

REVIEW

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Research Development on Fish Swimming



Yanwen Liu and Hongzhou Jiang*

Abstract

Fishes have learned how to achieve outstanding swimming performance through the evolution of hundreds of millions of years, which can provide bio-inspiration for robotic fish design. The premise of designing an excellent robotic fish include fully understanding of fish locomotion mechanism and grasp of the advanced control strategy in robot domain. In this paper, the research development on fish swimming is presented, aiming to offer a reference for the later research. First, the research methods including experimental methods and simulation methods are detailed. Then the current research directions including fish locomotion mechanism, structure and function research and bionic robotic fish are outlined. Fish locomotion mechanism is discussed from three views: macroscopic view to find a unified principle, microscopic view to include muscle activity and intermediate view to study the behaviors of single fish and fish school. Structure and function research is mainly concentrated from three aspects: fin research, lateral line system and body stiffness. Bionic robotic fish research focuses on actuation, materials and motion control. The paper concludes with the future trend that curvature control, machine learning and multiple robotic fish system will play a more important role in this field. Overall, the intensive and comprehensive research on fish swimming will decrease the gap between robotic fish and real fish and contribute to the broad application prospect of robotic fish.

Keywords: Fish swimming, Kinematics optimization, Motion control, Bionic robotic fish, Fish locomotion mechanism

1 Introduction

Considering the outstanding swimming performance like high speed, high efficiency and low noise, fishes have been the excellent reference for autonomous underwater vehicle (AUV) designers. Bionic robotic fish can be applied in many field as an underwater mobile platform, such as water quality monitoring and animal tracking [1–5].

The fish locomotion research can be tracked back to Aristotle. However, until in early 1900s, the qualitative research made significant progress under collaborations of zoologists and engineers. In this stage, Breder made a classification of fish species based on swimming modes, later Gray put forward the famous paradox that the drag power experienced by a dolphin is larger than the estimated muscle power [6, 7]. The mathematically oriented scientists entered this field around 1950. They developed

relevant theories and made it possible for quantitative studies of fish propulsion. Among these scientists, Lighthill, Taylor and Wu made a great contribution to fish hydrodynamics [8]. Compared with the resistive drag model developed by Taylor and waving plate theory proposed by Wu, Lighthill's large-amplitude elongated-body theory (LAEBT) is more realistic, intuitive and elegant, thus contributing to its wide application. A rigid robotic tuna made by Triantafyllou led to a wave of bionic robot fish research [9]. Almost at the same time, the development of computational fluid dynamics (CFD) made it easier for fish swimming simulation. In the year around 2014, Autonomous soft-bodied robotic fish fabricated by Marchese marks the arrival of the era of soft robotic fish [10].

Fish locomotion research has increased exponentially in recent years. Some influential research teams and their main research directions are summarized and listed in Table 1. It can be found that the related research takes place mainly in the USA, China and Europe. In particular, MIT and Harvard University are still the sources of innovation. China has advantages in motion control and

*Correspondence: jianghz@hit.edu.cn

School of Mechatronics Engineering, Harbin Institute of Technology, Harbin 150001, China

stiffness adjustment mechanism, but needs to take effort in biomechanics of fish swimming. Although significant progress on understanding fish locomotion mechanism has been made and a large number of robotic fish prototypes aiming to improve locomotor performance has been fabricated, there remains a gap between robotic fish and real fish to be addressed. Therefore, it is necessary to review and summarize the recent research development of fish swimming, which can provide a reference for the further research.

For convenience of later description, some basic knowledge about fish propulsion is added here. Generally, the propulsion modes can be divided into body/caudal fin (BCF) propulsion and median/paired fin (MPF) propulsion. About 85% of fish employ BCF propulsion for regular propulsion [11]. These fishes are further subdivided into three categories: anguilliform, carangiform, and thunniform modes [12].

This paper is organized as follows. Section 2 describes the research methods applied in fish locomotion. Section 3 presents the research directions at present. Section 4 discusses future trends. Finally, conclusions are summarized in Section 5.

2 Research Methods

Fish swimming is indeed a combination of active swimming and passive swimming. Internal biomechanics dominate the active swimming and external flow field influence the passive swimming, resulting in a fluid structure coupling (FSI) problem and then determining the final swimming performance. The following part will be detailed around this center.

2.1 Experiments

The outline of experimental research on fish swimming is shown in Figure 1.

