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SURVEY PAPER

A Review of Locomotion, Control, and Implementation of Robot Fish

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Abstract

A comprehensive review of bio-inspired robot fish is presented in this paper with an emphasis on locomotion, actuation, and control methods. Different swimming modes of biological fish, such as Body and/or Caudal Fin propulsion (BCF) mode and Media and/or Paired Fin propulsion (MPF) mode, with their classification, are discussed in detail. Furthermore, the mechanics' principles behind the locomotion, both kinematic and dynamic, are also introduced. In addition to dynamic modeling, motion control is also one of the key problems in the research of robot fish. In this paper, in addition to the classic control methodologies used for rigid robot fish, we also summarize the control approaches for soft robot fish, and the intelligent control based on machine learning that emerged in recent years. With basic ideas bear in mind, we will introduce two typical examples illustrating how to utilize these principles in the robot fish design. In the end, the potential research gaps and future research directions are summarized.

Keywords Bio-inspired · Robot fish · Fish locomotion · Actuation · Control

1 Introduction

More than 70% of the surface of our planet is covered by water, dominated by fish. With millions of years' evolution, fish can exhibit astonishing performance and energy harvesting ability. For example, the rainbow trout extracts energy from the oncoming vertices, and even dead trout fish can be propelled upstream [1]. Fish also demonstrates extraordinary propulsion efficiencies, superior acceleration, and excellent maneuverability [2]. Therefore, learning the morphology and swimming behaviors of fish, and implementing those principles into the design of robot fish opens a new door for the next generation underwater vehicles [3]. Nowadays, bionics has emerged at the historic moment, providing many ideas for the design of new forms of underwater vehicles. Inspired by biological systems, through learning, imitating, copying and recreating their structure, function, working principle and control mechanism, the existing underwater robots can be improved, and brand new forms of underwater vehicles—biologically inspired robotic underwater vehicles, or in short, robot fish—has appeared [4–6].

Suggested by its name, a robot fish is the outcome inspired by the morphology of its bionic counterparts, aiming at achieving similar shape and swimming locomotion. In the past years, the idea of robot fish has attracted continuously increasing attentions academically and publicly. Prompted by both scientific and commercial needs, we have witnessed a boom in the development of robot fish. Since the first robot fish—RoboTuna was built in 1994 [4], the idea of bio-inspired robot fish has gradually become a hot spot [7]. It imitates the shape and movement pattern of biological fish to achieve high-efficient and fast movement [8]. The development of robot fish is the outcome of robust combination of comprehensive research realms, such as bionics, mechanics, electronics, automatic control, and material science. Compared to the classic rigid-form underwater robots, e.g., the widely used Autonomous Underwater Vehicles (AUVs), the robot fish has the advantages of advanced maneuverability, high propulsion efficiency, and low noise [9]. Underwater robots using traditional propellers will produce lateral eddy currents during propeller rotation, which increases energy consumption, reduces propulsion efficiency, and is noisy [10]. Imitating the swimming propulsion mode of fish, the development of high-efficiency, low-noise, flexible and

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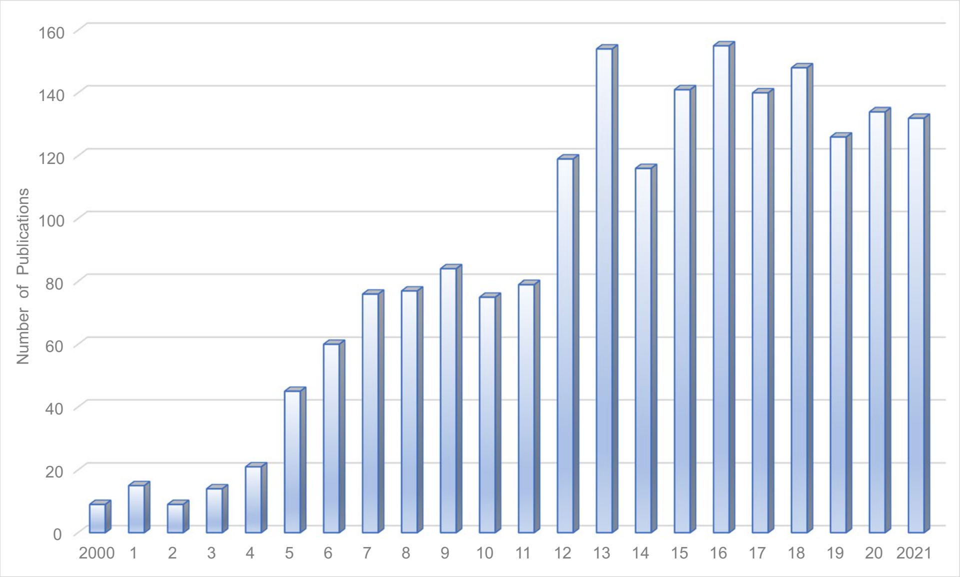


Fig. 1 Number of publications on robot fish each year

mobile robot fish for underwater operations in complex environments has become the goal pursued by researchers [11, 12]. As shown in Figs. 1 and 2, the related research is attracting more and more attention.

This paper is dedicated to providing an extensive introduction on the robot fish locomotion, control and physical design implementation. Instead of introducing the robot fish development following the timeline, we categorize the representative robot fish designs into genres and stages. In spite of the extensive reviews in the literature, as summarized in Table 1 with their specific review focus, a detailed survey on the approaches to implement the biological fish swimming principle into robot fish design is less studied. In recent years, significant developments in the continuum mechanism, smart and soft materials have enriched the realms of robot fish study and continue to break the performance limit of robot fish, which are worth to be reviewed. To ease the readers with a straightforward access to specific area of robot fish research that they are interested in, the state-of-the-art is classified and illustrated in tables, based on different design focuses, e.g., locomotion study, dynamics, control, materials, and others, along with the analyses of each development milestones and the room for improvements. In addition to thorough reporting the latest research achievements and analyzing the future research directions, this paper is also unique by providing two typical paradigms covering both rigid and soft robot fish in details, to elucidate the approaches in applying fish swimming morphology into robot fish design.

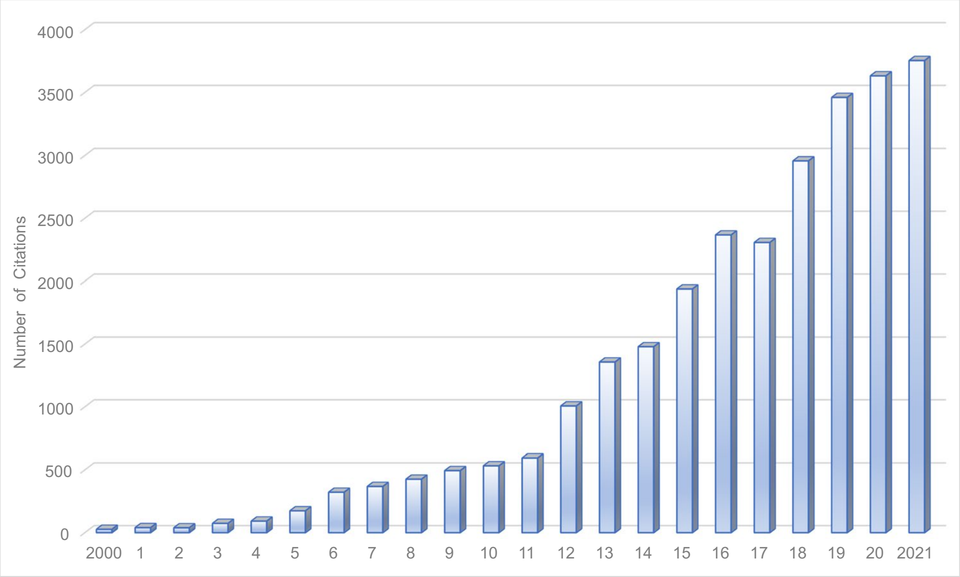


Fig. 2 Number of citations on robot fish each year

Table 1 A summary of current robot fish reviews in the literature

Robot fish principle	Review details
• Swimming morphology	• Biological fish swimming locomotion and their inspiration for robot fish design [13–19] • Hydrodynamics research on fish interaction with the liquid environment [16, 17, 20–23]
• Robot fish mechanism design	• Multi-joint rigid robot fish and actuation/propulsion design [13–15, 22, 24, 25] • Soft robot fish design and actuation [24–30]
• Robot fish component design	• Smart materials including Ionic Polymer Metal Composites (IPMC), and Shape Memory Alloys (SMA) [13, 18, 31–33] • Robot fish sensing systems [13, 17, 28, 34–38]
• Robot fish control	• Localization and motion control of robot fish [16, 17, 23, 25, 30, 36] • Swarm cooperation of multiple robot fish [21, 35, 39]

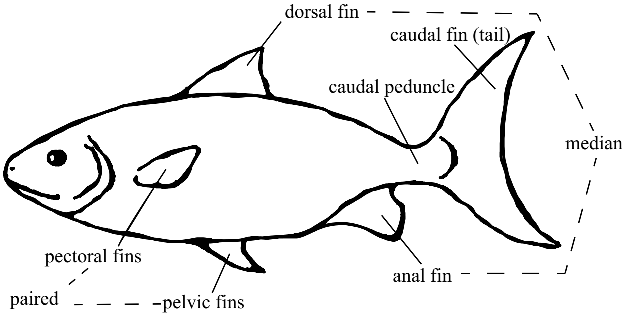


Fig. 3 Morphological features of fish

This paper is organized as follows: being the fundamental of robot fish design, we will first introduce the principles behind the biological fish locomotion in Section II. Afterwards, in Section III, we will elucidate the general design considerations for building a robot fish, namely actuator, materials, and overall layout. Section IV focuses on control aspects from both algorithm and hardware. Section V elaborates on examples to show the general process and principle of designing a robot fish, and analyzes design trade-offs in different application scenarios. Lastly, Section VI provides an overview in robot fish technologies and applications, as well as an prediction of the future research opportunities of robot fish.

2 Biological Fish Fundamentals

2.1 Fish Locomotion Types Overview

The robot fish is promoted by imitating the swimming mode of fish, with its classification divided according to that of fish swimming. Thus, being familiar with the types of fish swimming is significant to grasp the big picture of robot fish. Fish or cetaceans commonly use tail-wagging as the main propulsion method, supplemented by other fins, such as pelvic fins and anal fins, as auxiliary sources of thrust or to control the direction of travel. Figure 3 shows the commonly-adopted terminologies on the description of fish morphology [15].

The fish swimming types classification scheme and nomenclature are originally proposed by Breder [40]. Lindsey [41] and Webb [42] concluded the above classification into two modes according to the different body parts used by propulsion: Body and/or Caudal Fin propulsion (BCF) mode, and Media and/or Paired Fin propulsion (MPF) mode [19]. The BCF mode waves a certain part of the body and the tail fin to form a backward propulsion wave. Around 85% fish use this method of propulsion [43]. BCF mode can achieve continuous, fast and efficient swimming. The dorsal, anal, pectoral, and pelvic fins of most fishes are only used to assist in propulsion and adjust posture; on the other hand, the MPF mode fish, which accounts for about 15% of the total fish population [43], use these fins as their main propulsion components [44]. In spite of owning good stability and high mobility, the MPF mode is accompanied by slow swimming speed [36].

