However, it is really time-consuming and not applicable for the real-time closed-loop control. More recently, models of fish swimming may be completely developed based on experimental data, which is known as the data-driven or data-assisted method [122, 123]. However, it requires tremendous information, and even a minor change of the design can lead to large errors of the model.

In terms of the mentioned challenges, promising research directions to push the boundary on this field may be:

(1) **Multi-fin coordination control.** In nature, multiple fins, including the dorsal fin, the anal fin, and the pectoral fins, play a very important role in fish's cruising, turning, braking, and stabilization. The dorsal and anal fins have similar functions in cruising. Drucker et al.. utilized Digital Particle Image Velocimetry (DPIV) to visualize bluegill sunfish's wake structure, finding that flapping of the caudal fin lagged behind the dorsal fin. This resulted in inverse Von Karman Wake and a 12% increase of thrust [124]. Mignano et al. conducted a computational study, finding that the amplitude and shape of thrust were influenced by the relative positions among the caudal fin, the dorsal fin, and the anal fin [125]. Zhong et al.. found that when the dorsal fin become sharper, the swimming speed and efficiency could have 15% and 50% increase, respectively [126]. Wen et al.. implemented a biomimetic robotic fish, whose median fins were fabricated by using multimaterial 3D printing, to study the linear acceleration of fish swimming. It was found that when the soft dorsal/anal fins were erected, the linear acceleration could be significantly improved up to 32.3% and the magnitude of the side force oscillation decreased by 24.8% [127]. Han et al.. utilized a 3D teleost fish model to study how the dorsal/anal fins areas and their flapping phases with caudal fin affected the thrust and efficiencies, finding that the thrust and swimming efficiency could be improved by 25.6% and 29.2% simultaneously because the caudal fin leading edge vortices were strengthened by the posterior body vortices. Moreover, the presence of the dorsal and anal fins could also decrease the drag [128]. According to the above studies, it is seen that the dorsal and anal fin have positive effects on the fish cruising performance, such as the swimming speed and efficiency. However, it is also seen that most are only computational studies, or conducted on a fixed/semi-fixed platform. The working principles of various fins are not fully understood, and their applications are limited. If we can utilize newly developed technologies, such as Artificial intelligence (AI) and 3D imaging, to explore the working principles and integrate them into the design, modeling, and control of a biomimetic robotic fish, the swimming performances can be further improved. In addition, flapping of the dorsal and anal fins generate a lateral force. This force can be used to overcome the lateral force produced by the flapping tail propeller, thus, decrease or even eliminate the headshaking problem.

(2) **Confusion of multiple sensors and artificial intelligence.** Currently, intelligence of robotic fishes is relatively low. One major reason is its poor perception of surrounding environments. The underwater world is complex, unpredictable and even dangerous. Cameras [94, 129], GPS [130], Doppler velocimeter, inertial measurement unit [18], depth sensor [131], sonar, are integrated into the robotic fish's design and control, but their capacities are limited by the medium of water. For example, cameras are affected by luminance, headshaking, turbulence and clearity of water. The GPS signal become weak when the robot dives. More recently, some interesting works are reported in terms of underwater sensing and communication. Wang et al.. developed a bio-inspired electrocommunication method capable of 1k baud rate in the range of 3 meters [132, 133]. Artificial lateral lines, consisting of arrays of pressure sensors, can detect inverse Von Karman vortex generated by adjacent robots [134].

Yu et al.. developed a miniature sensor, installed in the tail end, to enable real-time measurement of angle-of-attack relative to the flow [51]. In the future, information obtained from multiple sensors can be fused to provide a more comprehensive map of the robot's surroundings. By utilizing artificial intelligence, such as reinforcement learning, sufficient surrounding information are used to train the robotic fish, enabling it with the ability to make decisions in complex and unknown environment. To this end, the robotic fish is becoming more intelligent and more autonomous.

(3) **Multi-agent control among multiple biomimetic robotic fishes.** It is known that fishes live in groups, demonstrating highly efficient group-level capacities to capture prey, escape from enemies, migrate, etc. The biomimetic robotic fishes provide a feasible method to study these collective behaviors among fish schools, or among live fishes and robots. For example, Bonnet et al. demonstrated collective decision making about swimming directions between a shoal of zebrafish and a group of robotic fishes [135]. Swain et al. introduced a cyber-physical implementation of a real-time feedback-controlled robotic fish capable to respond to a school of fishes and environment features [136]. An IPMC-based robotic fish developed by Aureli et al. succeeded to engage a shoal of golden shiners [89]. These studies can be used to guide the cooperation control among multiple biomimetic robotic fishes, which has great potentials in offering an agile, efficient and powerful solution for various applications, like reconnaissance, goods transportation and environment monitoring. Ryuh et al. developed a multi-agent robotic fish system to collect marine information, like water temperature and pollution level [137]. Even so, the demonstration of multiple robotic fishes as a stable group, just like its counterpart in nature, is not yet realized so far. One reason may be the lack of robust bottom-level motion control system [138]. Moreover, how to share information among individual robotic fishes, how to respond as a group, how to properly settle multi-task allocations are the questions needed to be well answered before the practical applications of multiple robotic fish systems. Recently, the prosperous development of artificial intelligence and swarm intelligence sheds light on the settlements of these problems. Leveraging the strong learning capability of artificial intelligence, collective behaviors observed from the live fish groups can be used to train the robotic fishes. And the newly-developed swarm intelligence algorithms can also be applied to the multiple robotic fish system to enhance the autonomy and decision-making capability.

(4) **Novel actuators.** Actuation is the foundation of a robotic system. On one hand, traditional DC motors and servomotors dominate the designs of biomimetic robotic fishes, and they also represent state-of-the-art regarding to swimming performances. Please refer to Table 3, from which it is found that robotic fishes whose highest swimming speeds are over 3 BL/s are all driven by motors. On the other hand, the robotic artificial muscles possesses characteristics extremely suitable for biomimetic robots, i.e., large power-to-weight ratios, large range of motions, inherent compliance, no need of cumbersome mechanisms [58]. Recently, there is a trend to utilize them in biomimetic robotic fishes. Most of those works focus on the design [139], fabrication [140, 141], modeling [142] and control [74]. The key challenge is that how to achieve desirable soft body motions using smart materials that integrate sensors, actuators and computation [143]. Even though most of the biomimetic robotic fishes based on smart materials currently do not have excellent swimming performances, they outperform the robotic fishes driven by motors in some ways, like noiselessness, light weight and compact mechanical structure. In the future, in addition to SMA, IPMC, PZT, more artificial muscles, like dielectric elastomer actuators (DEAs), shape memory polymer (SMP) actuators, soft fluidic actuators, twisted string actuators (TSAs), and supercoiled polymer (SCP) actuators, may be applied, flourishing this field and pushing the boundary of it.

Author Contributions

- Fengran Xie: conceptualization; data analysis; draft the manuscript
- Qiyang Zuo: literature search;
- Qinglong Chen: literature search
- Haitao Fang: funding acquisition; data analysis
- Kai He:revise the manuscript; funding acquisition; resource
- Ruxu Du: revise the manuscript; supervision; funding acquisition
- Yong Zhong: review; data analysis; edit
- Zheng Li: review; edit

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Declarations

Ethics approval The manuscript is not submitted to more than one journal for simultaneous consideration. The submitted work is original and has not been published elsewhere in any form or language (partially or in full).

Consent to Participate Written informed consent was obtained from every author.

Conflict of Interests The authors declare that they have no conflict of interest.

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