The swimming performance: For real fish, the most direct method to obtain swimming characteristics is video recording. Scientists can get abundant data through this observation and know better about the tail-beat frequencies, swimming speeds, turn rates, swimming motions and so on of different fish species. For the purpose of making full use of the kind of data, Feeny developed a complex modal analysis technique to describe the main modes of lateral displacement, and the associated frequency and wavelength [16].

The internal biomechanics: Vivo experiments are the most important way to comprehend muscle activity and neural activity of fish. By using electromyograms (EMGs), Hamlet analyzed the calcium kinematics between muscle activity and neural activity [17]. Schwalbe studied the red muscle activity in bluegill sunfish [18]. Jayne found the red muscle motor pattern [19]. So far, compared with anguilliform fish, the neuro-musculo-mechanical model of carangiform fish and thunniform fish is far from perfect owing to its complexity.

The external flow field: The techniques of particle image velocimetry (PIV), digital particle image velocimetry (DPIV) and volumetric imaging system allow the visualization of flow field. FE Fish applied DPIV to get the vortex wake shed by fish tail [20]. Lauder used volumetric imaging systems to get 3D instantaneous snapshots of wake flow patterns [13]. Thandiackal used a modified PIV technique to obtain flow fields around the zebrafish body [21].

Nonetheless, quantifying time-varying forces and moments along the fish body in an experiment is still a challenge at present [22]. In addition, some cases like altering individual parameters such as body shape, body stiffness cannot be achieved in real fish. To address these problems, three alternatives could be considered: foil

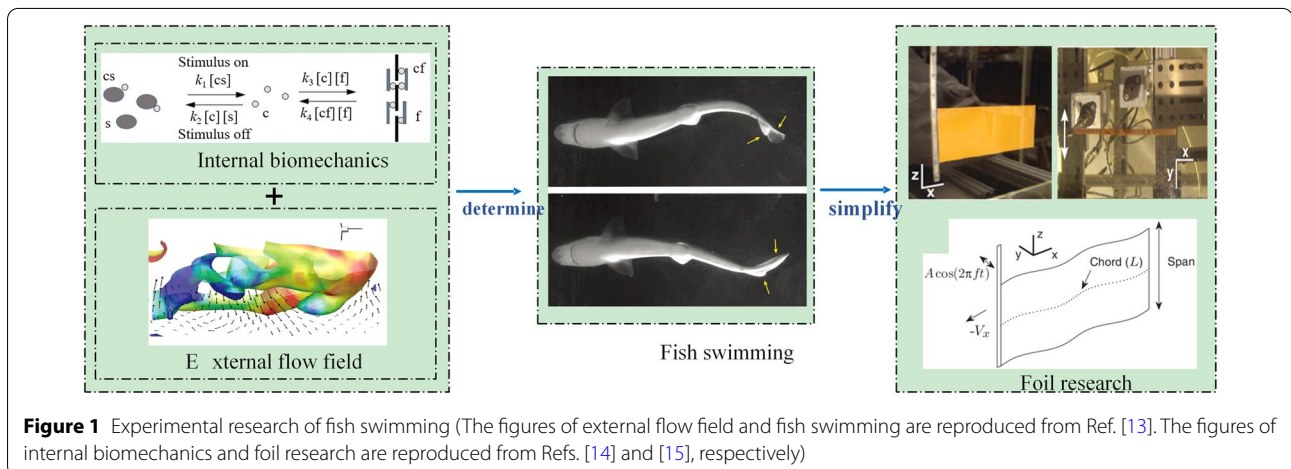


Figure 1 Experimental research of fish swimming (The figures of external flow field and fish swimming are reproduced from Ref. [13]. The figures of internal biomechanics and foil research are reproduced from Refs. [14] and [15], respectively)

research, simulation and robotic fish platform. The latter two will be presented in Sections 2.2 and 3.3, respectively.

Foil research: Because of the similarity between fish body and airfoil, fish can be simplified to periodically heaving and pitching foils in a steady free stream velocity [23]. Triantafyllou concluded that the Strouhal number St ($St = fA/U$, where f is the tail-beat frequency, A is the peak-to-peak tail amplitude and U is the mean swimming speed) of optimal fish propulsion should be in the narrow range 0.2–0.4 [8]. A further experiment carried about by Anderson validated the maximum efficiency can be reached in this interval [24]. Lauder used a robotic flapping foil platform to explore relevant parameter effects [25]. Alben found resonant-like peaks in the swimming speed as a function of foil rigidity [15]. Paraz showed thrust generation mechanism by a heaving flexible foil [26]. Van Buren analyzed the effect of flow speed on oscillating foils [27]. To some extent, foil research can be regarded as a pilot study for fish swimming research.