Furthermore, both BCF and MPF modes can be divided into two movement types: undulatory or oscillatory. In undulatory motions, the propulsive structure, e.g., tail, shows the passage of a wave along the main axis. On the other hand, there is no wave feature on the propulsive structure in oscillatory motions. Instead, the propulsive structure, e.g., tail, swivels on its base [19]. However, undulatory movements can evolve into oscillatory movements by increasing the undulation wavelength. In addition, fish swimming can also be divided into smaller segments based on the propulsor. A detailed classification on fish swimming modes is illustrated in Fig. 4 [41].

In the following subsections, each segment is explained in detail with specific examples.

2.1.1 BCF Swimming Mode

Categorization of the BCF mode can be determined in standards such as five forms by different wavelength, propulsive wave amplitude envelop, and thrust generation methods [19, 24], as shown in Fig. 4(a). It is noteworthy that there is no clear boundary between undulatory and oscillatory in the

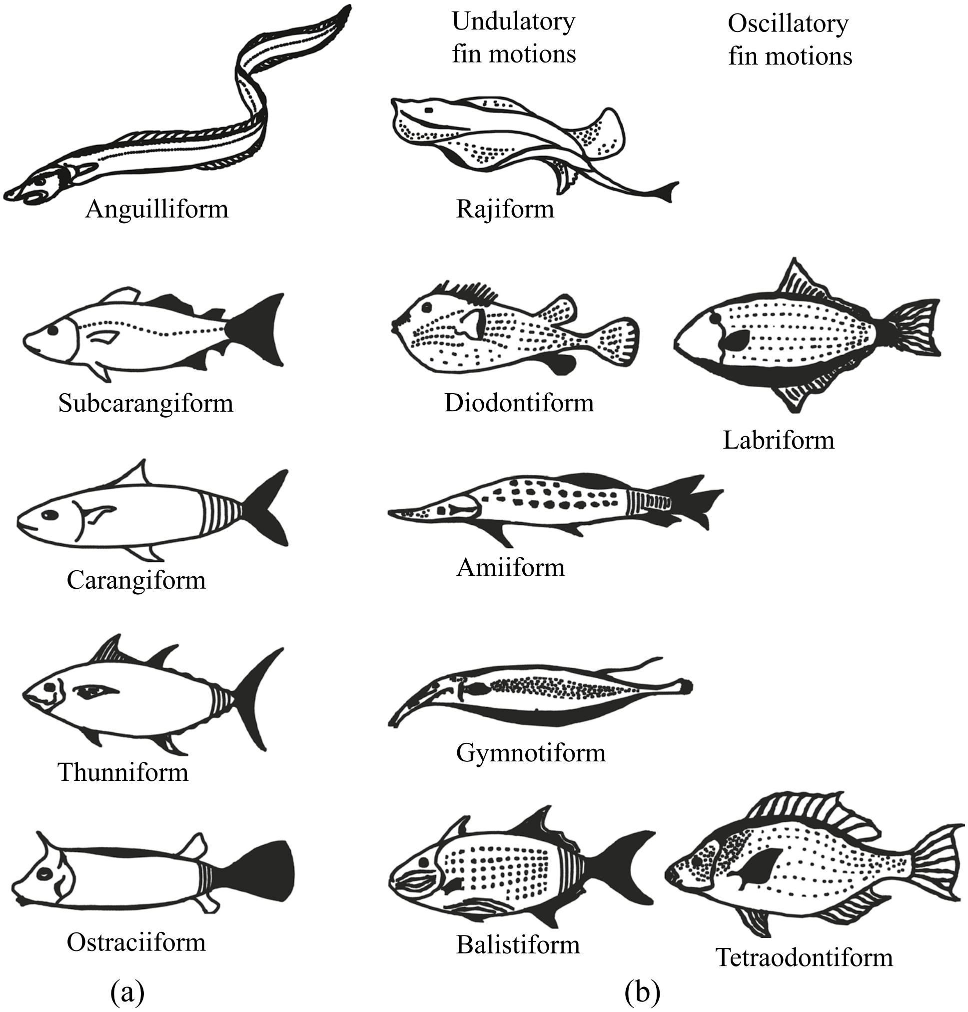


Fig. 4 Fish swimming with (a) BCF mode, and (b) MPF mode, where the thrust generation is highlighted in shaded areas

BCF mode. From anguilliform to ostraciiform, the movement type is transited from undulatory motion to oscillatory motion.

1. Anguilliform mode: eel being a typical example adopting this form. An apparent feature for anguilliform lies in the large amplitude of the fish body bend undulations. During the anguilliform swimming, at the minimum one complete wavelength can be passed along the fish body, leading to negligible yaw moment and tendency to recoil. Due to this feature, one distinguished characteristic of anguilliform swimmers, such as eel and lamprey, is that, they can move backward by reversing the direction of the propulsive wave. As a result, this mode allows high maneuverability, accompanied with low swimming speed [45].
2. Sub-carangiform mode: half of the fish body being involved in the undulations, leading to improved swimming speed. As a result, sub-carangiform fish is typically faster than anguilliform, with the price of decreased maneuverability.
3. Carangiform mode: including trout, herring, etc. One apparent feature is that the body part involved in the undulation is significant—about one-third of the posterior body length. As the most common form, it demonstrates faster speed, and suffers lower maneuverability.
4. Thunniform mode: typically seen in tuna, cetaceans, etc. It is significantly interesting by showcasing the optimal efficiency among all types of swimming modes. In thunniform mode, the caudal fin contributes more than 90% to the propulsive forces, leaving the rest produced by the added mass effect due to the lateral undulations near the peduncle; meanwhile, thrust can be generated during lift [46]. Fish adopting this swimming mode is distinguished by the ability to maintain high cruising speed for a long period of time, namely, the scombridae, including the tunas, mackerels and bonitos. This is achieved by minimizing the pressure drag due to the slender, streamlined fish body during forward motion, while reducing induced drag by lift generation thanks to the relatively stiff, crescent moon shaped caudal fin.

5. Ostraciiform mode: both the fish body and caudal fin are relatively stiff. For ostraciiform swimmers, the stiff caudal fins oscillate like a pendulum to create high speed locomotion, while compared to their thunniform counterparts, which have relative soft body, the rest of the fish body remains rigid. Besides, ostraciiform swimmers have lower hydrodynamic efficiency than the thunniform swimmers [47].

2.1.2 MPF Swimming Mode

Compared to the BCF, the MPF mode, on the other side, performs an undulatory locomotion accompanied by low speeds and improved maneuverability. In spite of the wide applications in nature, the MPF is less investigated partially due to its complexity. The MPF mode encompasses diodontiform, gymnotiform, amiiform and balistiform locomotion, as classified in [19].

1. Rajiform: as a combination of undulation and oscillation, the rajiform has inherent advantages of high maneuverability. Significantly large pectoral fins—the lateral expansion of the fish body—are used, which may lead to two different types of locomotion, namely the undulatory or oscillatory locomotion [19]. With an increased undulation amplitude from the anterior body to its posterior counterpart, a wave is generated in undulation mode. The oscillatory mode, on the other hand, depends on the fast-flapping fins with larger amplitude to produce a wave, similar to the wings of a flying bird.
2. Diodontiforms: with vertical and undulatory pectoral fins, the undulation is possibly formed of two different wavelengths simultaneously at each instant: along up-down and flapping. The vertical component of forces produced by the pectoral fins will provide up-down motions; at the same time, the pectoral fins will also create flapping motion accompanied with labriform mode. Consequently, though slow, diodontiform swimmers showcase precise manoeuvrability provided by the combination of these two modes, the blowfish being a typical example belonging to this category.
3. Gymnotiforms: using anal fin for undulation, instead of dorsal fin being used in amiiforms to achieve the similar locomotion. The South American electric fish is a typical paradigm adopting gymnotiform mode. A distinctive feature of gymnotiform is that it does not possess dorsal and caudal fins, or at least significantly small caudal fins, but having elongated anal fins. Due to this feature, in terms of reversing the rapid undulation direction of anal fins with short wavelength, fish with gymnotiforms can perform both backward and forward swimming [41].
4. Amiiforms: using the long dorsal fin to undulate for propulsion. The dorsal fin of amiiforms can see up to seven waves passing on it during undulation, with various range of undulation amplitude. The Gymnarchus niloticus—a freshwater fish in Africa—is a typical paradigm adopting amiiform for its swimming locomotion.
5. Balistiforms: defined for those swimming modes in which the dorsal and anal fins undulate simultaneously to create the propulsion. The undulation of the dorsal and anal fins creates a set of half-sized waves that can be seen on the fins. During undulation, both fins work together in an evolutionarily optimal way to efficiently produce horizontal forces to propel the fish forward.

MPF locomotion is normally composed of Tetraodontiform and Labriform, mainly in terms of the type of fins used and oscillatory mode [19].

1. Tetraodontiforms: puffer fish being a typical tetraodontiform swimmer. The propulsion mainly depends on the side-to-side flapping motion of dorsal and anal fins, which is similar to balistiforms. It is noteworthy that, both dorsal and anal fins flap in the same way as the caudal fins for ostraciiform.
2. Labriforms: angelfish being a representative in this category. While swimming, the narrow pectoral fins of angelfishes are able to provide both types of oscillatory motions: flapping and rowing. Another example is the bird wrasse, whose pectoral fins are also dominated by flapping motion [48].

Based on the discussion above, a comparison on different fish locomotion types and their corresponding characteristics is summarized in Table 2.

2.2 Kinematics

For robot fish, as the basis for the design of the mechanical structure, motion parameters, and the control system, establishing an mathematical model to accurately describe the fish motion characteristics is crucial. Hence, being one of the key issues—a steady-state kinematic model—needs to be solved in the robot fish study.