2.2 Simulations

Traditional theories like LAEBT are incompetent in a precise analysis. Nowadays, simulation methods are of two kinds in general: the dynamic model based on traditional theory and CFD method. The former focuses on the fish body and applies the traditional theory to simplify the forces exerted by external fluids, which is an

improvement of traditional theories. The latter simplifies the internal body dynamics and highlights hydrodynamics, which treats fish swimming as a FSI problem. In view of the advantages and disadvantages of dynamic model and CFD method (shown in Figure 2), some researchers have combined the two methods together to study the integrated system with both undulatory body and flexible fins systematically [28, 29].

Dynamic model: The premise of applying this method is to obtain the approximation of hydrodynamic force distribution along fish body. Once hydrodynamic force formulas are determined, calculations of dynamic models can be then carried out. When fish swims, the pressure field leads to a form drag in the forward direction and a resistive force in the lateral direction. The reversed Kaman vortex street generates a reactive force at tail and momentum transfer between fish surface and flow produces a skin friction. The sum of skin friction and form drag is the total drag force acting on the fish body. Ehrenstein analyzed the skin friction theoretically [33]. Lucas estimated the form drag in undulatory fish [34]. Zhang studied the total drag and Verma computed the force distribution on fish surface [35, 36].

There are two major approaches to the dynamic model: beam model and multi-body dynamic model. Cheng developed the continuous beam model based on waving plate theory [37]. Alvarado and Govindarajan

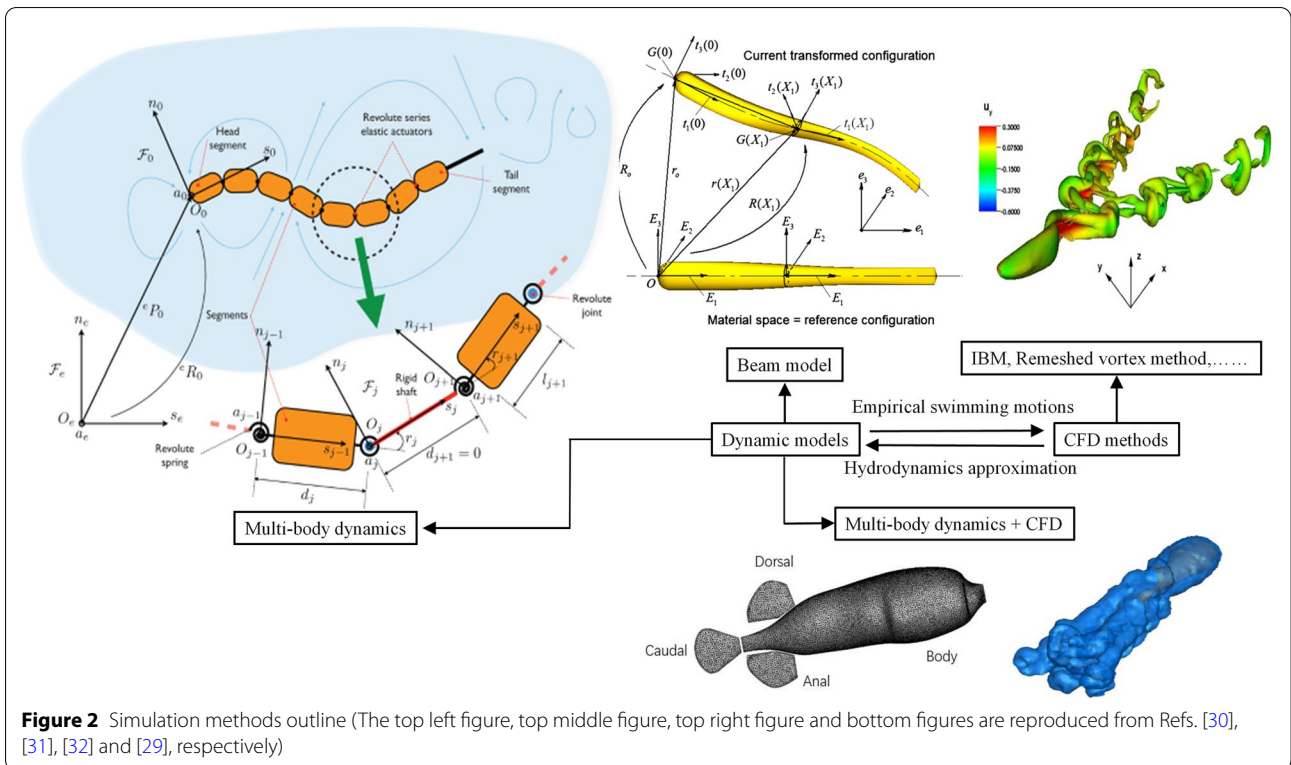


Figure 2 Simulation methods outline (The top left figure, top middle figure, top right figure and bottom figures are reproduced from Refs. [30], [31], [32] and [29], respectively)