Taking the Carangiform as an example, as shown in Fig. 5, a top view of a Carangiform fish shows the parameters and variables to describe the kinematics of the fish. A body-fixed frame $\mathcal{F}$ is attached at forefront of the fish body, with x-axis aligned with the forward-backward direction. Having a full length of l, the body is swimming forward at an average speed of U along the negative direction of the x-axis. The blue dashed line represents the centerline of the fish body, and its lateral offset relative to the median plane $h(x,t)$ propagates to the back of the body at a wave speed of V and a wavelength of λ along the positive x-axis direction. For uniform linear swimming, the centerline of the fish body

Table 2 A comparison on different fish locomotions

Locomotion		Example	Features	Maneuverability	Speed
BCF	Anguilliform	Eel	Hyper-redundant and whole body undulation	High	Low
	Subcarangiform	Herring	Undulation of posterior half of the body	Medium	Medium
	Carangiform	Trout	Undulation of one-third of the posterior body length	Low	High
	Thunniform	Tuna	Undulation of peduncle and caudal fin	Lowest	Highest
	Ostraciiform	Boxfish	Stiff body; pendulum-like oscillation of the (relatively stiff) caudal fin	High	Low
MPF undulatory	Rajiform	Manta ray	Large flexible triangular shaped pectoral fins	Medium	Low
	Balistiform	Triggerfishes	Simultaneous undulation of the dorsal and anal fins	Low	Low
	Gymnotiform	Knifefish	Undulation of elongated hyper-redundant anal fins	High	Medium
	Diodontiform	Porcupinefish	Broad undulating pectoral fin	High	High
	Amiiform	Bowfin	Long dorsal fin	Low	High
MPF Osillatory	Tetraodontiform	Puffer	Flapping motion of dorsal and anal fins for propulsion	Low	Low
	Labriform	Wrasses	Narrow pectoral fins to generate both flapping & rowing motions	Low	Low

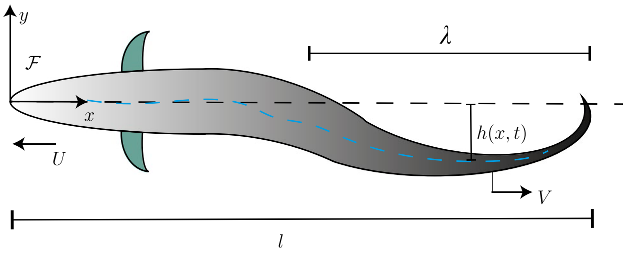


Fig. 5 Top view of Carangiform fish

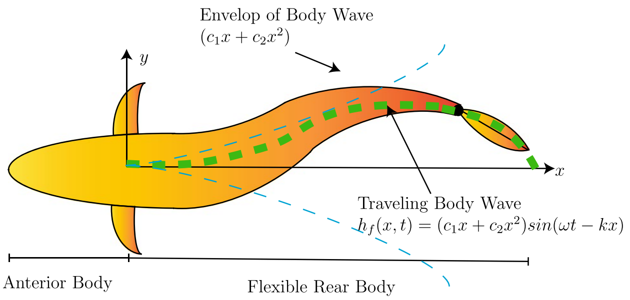


Fig. 6 Swing illustration of Barrett's lateral movement equation

always stays on the x-y plane, with its amplitude becoming larger from beginning to end. The specific waveform can be observed by the high-speed shooting of fish swimming, post-processing images and fitting. Videler [43] proposed a model that fits the fish's lateral movement h_f with six Fourier coefficients a_j, b_j ($j = 1,3,5$):

$$h_f(x,t) \approx \sum_{j=1,3,5} \left[a_j(x)\cos(2j\pi t/T) + b_j(x)\sin(2j\pi t/T)\right] \quad (1)$$

where T is the motion period. It is noteworthy that the first Fourier frequency has more significant influence on the amplitude and phase than the third and the fifth Fourier frequencies.

Barrett [49] takes the first Fourier frequency and simplifies it into a sine traveling wave with an amplitude envelope, as indicated in Fig. 6:

$$h_f(x,t) \approx \left(c_1x + c_2x^2\right)\sin(\omega t - kx) \quad (2)$$

in which ω is the frequency of the fish tail swing, $k = \dfrac{\omega}{V} = \dfrac{2\pi}{\lambda}$ being the wave number, the constants c_1 and c_2 defining the amplitude envelope. Barrett assumed that the head movement of the fish was negligible. This model and its similar variants are widely used in the theoretical research on fish swimming.

2.3 Dynamics

The theoretical research on the wave-like swimming performance of the fish body can be divided into two aspects: the kinematics describing the swimming movement of the fish body, and the dynamics of the force on the body in swimming.

According to the selected main forces, the current wave propulsion theory can be divided into two categories: resistive force theory and reactive force theory. Having experienced a rapid development, the reaction force theory is relatively complete and has been widely used in the actual calculations, mainly including the Elongated Body Theory (EBT), the wave plate theory, and the actuator disc theory. Each of these three theories will be reviewed in the following subsections.

2.3.1 Resistive Force Theory

The quantitative analysis of hydrodynamics on aquatic animal swimming began in 1950, when Geoffrey Taylor was the first to analyze the flow of slender bodies of microorganisms and worms. The theory focuses on using viscous forces to establish the resistance theory to investigate the dynamics of the propulsion mechanism by analyzing the static balance of the interaction between the fluid and the body, while taking into account the constraints of thermodynamics and kinematics [50]. The theory of resistance can well explain the motion laws of tiny aquatic animals; however, since it ignores the inertial forces of fluid motion, it is only applicable when the Reynolds number is less than one during the tiny aquatic animals' swimming.

2.3.2 Elongated Body Theory

The elongated body theory illustrates that the dynamics of fish swimming belongs to the motion problem under high Reynolds numbers (hereinafter referred to as *Re*). In 1960s, Lighthill [51] proposed a theory that investigated the effect of the fluid flow outside the thin boundary layer on the fish body. The theory makes inertial effects dominate and justifies the use of the inviscid fluid models. Lighthill's theory has the following premises or assumptions:

1. The fish body is laterally symmetrical and slender;
2. The surface slope of the fish body is small;
3. The cross-sectional area of the front and rear ends of the fish body is zero;
4. Compared with forward movement, the lateral disturbance caused by movement is smaller, namely: $\left|\frac{\partial h}{\partial x}\right| \ll 1, \left|\frac{\partial h}{\partial t}\right| \ll U$.

The y-component of the cross-sectional velocity of the fish body observed by the moving water slice is approximately equal to the material derivative of the lateral displacement $h(x,t)$, namely [52],

$$w(x,t) = \frac{\partial h}{\partial t} + U\frac{\partial h}{\partial x} = Dh \tag{3}$$

where the material derivative $D = \frac{\partial}{\partial t} + U\frac{\partial}{\partial x}$.

The added mass $m(x)$ of the cross-section per unit length at x is:

$$m(x) = \frac{1}{4}\beta\pi b(x)^2\rho_f \tag{4}$$

Among them, β is a geometrically dependent constant, with of an approximate value of 1; $b(x)$ is the length of the fish body along the x-axis; ρ_f is the density of the liquid.

The lateral force L_y exerted by the fish body on the water slice can be expressed as the satellite derivative of $m(x)w(x,t)$, as

$$\begin{aligned} L_y &= D(m(x)w(x,t)) \\ &= \left(\frac{\partial}{\partial t} + U\frac{\partial}{\partial x}\right)\left[m(x)\left(\frac{\partial h}{\partial t} + U\frac{\partial h}{\partial x}\right)\right] \\ &= m(x)\frac{\partial^2 h}{\partial t^2} + 2Um(x)\frac{\partial^2 h}{\partial t \partial x} + U\frac{\partial m(x)}{\partial x}\frac{\partial h}{\partial t} \\ &\quad + U^2\frac{\partial m(x)}{\partial x}\frac{\partial h}{\partial x} + U^2 m(x)\frac{\partial^2 h}{\partial x^2} \end{aligned} \tag{5}$$

The above formula describes the dynamics of a slender fish-like body moving in a flow field. If the shedding of the vortex only occurs in the contracted part of the fish-like body, L_y can be further simplified to the following form [53]:

$$\begin{aligned} L_y &= mD^2h = m\left(\frac{\partial}{\partial t} + U\frac{\partial}{\partial x}\right)^2 h \\ &= m\frac{\partial^2 h}{\partial t^2} + 2Um\frac{\partial^2 h}{\partial t \partial x} + U^2 m\frac{\partial^2 h}{\partial x^2} \end{aligned} \tag{6}$$

The dimensional analysis yields that $m\frac{\partial^2 h}{\partial t^2}$ dominates [52], thus we have:

$$L_y \sim m\frac{\partial^2 h}{\partial t^2} \tag{7}$$

2.3.3 Wave Plate Theory

In 1960, Wu [54] applied potential flow theory and linear boundary layer conditions to study the propulsion performance of flexible two-dimensional wave plates, and proposed the "two-dimensional wave plate theory". Since then, Tong et al. [55] have extended the two-dimensional wave plate model to three-dimensional conditions, based on the linear unsteady potential flow theory of small wave surfaces, studied wave plates of arbitrary planar shape and aspect ratio, and established the three-dimensional wave plate theory. The theory uses the vortex ring panel method in the potential flow theory to solve in both the time domain and the frequency domain. The three-dimensional unsteady linear solution given by the semi-analytical and semi-numerical method confirms the qualitative law revealed by the slender body theory.

2.3.4 Actuator Disk Theory

Researchers also refer to the actuator disk theory—an effort to apply the momentum principle into fluid dynamics—to study the dynamic behaviors of robot fish. Its basic principle lies in simplifying the propulsion mechanism acting on the fluid into an ideal device—an "actuator disk". When the fluid flows through the actuator disk, the surrounding pressure increases, and the thrust generated by the fluid on it is calculated by integrating the pressure increase on the surface of the entire actuator plate [56]. The main advantage of actuating disk theory is that it does not need to obtain the detailed dynamic characteristics of the propulsion mechanism. On the other hand, it suffers from the difficulty so as to fully satisfy the assumptions of energy and the existence of shedding vortices.

In summary, Table 3 lists the commonly used analytical methods that serve as prerequisite for robot fish design, mainly focusing on the kinematic locomotion and hydrodynamic effects of fish swimming underwater.

3 Design Considerations

Three main aspects are normally considered in the design of a robot fish: actuator design, material selection, and overall layout, which are summarized as follows. Actuator and material are the two most important research topics since they lay the foundation of the robot fish performance. The overall layout includes everything else, such as communication, perception, and control. Before building a robot fish prototype, these three parts should be carefully inspected and combined to maximize the potential of the design.

3.1 Actuation System

Being a core part of the mechanism design, the actuation system aims at recreating the fish caudal movement, such as forward and backward moving and turning, which is implemented by using the hardware. The design of the caudal fin swing system is the most important part of the robot fish. Therefore, a robust driving system design is the first priority, which should not only obtain high propulsion efficiency and good maneuverability, but also have the characteristics of small size, lightweight, large torque, and good controllability.

A close look at the existing robot fish designs reveals that mainly three types of actuators have been adopted: motor, hydraulic and pneumatic actuator, and smart material actuator.

3.1.1 Motor

The motor is the most commonly used actuation for robot fish. Through its rotational motion, the motor mainly drives the joints of the robot fish to move. The robot fish using motor as the actuation has the advantages of simplified structure, high reliability, and large torque, which in turn, makes it more suitable for imitating the biological fish type

Table 3 Summary of robot fish analytical methods

Methodology	Achievements	Room for improvement & future research directions
• Fish biology and locomotion	• Adoption of symmetrical NACA-like section to simulate fish locomotion [57]; • Exploration of natural modes of fish swimming locomotion to achieve required motions of robot fish [58]; • Study of different swimming forms depending on the fish body part used for propulsion, e.g., BCF and MPF for robot fish locmotion [36, 40–43, 59]; • Effects of pectoral, anal, pelvic and dorsal fins in fish locomotion, like complex conformational and wave motions [60–66]; • Multiple fin cooperative movement for fish locomotion beyond classical BCF and MPF swimming modes [63, 64]	• Correlation of the body asymmetry with the generation and control of locomotor torque [12]; • Modal analysis to capture the complex multi-fin and body locomotion; • Compromise the balance of adding active control surfaces in robot fish design, i.e., different fins, and the design complexity and computational cost; • Design of robot fish that can achieve the same level of locomotion as biological fish in both steady and unsteady manuvering pattern
• Robot fish hydrodynamics	• Numerical and practical modeling methods for robot fish hydrodynamics [52, 67–69] • Numerical analysis method – Lighthill analysis including elongated body theory to achieve a good balance between fidelity and model complexity [70, 71] – Solving Navier-Stokes equations and Euler-Bernoulli beam model are required, including the drag forces and quasi-static lift based on airfoil theory – Computational Fluid Dynamics (CFD) simulations to calculate the complex hydrodynamics with interaction with liquid environments [72–74] • Practical analytical method – 3D wake phenomenon measurement using Digital Particle Image Velocimetry (DPIV) [75, 76] – Experimental self-propelled method based on force feedback control using laser and high-speed camera [77, 78]	• Most significant challenge lies in accurate capturing fish swimming hydrodynamics • Significant time-consuming for CFD to capture fish hydrodynamics for various maneuvers • Accurate correlation between self-propelled experimental approaches and biological behaviors of real fish

with fast swimming speed and outstanding maneuverability. The commonly used drive types of the motor include the servo motor drive, the steering gear drive, and the DC motor drive. An overview of the application and examples w.r.t. each motor drive type are listed in Table 4.

Depending on the way of connecting the motor to the joint, there are two modes to implementing the motor in robot fish, i.e., direct drive and indirect drive.

- Direct drive: joints could be actuated directly by motor. For example, RoboTuna [79] uses the transmission mechanism of pulleys and ropes to transmit the rotation of the six motors to the eight connecting rods to realize the reciprocating swing of the body. Lachat et al. designed a small robot fish, BoxyBot, by imitating the boxfish, actuated by three DC motors. Two motors were used to actuate pectoral fins, with the third one used to swing the tail fin, achieving a maximum speed of 0.37 m/s [85].
- Indirect drive: joints are actuated indirectly by motors via the transmission mechanism. As the successor of RoboTuna, a typical paradigm of direct drive mode, the RoboPike [80], on the other hand, adopts the indirect drive mode by transmitting the motor torque to the tail joint angles using a motor-wire actuation mechanism. In [86], researchers proposed the mechanism of a pair of two motor-driven pectoral fins on both sides of the robot fish, leading to an improvement on the maneuverability.

3.1.2 Hydraulic and Pneumatic Actuator

Rigid materials make the robot fish body stiff. Thus, with rigid materials, it is challenging to accurately simulate the soft body of the fish when it swims. Hence, an important research and development direction for the current robot fish is to use the flexible material as the fish body, and the hydraulic device as the drive. By designing the cavity using flexible material, the spine structure of a real fish can be effectively simulated as that of a soft robot fish can be continuously deformed, with theoretically infinite degrees of freedom [87].

Equipped with high power density, hydraulic and pneumatic actuators can efficiently simulate the linear driving characteristics of fish muscles [88–90]. Festo developed a bionic robotic manta ray in 2007, using a high-power hydraulic propulsion system to control the movement of the pectoral fin with flapping wings [91]. Festo also constructed a pneumatically actuated carangiform robot fish with a flexible posterior body [92]. These robots demonstrated the feasibility of achieving completely fish-like movement through hydraulic and pneumatic actuators. The Draper Laboratory used four hydraulic cylinders to provide sufficient propulsion power in Vorticity Control Unmanned Undersea Vehicle (VCUUV) [93]. Marchese et al. designed a pneumatic-driven soft robot fish in 2014 [94], which is capable of achieving fast and continuously swimming performance, with a maximum of 15 cm/s. In spite of the aforementioned achievements, the hydraulic and pneumatic actuation systems typically take up considerable space and are difficult to control. In order to solve this issue, researchers at MIT proposed a soft fluidic circulatory actuator using gear pump [88, 95, 96], which is compact and efficient.

3.1.3 Smart Material Actuator

With the continuous research on materials and processes, new robot fishes made of smart materials have gradually emerged. Smart material actuators have inherent advantages of compact size, lighter weight, and less noise. Smart materials enable the robot fish more flexible when moving [18, 97]. Smart material can achieve complex movements without additional auxiliary devices [98]. Generally, there are mainly three types of smart material actuators for underwater robot fish: Shape Memory Alloys (SMA), Ionic Polymer Metal Composites (IPMC) [99–101], and piezoelectric material [16].

Shape memory alloys are a class of alloy materials with a shape memory effect. This is a specific effect that the deformed shape of the material will return to its original shape not by removing the applied external forces, but only

Table 4 Different motor drive types

Drive type	Usage	Example
Servo motor	Accurate control of positioning and movement	RoboTuna [79], RoboPike [80], SPC [81]
Steering gear	Accurate control of positioning and movement	PPF series [82]
DC motor	Auxiliary drive for special parts	TU Delft Robot Fish [83], iSplash [84]

by rising the temperature to a certain value, with properties that seem to retain a memory of the original shape [102].

Rossi et al. used the deformation of SMA to simulate the red muscles of fish, which can continuously change the curvature of the body [103]. Chen et al. attached the passive plastic fiber to the IPMC beam to make a caudal fin-driven robot fish [104]. Heo et al. designed a biomimetic fish robot actuated by piezoceramic actuators, which generates limited bending that is amplified and converted into a large tail swing via the transmission mechanism [105]. Seoul National University has developed a turtle-like swimming robot fish [106]. It uses a Smart Soft Composite (SSC) structure composed of SMA wire, ABS, and PDMS to make pectoral and caudal fin drivers. The shell is made of 3D printed ABS, while the head is formed by PDMS pouring. By doing this, MPF mode is achieved. Nevertheless, it is challenging to use the smart materials in practice due to their control complexity, slow reaction, and small payload. Hence, in the current robot fish research, the applications of the smart materials are mainly limited in small- or micro-scale. Rossi et al. designed a flexible robot fish using SMA drives in 2011 [103, 107], showing the potential of using SMA rather than motor and gears. Wang and others developed a small flexible robot fish [108]. The robot fish embeds shape memory alloy wire into an elastic substrate to make an SMA driver, which drives the tail fin to swing and advance. In 2009, the team also developed a robot devilfish, whose driver is made of SMA cable embedded in the PVC film, with a maximum swimming speed of 57 mm/s [109]. The University of Science and Technology of China [110] made a bionic robotic eel with SMA drives. The robot fish consists of three drive joints connected in series, using wave propulsion. In addition, in 2002, Northeastern University [111] developed another type of robotic eel with an SMA drive, which swims with its tail fin swinging. New York University and others developed a modeling framework in 2010 to study the free motion of a robot fish driven by an IPMC caudal fin [112], and evaluated the motion parameters through bending force and vibration measurements by means of reduction of the deformation modeling based on modal analysis.

3.1.4 Hybrid Actuation System

In addition, different actuation methods could be integrated to combine the advantages. In other words, the motor could be used together with other actuation methods. For instance, a DC motor was used in the VCUUV to drive the piston pump of hydraulic cylinders, resulting in a stable, steady swimming speed up to 1.2 m/s and a turning rate up to 75 deg/s [113]. The great potential of a combination with motor and hydraulic actuators is demonstrated by the performance of the VCUUV, capable of achieving fast reaction and precise control. Liao et al. [114] developed a robot fish with a composite propulsion mechanism using dual swing tail fins and jet propulsive mechanism as the propulsion system. The tail fin swings in the opposite direction to offset the lateral disturbance caused by the swing of the single tail fin, while the jet propulsion system further improves its thrust. According to the experimental results, the composite propulsion mechanism exhibits higher controllability and maneuverability than the single tail fin swing mechanism, and the jet propulsion system system generates high instantaneous acceleration. Aubin et al. [115] developed a robot fish powered by the battery fluid, with the “Robot blood” formed by an electrolyte of zinc iodide. During the discharge process, the zinc will be oxidized, releasing both electrons and soluble zinc ions; meanwhile, an electron flow is created. The electric current generated by the movement of the electrons powers the microcontroller and the pump of the artificial circulation system. The electrolyte is used as hydraulic oil to make a hydraulic device to drive the fins to swing. Although the robot fish is significantly slow to respond, this idea has shed light on using novel approaches in solving soft robot fish driving problems in the future.

Table 5 lists the pros and cons of different actuation types, with specific examples given under each type.

Table 5 A comparison among different actuation systems of the robot fish

Actuation	Pros	Cons	Example
Motor actuated	Easy to design the mechanical propulsion; structure can simplify the control task	Must use at least one motor; limitations of motor on weight, volume and torque	RoboPike [80]
Hydraulic and pneumatic actuator	High power density; efficiently simulate the linear driving characteristics of fish muscles	Typically take large space; difficult to control	SoFi [96]
Smart material actuator	Can achieve more flexible and complex movements without additional auxiliary devices; the robot fish made by smart material could be smaller, lighter, and quieter	Hard to be used in practice due to their control complexity, slow reaction, and small payload	ZJU soft robot [116]
Hybrid actuation	Combine the advantages of the above three types	Hard to design and control	VCUUV [93]

3.2 Materials

Typically, the materials used are determined by the structure of the robot fish. For robot fishes with discrete structures, rigid materials are used, while for continuous fish bodies, soft materials are chosen.

3.2.1 Rigid Material

In spite of the boom in the development of soft robots in recent years, the majority of robots on the market follows the classical rigid and discrete form, which is mainly composed of the assembly of multiple small rigid systems by means of linkages, gears, cables, pulleys, to name a few. The complicated assembly of multiple rigid parts is accomplished by significantly increased complex transmission of actuation power and high number of DOFs to control. Current state-of-the-art rigid biologically inspired underwater robots also have complex mechanisms. For example, in order to replicate the fish-like undulations, robot fish with rigid materials is designed as manipulator-like mechanism, driven directly by actuators, or indirectly using transmissions.

3.2.2 Soft Material

The past few years have witnessed an impressive growth in soft robots, the compliant grippers [117] and OctArm [118] being some typical paradigms. Thanks to the success of some soft robots, the soft robot fish has experienced significant development by implementing a similar idea. The design of soft robot fish follows a totally different principle from that of its rigid counterpart, i.e., by replicating the undulations of biological fish in a straightforward approach. Since in nature, a live fish achieves the swimming locomotion by the movement of its soft and flexible body, soft robot fish replicates this mechanism by directly applying an excitation on the soft robot body. One distinguished advantage of soft robot fish lies in its less complex but robust mechanism—only a flexible body and an excitation source are included.