established the Timoshenko beam model based on LAEBT [38, 39]. Piñeirua used the Euler–Bernoulli beam model to quantify the reactive and resistive contributions to the thrust [40]. Boyer built the Cosserat beam model based on LAEBT [31]. These models have four-order governing equations, which is hard to solve and limit the further application. Under such circumstances, a reduced dynamic model is usually used by introducing some approximation treatments. As for the multi-body dynamic model, Boyer has done much fruitful work in this field [41, 42]. Hongzhou Jiang and Zhao developed multi-body systems by capitalizing on decoupled natural orthogonal complement matrices and the Udwadia-Kalaba theory, respectively [43–45]. Bhalla incorporated a forced damped oscillation framework and resistive drag theory into a chain-link model to study undulatory propulsion [46]. Multi-body dynamic models have an active role in control and motion planning of robotic fish.

CFD method: Some main CFD methods applied in fish locomotion are listed in Table 2. Koumoutsakos, Patankar, Battista, Borazjani and Weymouth made plenty of achievements in this area. Besides, the immersed boundary method (IBM) has become the main stream. Conventionally, the body-fitted mesh approach based on unstructured grids is used to cope with such FSI problem, which can achieve a sharp resolution of solid-fluid interface. However, it usually requires frequent remeshing, complex mesh techniques and high computational

cost. IBM, first proposed by Peskin to study the heart valves, can overcome these difficulties by using a fixed Cartesian grid to discretize fluid domain and describing elastic body via a Lagrangian mesh [47]. The drawback of this method is that it cannot resolve the solid-fluid interface sharply. To address this problem, the adaptive mesh refinement (AMR) approach is used to deploy these localized regions of high resolution. Different methods like Level-set immersed boundary method (LS-IBM) and sharp-interface IBM are developed to deal with complex immersed surface problems.

3 Research Directions

3.1 Fish Locomotion Mechanism

The outline of research on fish locomotion mechanism is shown in Figure 3.

3.1.1 Macroscopic View

Researchers hope to find a unified principle like the Strouhal number St to reveal the intrinsic mechanism of fish locomotion. Gazzola uncovered a power law $Re \sim Sw^\alpha$ through existing observation data and numerical methods, in which Re is Reynolds numbers and Sw is a dimensionless swimming number (see Eqs. (1) and (2)) [82]. α equals 4/3 for laminar flows and 1 for turbulent flows.