Within the framework of dynamic analysis of mechanical structures, the vibration modes of a structure are determined by its geometry, material and excitation source, e.g., forces or torques being applied. It inspires researchers to design a mechanical structure in which the desired body motions are in compliant with the dominant vibration modes to reduce the number of actuations, in further, to reduce mechanism complexity. Therefore, for robot fish design, the dominant vibration mode of the robot fish body can match the flexible body motions of its biological counterparts under relatively simple actuations. Normally heterogeneous soft materials are used, whose dynamic responses are in agreement with the desired flexible body motions. The soft body also endows advantages of improved protection from the environment by encapsulating the mechanism and electrical components inside the continuous soft body.

3.3 Overall Design

Both hardware and software are included in the architecture of a robot fish. Being the dominant system of hardware, the mechanical structure is equivalent to the “trunk” and “muscles” of a robot fish, along with the execution mechanism, while the control system, being the core of the entire system, is like the “brain” of a robot fish. The system design acts as a bridge to connect the conceptual design to reality: it not only realizes the engineering design into a practical robot, but also deals with many factors such as stability, endurability, and so on. Generally, the mechanical structure of a robot fish includes two parts, namely, the fish body and tail fin. The fish body is normally simplified as a rigid body for the installation of drivers, control systems, and sensors. The architecture of a robot fish can be divided into four layers, namely, the perception layer, the information exchange layer, the decision layer, and the execution layer, in terms of the corresponding basic function of each one. A schematic illustration showing the interaction of the robot fish and all design layers is demonstrated in Fig. 7.

3.3.1 Perception Layer

In the perception layer, the robot fish obtains real-time external environment information, self-information, and target information, including the system resources, power performance, navigation information, the surrounding environment, as well as the perception and understanding of the target. It is difficult to provide complete information resources with a single sensor. Hence, in the design of a robot fish, multiple sensors are integrated to provide information about the surrounding environment and the robot’s motion. Fusion and filtering processing enhance the accuracy and reliability of the robot fish’s perception of the outside world and its own state.

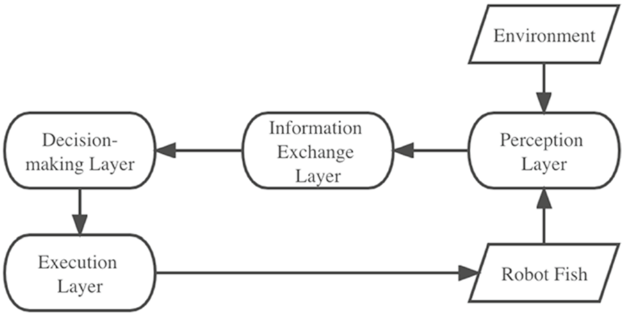


Fig. 7 Overall design layers

3.3.2 Information Exchange Layer

Using the information exchange layer, a robot fish receives commands from the control system by means of the wireless communication module. Meanwhile, the measurements from the sensor installed on the robot fish provide information on the internal execution state, being fed back to the decision-making layer.

3.3.3 Decision-making Layer

The most basic performance of a robot fish is to be able to autonomously navigate, track, operate and avoid obstacles. The robot fish obtains information resources through the perception layer, while the decision-making layer makes the judgment of various information and instructions according to the input signal and the unique control strategy of different tasks, generates corresponding control commands, and completes the specified task.

3.3.4 Execution Layer

A robot fish receives commands from the decision-making layer and performs corresponding actions.

In summary, various state-of-the-art robot fish design, adopting different principles, are listed in Table 6, with their respective achievements and room for improvement, leading to future research directions.

4 Robot Fish Control

The control of a robot fish covers a wide range of research realms, including swimming attitude control, swarm cooperative control, and path planning. When swimming underwater, various types of sensors are required to provide an accurate estimation of state parameters, for safe arrival to the designated position without colliding obstacles. The control algorithm is employed based on the measurements to perform the real-time movement. Establishing an accurate motion model is the basis of the robot fish control. The application of advanced control methods, such as neural networks, is the key to achieving high mobility and stability of a robot fish. Besides, group collaboration and coordinated control are also emerging in recent years, which are the prerequisites for the practicality of a robot fish.

One of the most widely used classical categorization methods of robot fish control is summarized following the way of locomotion, e.g., direction control for forward/backward and turning locomotion; depth control for upwards/downwards locomotion; also the speed control, stabilization control and trajectory control [16]. Within the development of robot fish, the control becomes more and more complex, which accompanies the significant progress in simulating the swimming morphology of the real fish. The control involves almost all design components of a robot fish, from live fish morphology to robot navigation, from mechanical structure to electrical system design.

Taking the autonomous navigation of a robot fish for instance. The objective is to safely and efficiently reach the final destination without crashing into any obstacle. In such cases, the direction control, depth control, speed control, trajectory control, as well as stabilization control are being involved to create a closed-loop system. Similar to its counterparts operating on ground, the prerequisite of the successful trajectory control of robot fish is the prediction of locomotion state, including position, orientation, and velocity within time history w.r.t a given reference trajectory [146]. Therefore, an integration of different control approaches depending on the way of locomotion is required to achieve such complex tasks. At each time instant, control of at least two locomotion parameters is involved, leading to task-orientated categorization of control. From the starting point to the final destination, the robot fish needs to adjust its direction from time to time, in terms of direction control mainly by flapping the caudal fin. In a clear water zone without obstacles, the robot fish will flap the caudal with equal actuation amplitude for a straight forward movement; at the same time, the undulation amplitude and undulation frequency of the caudal fin also contribute to the speed control [147]. Therefore, it is like a coupled integration of both direction control and speed control.

In addition to caudal fins, for both control of the direction and speed, the flapping of pectoral fins and head swing also play a relatively non-major role. Meanwhile, it is noteworthy that parameters affecting direction and speed control accompanies, which are required to be compensated to achieve the desired swimming morphology, including thrust gradient and delay, and most noticeably, the drag force [148]. For example, Kato [86] presents a method involving the approximation of thrust force with a nondimensional coefficient of thrust. In face of turning directions, the robot fish will mainly control the undulation with unequal amplitude and frequency, along with the adjusting of actuation phase angles, in coordination or independently. Moreover, for 3D navigation of robot fish, depth control is always involved, which is based on a straightforward idea: by obtaining the buoyancy higher than the gravity, the robot fish moves upwards, and vice versa. The velocity of upward/downward motions depends on the difference between the buoyancy and the gravity. Various techniques have been developed to achieve depth control, including ballistic tank control [88], sliding mass, and tilted pectoral fin control [149, 150]. Taking the traditional ballistic tank approach as an example: the buoyancy is controlled via controlling the volume of the tank chamber.

Table 6 Different types of robot fish with their achievements and drawbacks

Research focus	Research highlights	Room for improvement & future research directions
• Multi-joint rigid mechanical fish	• Multi-joint mechanism to behave fish-like Carangiform swimming mode with oscillating caudal fin in crusing, turning, and whip-sweeping propulsion [119–122]; • Multi-joint oscillating pectoral fin to achieve high stability, efficiency and maneuverablity [123, 124], like robotic manta ray [125–127]; • Design and modeling of amphibious underwater robots [128]; • Multi-joint Anguilliform robotic fish [129]	• Apparently low swimming performance compared to biological fish, especially in complex working environments [12], thus performance bottlenecks needs resolved; • Efficiency loss due to multiple joints adopted [130]; • Difficulty in control in uncertain and ever-changing environments using traditional CPG controller; • High degrees of freedom to deal with
• Wire-driven robot fish (Biomimetic Wire Driven Mechanism)	• Simulation of the flexible fish body backbone motion using wire-driven mechanism like muscle arrangement to realize undulatory and vector (e.g., dolphin-like swimming both forward and upward) propulsion of the caudal fin [12, 131]; • Wire-driven mechanism to replicate the locomotion of soft and boneless mullusks, e.g., the octopus [132]	• Accurately replicate the different forms of biological fish muscle extraction in various working environments; • Achievement of mutliple control surfaces working together using wire-driven mechanism
• Robot fish made from smart materials, like Ionic Polymer-Metal Composites (IPMC), and Shape Memory Alloy (SMA)	• IPMC used as artificial muscles to undulate caudal fin, to achieve carangiform swimming locomotion of light weight robot fish [133, 134] • Using IPMC to actuate pectoral fins for lightweight manta rays and mullusks to improve maneuverability [135, 136] • Hybrid actuation of tail using IPMC beam with excitation at its base, for improvement of swimming speed with less power consumption [137] • Design of robot fish with flexible rays actuated by SMAs [103, 138, 139]	• Low oscillatory frequency of caudal fin actuated by IPMC and SMA, not suitable for fast swimming and quick turning [32] • Unable to produce 3D caudal or pectoral fin locomotion since only bending motion can be generated using IPMC or SMA
• Actuation of soft robot fish	• Multi- or single-joint internal actuated robot fish with soft body [130, 140] • Hydraulic- or pneumatic-powered soft robot fish [96, 141, 142] • Dielectric Elastomer Actuators (DEAs) as artificial muscles to actuate soft robot fish [116, 142–144] • Electrochemical and microscopic soft robot fish to actuate soft fins without recharging frequently [138, 145]	• Challenging for control due to large number of DoFs involved in soft continuous structure [130] • Complexity in maneuver and control • Low efficiency and maneuverabiltiy compared to biological fish, with limited working space underwater • Challenges in reducing power loss and driving voltage, while maintaining increased mobility and high energy density using DEA actuation • Apparent low power and efficiency attained using electrochemical power source

One of the design objectives of robot fish is to emulate the motion of their biological counterpart that has been improved via millions of years' evolution. In general, the live fish locomotion is achieved by means of a sequential muscle operation of caudal fins. In order to achieve the similar sequential operations as their biological counterparts, two different control approaches are employed in robot fish: the kinematic-based method [151, 152], and the Central Pattern Generator (CPG) [153–156]. In the context of these two approaches, the motion control methods thus can be divided into three different groups: the body curve fitting method based on multi-link mechanism, the sinusoidal controller method, and the motion control method based on CPG.

4.1 Body Curve Fitting Method

The fish body wave curve fitting method based on the multi-link mechanism is essentially a method based on kinematics. If the swinging body of the biomimetic robot fish is a multi-link mechanism connected by hinges, then the desired body curve could be achieved by adjusting the relative position of each link during swim [157]. With reference to [158], the authors argued that Eq. 2 is easily to be reformed to obtain the control angles associated with each joint being actuated by the servomotors. As shown in Fig. 8, in a four-link carangiform robot fish, it is sufficient to ensure that the endpoint of each link at each swing movement falls on the theoretical curve of the fish body wave [159]. Thus, as long as the appropriate parameter set is selected, a desired robot fish swimming gait can be generated. However, it is difficult to optimize the control performance and swimming efficiency due to the discretization [160].

4.2 Sinusoidal Controller Method

A simple sinusoidal controller is used to drive multiple series joints of the robot fish, where the forward joints are brought forward by the phases of the rear joints to generate push waves. The motion control method based on the sinusoidal controller is essentially a method based on kinematics [161, 162], which is formulated as

$$\varphi_i(t) = A\sin\left(2\pi ft + i\varphi_{\text{lag}}\right) - \psi, \quad 1 \le i < N \tag{8}$$

in which φ_i is the phase lag angle between adjacent joints, A is the maximum angular offset of each joint, f is the frequency, t is the time, N is the number of links, φ_{lag} is a constant phase lag between consecutive joints, ψ is the angular offset.

The motion control method of the sine controller are not complex. The swimming gait of the biomimetic robot fish can be generated online, while the diversified swimming gait can be obtained by modifying the control parameters.

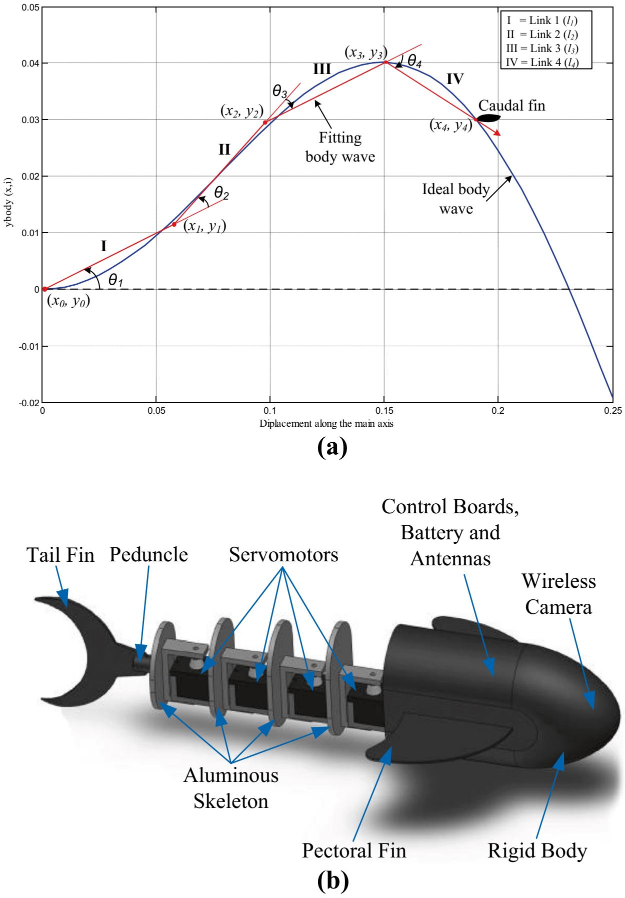


Fig. 8 Demonstration of body curve fitting method [159]

However, it is obvious that with using the sine controller, a sudden change in frequency and amplitude will cause an abrupt variation in the swing angle, so that smooth and natural speed adjustment cannot be achieved [157]. A bio-inspired robot fish undulating fin composed of a series of link structures is presented in [161]. With a specially designed strip, each link can rotate or slide relative to its adjacent link. The swing of the link mechanism is controlled by a sinusoidal controller. The generated sine curve is used to fit the wave of the fish fin, and the sine wave controller method is successfully applied to the motion control of the buoyancy tube equipped with the bionic wave fin.

4.3 Central Pattern Generator

As a well-known bionic analysis method, the CPG is a network composed of interneurons, which can lead to self-excited oscillation of the system by means of mutual inhibition among neurons that have local oscillations, resulting in multiple (or single) periodic signals with a stable phase interlock relationship. It is a common method used for the control of rhythmic movement of limbs, or other related body parts [163, 164]. As a rhythmic motion control, CPG has the following characteristics [164, 165]:

1. It can automatically generate a stable rhythm signal even in situations where high-level commands and external feedback are unavailable; meanwhile, it is noteworthy that, the high-level commands and external feedback can adjust the behavior of the CPG.
2. Under the adjustment of high-level commands, through phase locking, a variety of stable and natural phase relationships can be generated to achieve different motion modes.
3. It is easily coupled with input signals or physical systems so that rhythmic behaviors are transmitted throughout the system.
4. It has strong adaptability and robustness.

These features are suitable for robot motion control, leading to a widespread bottom controller of robot motion using CPG. Ichthyological studies have proved that the movements of fish's fins and bodies are caused by the periodic activities of the central nervous system. Therefore, the CPG control mechanism is introduced to produce the swimming gait of modular robot fish. There are mainly three types of CPG models: the neuron oscillator model, the recursive oscillator model, and the phase oscillator model [166]. We will introduce the first two in detail, as the third model is rarely used in robot fish.

4.3.1 Neuron Oscillator Models

CPG model based on Amari-Hopfield neuron oscillator is widely used and has a stable limit cycle [167]. It is composed of two types of neurons, excitatory and inhibitory, with excitatory and inhibitory connections between neurons. To produce a fish-like swimming gait, a CPG neuron model can be established for each joint of the robot fish. As a result, multi-joint CPG coupling model based on Amari-Hopfield neuron is expressed as follows [168]:

$$\begin{gathered}\Delta\theta_i = \theta_i - \bar{\theta}_i \\ A_i\Delta\dot{\theta}_i = A_i\omega\left(v_i + \Delta\theta_i\right) - \Delta\theta_i\left(\Delta\theta_i^2 + v_i^2\right) \\ A_i\dot{v}_i = A_i\omega\left(v_i - \Delta\theta_i\right) - v_i\left(\Delta\theta_i^2 + v_i^2\right) \\ +A_i\sum_j\left(a_{ij}\theta_j + b_{ij}v_j\right)\end{gathered} \tag{9}$$

where A_i represents the amplitude, ω represents the body wave frequency, θ_i is the expected swing angle of the i^{th} joint, $\bar{\theta}_i$ denotes the offset superimposed on the center position of the i th joint swing, v_i is another control variables in CPG, without actual physical meaning, a_{ij} and b_{ij} are both the connection weight of the i^{th} joint and the connection weight of the j^{th} joint (the weight of the influence of the j^{th} joint on the i^{th} joint). An example of CPG control network based on Amari-Hopfield neuron oscillator, for a robot fish with 3-joint tail, is illustrated in Fig. 9.

By changing the connection weights a_{ij} and b_{ij}, the lead-lag relationship between the joints can be adjusted to form a stable fish body wave. According to the characteristics of the fish swimming, the amplitude, frequency, swing offset and other parameters can be set to produce a suitable body wave for the robot fish. Wang et al. [169] constructed a CPG control model based on the Amari-Hopfield neuron oscillator, proving the stable limit cycle of the model, and successfully applied the CPG model to a robot fish with pectoral fins. Yu et al. [154] investigated a method integrating the dynamic model with an optimization algorithm on particle swarm, to obtain the optimal CPG characteristic parameters for improved performance. Wu et al. [170, 171] then further applied this method to a robot dolphin to accomplish multi-modal motions.

4.3.2 Recursive oscillator model

Kimura [172] has made certain improvements on the basis of the Matsuoka oscillator model [173]. The oscillator model uses two mutually inhibiting neurons to form an oscillator, which corresponds to the animal's flexor and extensor control neurons. The extensor neurons provide different high-level input methods so that the oscillator produces asymmetric output [172]. Therefore, the Kimura neuron oscillator model can be employed to generate the swimming gait of a robot fish, as shown in Fig. 10.

Each joint of the biomimetic robot fish can be controlled by a Kimura neural oscillator. The output of the oscillator is used as the target angle of the joint. By means of adjusting the coupling relationship, along with the connection weight between the neural oscillators, the motion of multiple joints can be coordinated to produce a similar swimming gait to the biological fish. Based on the Kimura neural oscillator, the CPG model is designed for a multi-joint robot fish in [174].

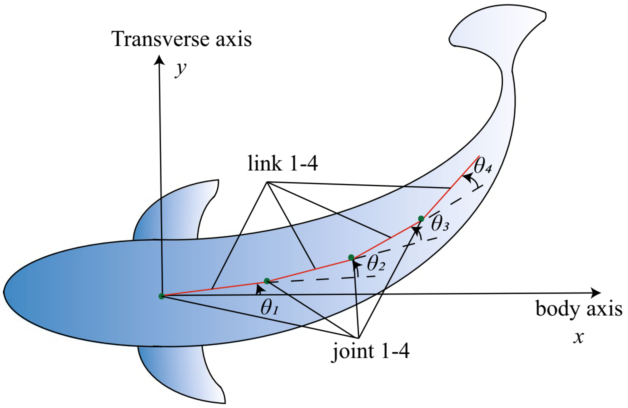


Fig. 9 The CPG control network of four joints robot fish

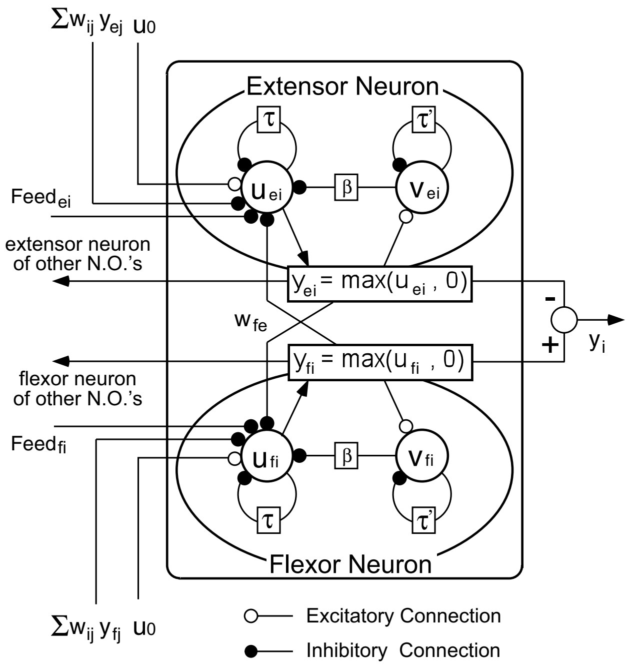


Fig. 10 Kimura neural oscillator model [172]

According to the relationship between the parameters of the CPG model and the feedback input, the robot fish pitch and turn feedback control methods are developed. By using the feedback information of the robot fish, the CPG parameters are adjusted from the main body to control the pectoral fins [175–177]. Hu et al. [178] studied how to generate the target joint swing angle of the robot fish, utilizing the CPG model based on the Kimura oscillator. Through the coordinated control of the thrusters, the diversified swimming gait of the robot fish is realized. It is noteworthy that, the model parameters of a robot fish do not always stay unchanged, rather, they may vary from time to time, which poses challenges to capture the dynamic behaviors of the system. In order to address this issue, the discrete-time adaptive control method has been proposed that can accurately predict the real system dynamics w.r.t the discrete time spots [7, 179].

Based on the above analysis, a comparison on different controllers is summarized in Table 7.