$$Re = UL/\nu, \tag{1}$$

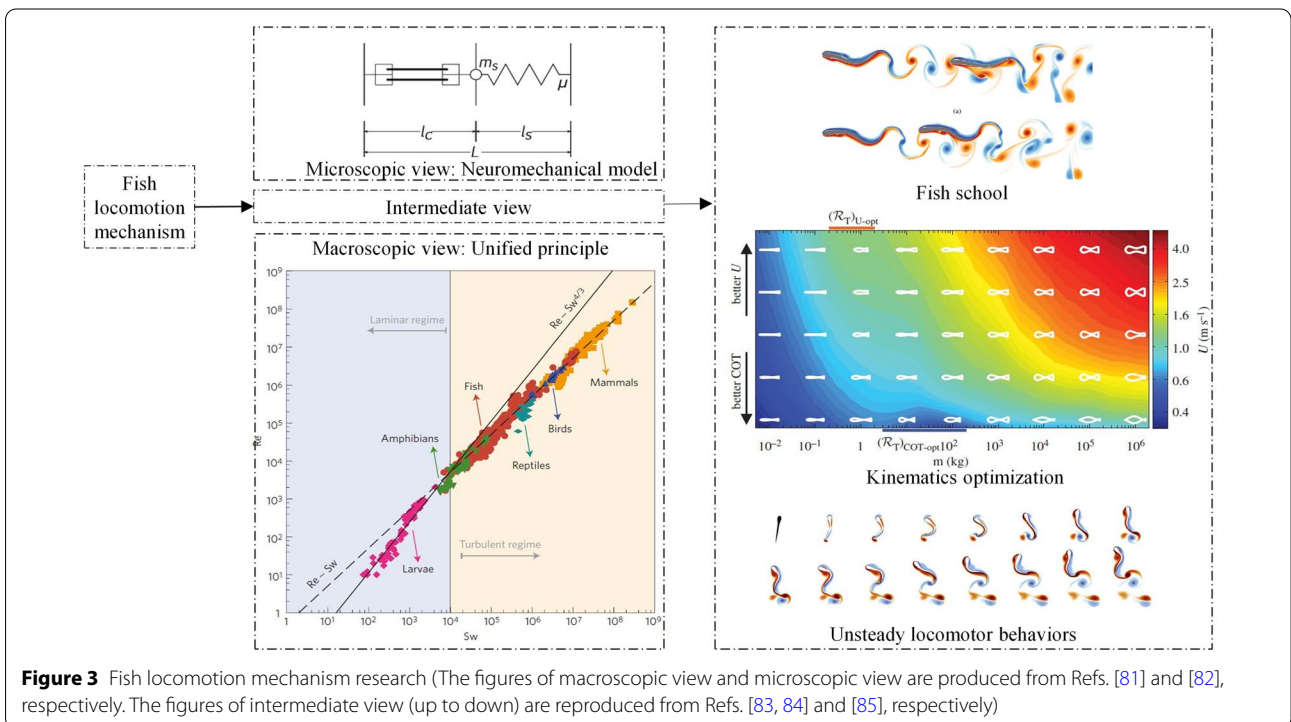


Figure 3 Fish locomotion mechanism research (The figures of macroscopic view and microscopic view are produced from Refs. [81] and [82], respectively. The figures of intermediate view (up to down) are reproduced from Refs. [83, 84] and [85], respectively)

$$Sw = \omega AL/\nu, \quad (2)$$

where U is the swimming speed; L is the fish length; ν is the fluid kinematic viscosity; ω is the tail-beat angular frequency.

Wiens found that efficient swimming kinematics can be characterized by a dimensionless variable (see Eq. (3)) [86]. The swimming efficiency peaks at $\Psi = 0.87$.

$$\Psi = 1 - \frac{\sin(\beta) - \pi St \cos(\beta)}{\beta - \pi St}, \quad (3)$$

where β is the pitch angle.

3.1.2 Microscopic View

Scientists hope to use both muscle activity and neural activity to interpret fish locomotion mechanism. Williams and Tytell analyzed the neuromechanical model systematically by considering fully the nonlinear muscles, passive viscoelasticity and body stiffness [17, 81, 87, 88]. Patel established hydrodynamically resolved computational neuromechanics by combining the neuromechanical model into the CFD method [89]. Ming and Zhao studied muscle activation patterns and muscle-contraction model of pre-strains, respectively [90, 91]. Tokić concluded the relationship between muscle efficiency and body size [92].

3.1.3 Intermediate View

Kinematics optimization: In face of massive observation data, researchers have limited information to determine which body movement is optimal. Numerical optimization can be helpful to overcome the above limiting constraint once the swimming optimization objectives are set. Swimming speed and efficiency are commonly used as optimization objectives. Due to the fact that swimming efficiency of a self-propelled flexible body is ill-defined, there is not a unified measure at present although scholars put forward different swimming efficiency measures respectively [93–95]. A further comparative research of different efficiency measures should be conducted like the work of Eguchi but it is beyond the scope of this paper [96].

Kern combined an ‘Evolution Strategy with Adaptation of the Covariance Matrix’ (CMA-ES) algorithm with hydrodynamics to get efficient and high-speed swimming motions of an anguilliform swimmer [97]; Van Rees utilized the same method to optimize kinematics and body shapes for undulatory swimmers [98]. Nevertheless, this technique fails to consider the internal dynamics and is not suitable for swimming at high Reynolds numbers. Eloy Optimized undulatory swimming at high Reynolds number based on an improved linear system [99]. Tokić

obtained optimal shapes and motions of swimming animals by applying elongated-body theory and evolutionary optimization algorithms [84]. The disadvantage of this model is that it only function for small-amplitude motion. Eloy found two kinds of optimal body shapes by using a reduced dynamic model, one with good swimming efficiency and the other with large stride lengths [100]. But the latter body shapes do not exist in nature, so the effectiveness of the model needs further verification. Patankar studied the optimal wave length in BCF swimmers and found that a rigid body attached to an undulating fin leads to an increased efficiency in MPF swimmers [101, 102].

On the other hand, optimality and resonance are closely inter-related with the hypothesis that fish can use resonance to lift swimming efficiency [103–105]. When the tail-beat frequency reached around the body’s natural frequency, fish consumes a minimal negative work. However, their relationship and influencing factors should be further studied because different scholars yielded inconsistent results [106, 107].

Unsteady locomotor behaviors: Except for steady swimming, there are also other locomotor behaviors for specific purposes: fast start, turning locomotion and burst-and-coast swimming [108–112]. C-start is a typical escape response of prey for predator. Fishes first bend their body to C-shape and then recoil their body quickly to accelerate. Gazzola identified the C-start pattern which minimize the escape distance and Currier designed a robotic fish that can generates fast-start accelerations of more than 20g by utilizing a dynamic snap-through buckling mechanism [85, 113]. As for turning locomotion, a fundamental life function, fish can use it to change swimming direction frequently and flexibly for finding food or mates. Thandiackal estimated pressure forces and the mechanical work along the body during turning [21]. Xin held that fish turn quickly on account of the directional control strategy of the swing of the head [114]. Dabiri analyzed rotational mechanics of turning maneuvers [115]. Feng revealed that thunniform fish have a poorer turning ability than anguilliform fish and carangiform fish [116]. The burst-and-coast swimming, as an intermittent form of locomotion, which can confer energetic benefits, has two successive stages: active undulation powered by fish muscles followed by a prolonged unpowered gliding. Li showed that fish adjust the bursting-to-coasting ratio to maintain the demanded speed [109]. Wang indicated that wake structures of burst-and-coast swimming are obviously different from these of continuous swimming [117]. Dan Xia explored the energy-saving advantages of this intermittent locomotion [118]. Verma discovered a range of intermittent-swimming patterns with multi-objective optimization [54]. Akoz found the relationship

between efficiency and a dimensionless heave ratio in intermittent swimming [119].

Fish school: The key to understanding fish-schooling behavior lies in making clear the role of fluid medium or flow structures [120–123]. A single fish can be a good analytical entry point. F E Fish held that the active flow control mechanism of swimming animals is to generate wake flow structures actively [20]. Macias concluded that net thrust appears in reverse Von Kármán wakes [124]. Khalid and Zhang studied the wake structure in different Reynolds numbers, respectively [125, 126]. However, Floryan deduced that wake structures are not a reliable method to study swimming performance [127]. The role of fluid medium for single fish still needs an in-depth study. On the other hand, with respect to the hypothesis that fish can exploit the neighbor-induced flow to save energy, different researches about fish school have been conducted. Li analyzed the interference of vorticity and pressure fields of a fish school [128]. If two fish are arranged in an in-line configuration, the follower can reduce up to 30% energy cost and the leader benefits energetically only for small distances by exploiting independent pitch control of its caudal fin [83, 129, 130]. Moreover, pitching motions can increase the group efficiency while heaving motions can lead to a slight increase in the swimming speed [122]. In this in-line configuration, Dai discussed the effect of the horizontal spacing and vertical spacing between two fish [131]; Verma improved coordinated patterns through deep reinforcement learning [132]; Li found that the follower can exhibit ‘vortex phase matching’ strategy [133]. In addition, Chao studied the tandem, parallel and staggered arrangements of two fish [134]. Dai, Li and Ashraf simulated the tandem, the phalanx, the diamond and the rectangle configurations for three fish or four fish, respectively [131, 135–137]. In spite of these achievements, scholars still do not reach a unified conclusion on the efficiency of fish school.

3.2 Structure and Function Research

It has to be admitted that fish are such a fascinating aquatic animal that almost every part of the body has been studied more or less. For example, the research team of Li Wen fabricated an underwater robot with of strong adhesion capability by fully understanding the function of adhesive discs in remoras [138, 139]. They also studied the function of shark skin denticles and designed an artificial shark skin that reduces the cost of transport by 5% [140]. Weymouth designed a size-changing robotic swimmer by using the jet pulsing mechanism in octopuses [141]. Long Jr, Chao and Nesteruk analyzed the evolution, asymmetric geometry and the effect on efficiency for fish shape profile independently [142–144]. Thus, it is difficult to give an overall review in this aspect. Nevertheless, we attempt to

classify this research into the following three categories roughly. Note that structure and function research is definitely not confined to the following types.

3.2.1 Fin Research

Among fish fins (shown in Figure 4), the most effective fin should be the caudal fin, which plays a key role in self-propelled locomotion. Besides, other soft appendages of fish, such as anal fin, dorsal fin and pectoral fins, also play an important role in precise fish swimming research, although they are usually ignored in past studies for the purpose of simplicity. Scholars expect to study the fins to improve swimming performance to some extent. The main fin research types are summarized and listed in Table 3. It shows that researches are more concentrated on the computational model and the integral study of body-fin system.