In addition to the classic control method comparisons listed in Table 7, we also summarize the commonly used control approaches for soft robots, as well as the

Table 7 Classic control methodologies comparison

Methods	Pros	Cons
Body curve fitting method	Can generate arbitrary robot fish swimming gait; easy to design and control	Difficult to optimize the control performance and swimming efficiency
Sinusoidal controller method	the swimming gait of the robot fish can be generated online; diversified swimming gait can be generated by modifying the control parameters	Sudden changes in frequency and amplitude will cause abrupt variations in the swing angle, so smooth and natural speed adjustment cannot be achieved
Central pattern generator	high-level commands and feedback from external environment not needed to generate a stable rhythm signal; a variety of stable and natural phase relationships can be generated to achieve different motion modes; strong adaptability and robustness	Difficult to design; hard to fine-tune parameters

Table 8 Soft robot fish control and intelligent control based on machine learning

Research focus	Research highlights	Room for improvement & future research directions
• Control of soft robot fish	• Dynamic control based on fish physical models, like CPG for rigid robot fish [17, 180] • Continuum control strategy for flexible soft robots based on a compromise of control accuracy and complexity [181, 182]	• High correlation with the fish dynamic model, i.e., specific model-dependent • Difficulty for accurate control under complex interactions with the envrironments that affect the continuum soft fish body locomotion
• Machine learning (ML) control method	• ML, independent of fish kinematic and dynamic model, addresses issues related to the complex, nonlinear fish-environmental interaction [183–186] • Hybrid approach by integrating CPG-based control and ML & deep reinforcement learning to optimize robot fish control strategy [187–191] • Reinforcement learning method is optimal for the control of mollusks soft robot fish such as jellyfish [192]	• Model-free control method suffers challenges of extensive training data required, endured training cost and difficulty in attaining the data considering the complex operation environments • The hybrid approach addressed some of the bottlenecks of model-free method and remains in infancy, which will be a significant research direction

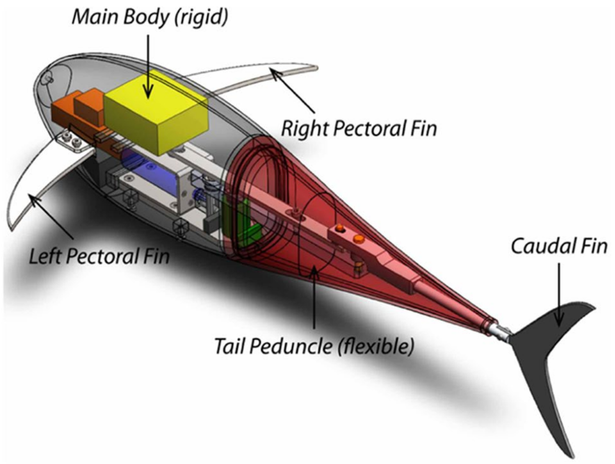
development of the machine learning algorithms for robot fish control, as shown in Table 8.

5 Case Studies

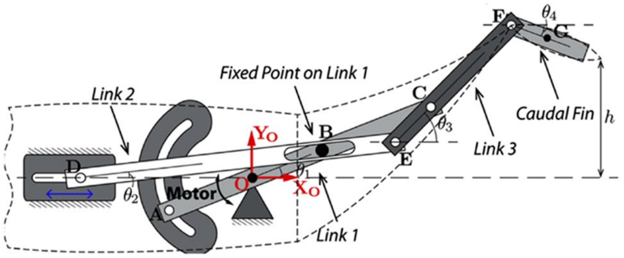
A successful bionic robot fish is the outcome of robust integration of multiple realms of study in robotics and biology, including dynamic modeling, control, electronics, mechanics, fish biology, and so on [193]. With the boom of biomimetic robotics, biologically inspired robot fish has attracted more and more attention, with several paradigms of robot fish emerging. In this section, we will investigate the process of robot fish design and fabrication by means of a case study of two state-of-the-art robot fish: one being rigid robot fish, the other being the soft one.

5.1 UC-IKA

In an effort to implement the design principles into the robot fish design, the UC-IKA 1, as illustrated in Fig. 11(a), attracts researchers' attention [194, 195]. The UC-IKA 1 is chosen here as it is a typical paradigm in the development of rigid robot fish, due to its straightforward design, robustness, reliability, and impressive good shape. The design objective of UC-IKA 1 is to mimic the undulatory swimming locomotion of tuna. As shown in Fig. 11(a), two main parts are included into the robot, namely, the main body and the fish tail. The rigid main body, and the caudal fin—also rigid—are connected by a flexible tail peduncle. The peduncle is able to drive the caudal fin under undulation movement through an actuation mechanism inside. The mechanism is designed to transmit the output of the DC motor, which is installed in the main body, to the caudal fin.



(a) UC-IKA Design: with a length of 65 cm and a weight of 4 kg



(b) the link mechanism of the tail peduncle

Fig. 11 UC-IKA Design [195]

As a rigid and waterproof part, the main body is primarily designed to hold stationary components of a robot fish, including the microcontroller, batteries, and the DC motor. The pectoral fins, which are rigid as well, are fixed to the main body to provide additional stability. The tail, on the other hand, is not 100% rigid. It contains a tail peduncle, which is soft and flexible, and a rigid caudal fin. The tail peduncle connects the main body with the caudal fin, with an undulation actuation mechanism installed inside. Thanks to its sophisticated design, the actuation mechanism can transfer the output torque of the DC motor to the undulation of the caudal fin effectively.

Though much room exists ahead of researchers to match the real swimming location of tuna [196], the UC-IKA 1 has made remarkable achievements by virtue of its sophisticated actuation mechanism in its tail, as highlighted in Fig. 11(b). The tail fin is composed of a set of bars and joints, to be connected together, to form an oscillatory motion. When the fish stays still, rod *AB* overlaps with the center reference line. By rotating *AB* w.r.t. frame OX_oY_o using a motor attached at point *O* by only 14 degrees, a heave of 17 mm at point *C* and 56 mm at point *F* will be reached, in terms of the four bar linkage system.

This mechanism has a set of distinguished features. One being low number of DC motors used—the whole mechanism is actuated by only one motor. Thanks to this compact feature, it is easy to install the motor at, or close to the center of mass of the robot, resulting in low peduncle weight and low system moment of inertia. This will ease the control of the system. The mechanism also showcases improved capability to match the swimming locomotion of tuna cruising. For example, instead of providing undulations more close to the carangiform mode like mackerel, the UC-IKA 1 has a much closer agreement with tuna swimming, compared to some other counterparts. The tail of UC-IKA 1 simulates the tuna caudal fin motion by limiting the undulation of the peduncle part close to the rigid body, since in nature, only the body part very close to the caudal fin takes part in their lift-based propulsion. While for carangiform swimmers, almost one-third of the fish body participates in undulation locomotion. Therefore, UC-IKA 1 not only improves mimicking the locomotion of tuna swimming, but also lowers energy dissipation. In addition to relatively simple mechanism assembly, it is also noteworthy that the third link is passively controlled, further leading to less DOFs to be controlled for the whole system.

The system allows quite satisfactory motion for tuna-like undulations underwater. According to the test results, a cruising speed of 0.29 m/s and 78% efficiency have been achieved. It is noteworthy that these satisfactory results are obtained without system optimization on the actuation mechanism. Therefore, upon optimization, improved performance will be anticipated for both swimming speed and efficiency. UC-IKA 2, an improved version, achieved an efficiency of 89% with the ability to make multiple gaits of locomotion [197].

In summary, the mechanism design and control principle within UC-IKA are listed below in Table 9 for ease of reading.

5.2 SoFi

Being one of the most successful soft robot fish, the idea of SoFi (Soft Robot Fish)—a hydraulically driven soft robot fish—was initiated in 2014 [94]. Through three generations of improvement [94–96], SoFi has proven to be a flagship paradigm in the development of soft robot fish [96]. It is 18.5 feet long, weighs 3 pounds, can dive to a maximum depth of 60 feet. SoFi is also capable of working underwater for 40 minutes on a single charge, taking photos and videos through a fisheye lens. One distinguished feature of SoFi is the hydraulic power system. The hydraulic system creatively introduces the close water circulation system in the body. In terms of cyclically moving the water in the circulation system using a specifically designed water pump, the tail fin, which contains two symmetric chambers, with an elastic thin plate in between, can behave cyclic undulation motions under the water forces. The closed water circulation system in the body makes the tail bend and deform to complete the swimming. Thanks to the hydraulic power system, SoFi is able to swim in deeper water for a long period.

An exploded view of the structure of SoFi is shown in Fig. 12. More detailed explanation on the function of each module can be found in [96]. The outer shell of SoFi is made of 3D printing, such as the head that holds the electronic parts, while the rear body is mostly made of silicone and soft plastic. The idea of soft robot fish opens a brand new window for the design of biologically inspired underwater vehicles, as it offers totally different approaches compared to the traditional rigid underwater vehicles with some apparent advantages. For example, SoFi has showcased significantly improved control levels due to its soft body compared to rigid underwater drones. Another advantage is no fear of collisions by virtue of a soft body. Relying on the structure of a fish-like tail, SoFi can swim straight in the ocean, turn around, and even float up or down in the ocean.

In efforts to upgrade SoFi, researchers further replaced the radio with a waterproof controller and a special acoustic communication system they developed. By doing this, not only can sound waves travel farther, but the energy requirement is also lower. A special acoustic communication system can be used to change the speed and direction of SoFi's movement.

Likewise, the mechanism design and control technique of SoFi are showcased in Table 10 for ease of reading.

6 Discussion

The development of biomimetic robot fish is a complex research topic that involves interdisciplinary research of many disciplines, including biology, automatic control, mechanism design, fluid dynamics, manufacturing, material science, and machine learning, to name a few. Difficulties can arise in each of these fields, not to mention the integration of different research realms. For example, the accurate

Table 9 Summary of mechanism and control principle of UC-IKA

Design parameter	Design principle
Locomotion	A combination of a tuni- and labri-form body
Propulsion	Propulsion using the caudal fin
Kinematics	Velocity and acceleration of the caudal fin at point *F* in Fig. 11(b) being derived in terms of linkage relationship. Hence, given a specific motor movement, the corresponding tail movement can be calculated
Dynamics	Compensation of drag forces on the main body. The lift and fluid inertial forces on the caudal fin are calculated using Lighthill's elongated body theory, as introduced in Section 2.3.2
Material	Rigid material for fish body and caudal fin, while soft material for tail peduncle
Actuation system	One DC motor whose power being transferred to linkage system
Mechanical & electrical components	Microcontroller, battery and DC motor in the rigid main body, while transmission mechanism in the flexible tail peduncle
Control method	An open loop controller for the horizontal swimming