3.2.2 Lateral Line System

Biologists have discovered that fish can obtain surrounding fluid environment information by lateral line system (LLS) to achieve some basic activities including hunting, swarming and obstacle avoidance. LLS has two perceptual functions: one is the identification of the flow direction and flow speed by surface nerve mound, and the other is pressure gradient sensation by duct nerve mound [167]. More details about the flow-sensing mechanism of these two mounds can be referred to Ref. [168]. Inspired by the nature, different artificial LLS systems that are equipped with a pressure sensor array have been developed to sense the fluid environment (shown in Figure 5). Guijie Liu investigated the effect of speed and flow angle and studied not only near-field detection but also the AUV’s pitch motion parameters perception [169, 170]. Although the sensing capability has been achieved, the sensitivity and stability of these current systems need to be further improved. The sensor configuration, the flow field perception algorithm and state recognition are the keys to be addressed. Verma studied the optimal spatial placement of these sensors and found that a high density of sensors should be located in the head and other sensors only need to be distributed along with the body uniformly [171]. Guijie Liu used pressure difference matrix to identify the flow field, Tang utilized the free surface wave equation to percept the vibrating sphere and Maertens combined potential flow model with a linear analysis of the boundary layer to improve the existing object identification algorithm [172–174]. As for state recognition, a back propagation neural network and convolutional neural network are applied to predict the flow information quickly [169, 170], respectively. In addition, Gao held that vorticity control can be conducted precisely based on LLS when fish swim in schools [175].

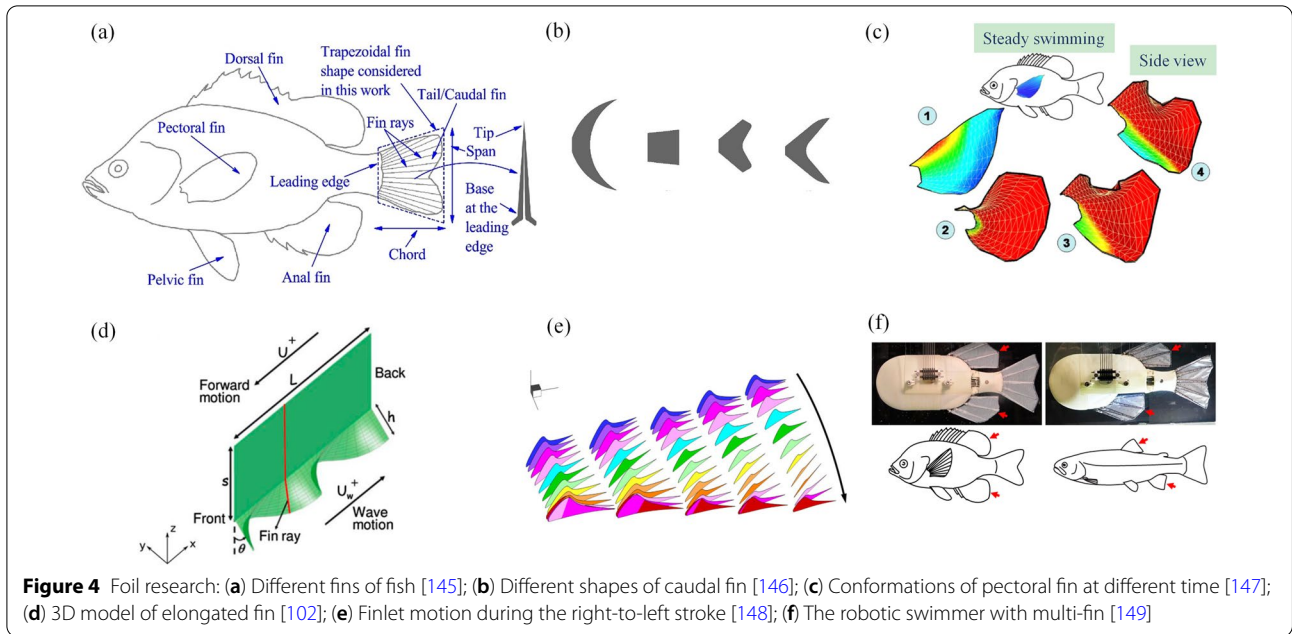


Figure 4 Foil research: (a) Different fins of fish [145]; (b) Different shapes of caudal fin [146]; (c) Conformations of pectoral fin at different time [147]; (d) 3D model of elongated fin [102]; (e) Finlet motion during the right-to-left stroke [148]; (f) The robotic swimmer with multi-fin [149]