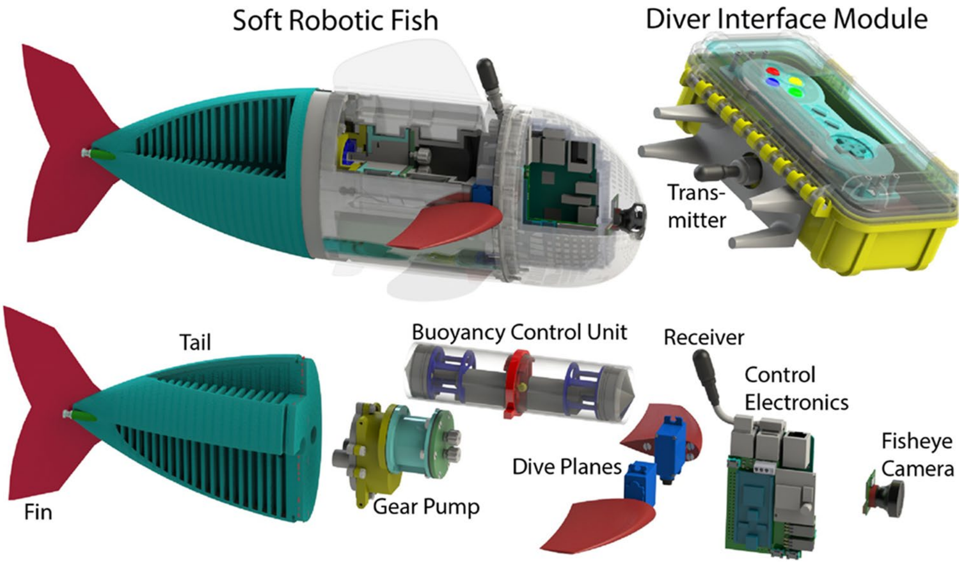


Fig. 12 The structure of SoFi [96]

Table 10 Summary of mechanism and control principle of SoFi

Design parameter	Design principle
Locomotion	BCF carangiform
Propulsion	Propulsion by the undulation of caudal fin and bend of fish body
Kinematics	Posterior body undulation is achieved by undulation of each chamber. Kinematic performance is captured using high-speed video camera
Dynamics	Dynamics of multi-segment soft fluidic elastomer manipulators is analyzed. Hydrodynamics of the robot fish is not analyzed
Material	Rigid 3D printing material for fish head and body, elastic thin plate for tail fin, while soft silicon rubber for tail
Actuation system	Hydraulic power system. A DC motor actuates the water pump, and circulates the water to flow in the tail chamber
Mechanical & electrical components	Microcontroller, camera, battery, gear pump, DC motor, servo, and buoyancy control unit in the rigid main body
Control method	Direction and depth control involving yaw control and pitch control for 3D swimming

dynamic analysis of a robot fish is challenging, since the consideration of the interaction with water, which also requires fluid dynamic analysis, is a must. Besides, a range of challenges may accompany when deploying the robot fish in the harsh environments, e.g., strong currents, cold water, under ice, etc., including underwater communication, control, as well as the proper numerical model to investigate the interaction with water in those environments.

In this paper, a comprehensive review of locomotion principles, actuator types, and control, along with two case studies demonstrating the implementation of the robot fish is presented. Some performance parameters, e.g., the swimming speed, efficiency, and maneuverability, are not the focus of this paper.

The development of robot fish is a very promising field. Swimming mechanism, driving materials, propulsion technology, control, energy supply and underwater communication technology are the key issues in the research of the biomimetic robot fish. In spite of various types of robot fish to replicate different fish locomotion, significant challenges exist ahead of researchers and engineers. For example, for swordfish, the maximum swimming speed can reach 27 m/s, whereas that for its robot counterpart is only 3.7 m/s up to now [198]. The same situation exists in terms of acceleration, hovering, turning, etc. To achieve these high-performance behaviors, challenges exist in achieving a high-power density actuator, attentively designed shape, and robust controller for robot fish design.

Optimization plays a key role in the determination of robot fish design and control parameters. Within the boom of evolutionary optimization methods in recent years, investigations on developing optimization techniques for robot fish like genetic algorithm, cuckoo search, and artificial bee colony algorithm would be an interesting future research direction. Since the swimming performance of a robot fish is highly dependent on the swimming style adopted, the choice of swimming style to achieve the design objectives is the basis for robot fish optimization. For example, thunniform swimmers are born to have energy-efficient locomotion [196], while their carangiform and sub-carangiform counterparts can often achieve high speed.

Maneuverability is also a significant element of the design objectives. As discussed before, by virtue of its high compatibility to the environment, the soft body is endowed with improved maneuverability and has become more and more popular in the realm of robot fish research to meet the increasing demands of high maneuverability in complex underwater environment [94]. However, it is still challenging to establish an accurate relationship of the soft body deformation w.r.t actuation, not to mention the complex fluid mechanics between the soft body and underwater environment that can cause irregular, even sudden change in deformation.

At present, there are some existing problems to be solved in the research of robot fish, which are summarized below:

6.1 Design of Robot Fish Structure

The basis of the biomimetic robot fish swimming is “proper” mechanism design that can meet the design objectives. After millions of years of biological evolution, fish, one of the oldest vertebrates in the world, has completed countless natural selections. The skeletal structure of fish is highly compliant with morphology requirements. At the same time, when the fish swims, each part of the biological body brings great power via the synergy of bones. It is very difficult to completely imitate fish swimming through the use of mechanical structure and motor rudder maneuvering energy drive. Therefore, it is necessary to carefully study the bone structure, biological trunk, and movement patterns of the bionic fish to recreate the movements. Through these biology studies, we could abstract the principles behind fish swimming, and then transform these principles into a mechanical structure, e.g., the motor steering gear.

In addition, differences in the environment have led to totally different fish body forms during the long history of evolution, which would further results in different swimming morphology. Depending on the design objectives, a key step is to extract the appropriate morphological and motion parameters, along with proper materials and control strategy based on different fish morphology, for an optimal robot fish design that shows outstanding performances.

6.2 Kinematics and Dynamics Analysis

While conducting the kinematics and dynamics analyses of the robot fish, the analysis of hydrodynamics should also be taken into account. Besides, the bionic analysis of fish habits is also required through the kinematics and dynamics of the fish propulsion process. Dynamic analysis uses hydrodynamics to analyze the caudal and pectoral fins and the mechanism of fin propulsion, and finally establishes the relevant mathematical model. The kinematic analysis of robot fish mainly includes the analysis of fish swimming mechanisms of different propulsion modes, and the establishment of kinematic and dynamic models of different types of fish.

6.3 Control method

Besides the traditional control methods for robot fish based on kinematic and dynamic models, the neural network control algorithm has also emerged in recent years.

Being the mainstream method, control algorithms based on the kinematic model is established mainly by observing the swing posture and body curve of the biological fish body. The key features, such as the joint swing angle of the robot fish, can be calculated afterwards. However, most of the current motion control for the biomimetic robot fish is based on a relatively simple hydrodynamic model, due to two reasons:

1. The analysis of fish swimming in the water requires not only the analysis of the kinematics of the fish itself, but also the complex hydrodynamics;
2. The complexity of the robot fish obeys a linear relationship with the increase of the DOFs. Higher DOFs would result in higher problem complexity, thus leading to a greater control level.

As discussed above, the complex robot fish system will result in high DOFs, which will further require robust, efficient control algorithms. Compared to the mobile robot working on the ground, the complex underwater environment of robot fish poses challenges to control. For example, unstable operation in a complex underwater environment is a headache for accurate control. In order to address this issue, precise perception of the environment information, as well as the sensation of the interaction with the environment, by means of the state-of-the-art multi-sensor information fusion technique, was proposed [199, 200]. In such cases, the control algorithms are combined with the perception of complete and accurate information of the environment and interaction using sensor fusion, which allows autonomous control of robot fish operating in complicated environment. For example, in real-world applications, some complementary tasks would require using sensor fusion to measure the water flow around the underwater vehicles, force estimation and wall detection being some of them [201, 202].

Subdivided from the control level, the research on the control performance of the robot fish should include the following aspects:

6.3.1 Positioning and Navigation

Accurate knowledge of the specific position and orientation is the key point for controlling a robot fish to complete underwater operations. When it comes to real-world application, positioning and navigation typically are indispensable terms. As the robot fish has the function of floating/diving, the range of motion of the robot fish has changed from the original two-dimensional plane motion to the three-dimensional motion, i.e., the robot fish can reach an arbitrary position underwater. At the same time, ordinary GPS positioning technology cannot be used directly underwater due to a rapid accuracy decrease w.r.t. depth underwater. Therefore, in the face of complex and diverse unknown environments, sonar, vision and other means to obtain environmental elements are used instead. The sensor's capability to quickly and accurately identify the surrounding environments and targets from a large amount of complex information is critical to the maneuverability of the robot fish.

6.3.2 Swimming Control Algorithm

The swimming control of a robot fish is the robust integration of speed and direction control. Recently, higher demands for tasks such as obstacle avoidance and swarm robots motivate further development in swimming control of robot fish. The conventional controller usually requires an accurate state-space model, yet challenging for robot fish which is a complex non-linear system, whose kinematic and dynamic model are extremely difficult to establish accurately. The complex underwater environment which keeps changing is also a challenge. In order to address these issues, robust controllers based on machine learning becomes attractive. Thanks to the intelligent controller within the framework of machine learning technique, novel controllers for robot fish such as fuzzy controllers, adaptive controllers, and neural network controllers, along with others, have showcased improvement in the swimming control of robot fish [166]. In addition, efforts in improving the swimming efficiency are also significantly beneficial. Fish in nature perceive the water flow through the curve on the side body, and then continuously adjust the shape of the body to reduce the resistance during swimming, leading to improved swimming efficiency. This is a natural and complex process which is the outcome of millions of years' evolution, yet challenging for artificial systems in underwater environment. The complex coupling of system dynamics and fluid mechanics pose substantial challenges in accurately establishing the numerical model, e.g., the governing motion equations to capture the dynamic behaviors of the robot fish under this coupling effect. Moreover, by means of accurate measurement of the water flow for various operations using artificial sensors, which is also challenging, autonomously adjusting the robot fish deformation and shape for higher efficiency would require extremely high level of control that the current state-of-the-art control technique is too infant to achieve, thus an important direction for future research.

Table 11 Industrial robot fish examples

Application	Example
Consumer product	Robosea biki
Education	LEZHI Robot Robosea Robolab-edu
Research platform	Robosea Roboshark
Exhibition	Robotswim Jessiko Robot Dolphin
Ecosystem monitoring	Pliant energy system Velox Robot

6.3.3 Coordination and Collaboration of Multiple Robot Fish

Multi-robot fish is the future development direction. To complete large-scale operations in a time-critical situation, the collaboration between multiple robot fish can be significantly helpful. Therefore, the research on a series of key technologies such as multi-fish coordinated control, multi-fish coordinated swimming and single-fish swimming hydrodynamic model difference, multi-robot fish cooperation, formation control, etc., can be investigated in robot fish research.

In spite of the significant progress in the development of robot fish, challenges remain to meet the increasing needs for highly reliable, sustainable and intelligent robot fish from the industry. Some of the "hot" research realms include the development of a new actuation system, shape-design optimization, interactions between fish bodies and fluid field, swarm control, and machine learning for robot fish. It is noteworthy that, besides the aforementioned achievements, which mainly focus on robot fish research in laboratory, scientists and engineers have also devoted great efforts to robot fish industrialization and commercialization. Thanks to their efforts, robot fish has drawn increasing attention from the public in recent years, with a set of successful paradigms for various applications, as listed in Table 11. Investigations on using robot fish for applications such as environment monitoring, ecosystem monitoring and pipeline inspection are also the focus of their industrialization. With the increasing further development, it is believed that robot fish will significantly expand their applications in the future to be used in more and more fields.

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