Table 1 Some research teams on fish swimming

Representative	Research direction	Affiliation	Representative	Research direction	Affiliation
Triantafyllou, MS	Comprehensive research	MIT, USA	Jiang HZ	Variable stiffness mechanism	HIT, China
Daniela, Rus	Soft robotic fish	MIT, USA	Chen WS; Xia Dan	CFD; Multi-joint propulsion	HIT, China
Lauder, GV	Comprehensive research	Harvard University, USA	Li TF	Smart materials	Zhejiang University, China
Frank E Fish	Biomechanics	West Chester University, USA	Du RX; Li Zheng	Motion control; Compliant robotic fish	CUHK, China
Patankar, NA	CFD	Northwestern University, USA	Hu HS	Multi-joint robotic fish	Essex University, UK
AJ. Smits	Fish locomotion mechanism	Princeton University, USA	GD. Weymouth	CFD; Size-changing swimmer	Soton, UK
Tyler McMillen	Biomechanics; Neural control	Princeton University, USA	Boyer	Dynamic model	IMT Atlantique, France
Long, JH	Reconfigure; Body stiffness	Vassar College, USA	Eloy	Fish hydrodynamics	IRPHE institute, France
Iman Borazjani	CFD	Texas A&M University, USA	Benjamin Thiria	CFD; Dynamic model	IRBI, France
ED. Tytell	Biomechanics; Neural control	Tufts University, USA	Petros K	CFD; Optimization	ETH Zurich, Switzerland
Xiaobo Tan	Dynamic model	MSU, USA	EL Daou	Compliant robotic fish	TalTech, Estonia
Su YM	Smart material, CFD	HEU, China	Ikuo Yamamoto	Oscillating fin propulsion	Nagasaki University, Japan
Li wen; Wang TM	Comprehensive research	Beihang University, China	DQ Nguyen	Compliant robotic fish	JAIST, Japan
Pan Guang	CFD; Foil research	NPU, China	Xu JX	Motion control	NUS, Singapore
Yu JZ; Tan Min	Motion control strategy	CAS, China	ZH Akpolat	Multi-joint propulsion	University of Firat, Turkey
Xie GM	Motion control; CFD	Peking University, China	Atul Sharma	CFD	IIT Bombay, India

3.2.3 Body Stiffness

Fish can modulates body stiffness actively to adjust its swimming performance through muscles, tendons and other biological tissues [179–181]. Through testing biological structures, Long Jr supported the biological

hypothesis that fish swimming behaviors are controlled by the body stiffness and the stiffness can be altered by the vertebral column [182]. Ardian Jusufi built a platform to modulate the whole body stiffness by changing the pressure of soft pneumatic actuators (SPA) that are

Table 2 Main CFD methods applied in fish locomotion

CFD method	Description	Representative
Conventional method	Finite volume approach for Navier-Stokes equation; Fluent use-defined function for Newton equation; Staggered integration algorithm for coupled system	Koumoutsakos [48]; Xia Dan [49–51]; Ningyu Li [52, 53]
Remeshed vortex method	A penalization technique for the no-slip boundary condition and a projection method for the action from fluid to body	Koumoutsakos [54, 55]
MPCDM	Only for low Reynolds numbers	Reid [56]
LS-IIM	Level-set function for solid-fluid interface	Thekkethil [57]
FuRMoRP	Distributed Lagrange multipliers methods for rigid and flexible bodies	Patankar [58]
Delta-plus-SPH	Delta-plus-SPH scheme for numerical accuracy and efficiency	Sun [59]
IBM		
Pure IBM	For idealized object like jellyfish or rigid foil	Battista [60–63]; Hemmati [64]
IBAMR	Cartesian grid adaptive mesh refinement (AMR) for motion equation discretization	Patankar [32, 65]; Pan Guang [66, 67]
LS-IBM	Level-set function for solid-fluid interface	Atul Sharma [68, 69]; Cui Zuo [70–72]
Sharp interface IBM	A discrete-forcing scheme a “sharp” representation of the immersed boundary	Dong Haibo [73–75]
BDIM	The field equations of whole domain are combined analytically	Weymouth [76, 77]
HCIB	Hybrid staggered/non-staggered mesh formulation for boundary conditions	Borazjani [78]
Other methods	A uniform Cartesian grid for Poisson equation and volume penalization method for deformable body	Ghaffari [79]; Bergmann [80]

Note: HCIB: Hybrid Cartesian/immersed boundary method; LS-IIM: A level-set function based immersed interface method; FuRMoRP: Fully resolved momentum redistribution for self-Propulsion algorithm; BDIM: Boundary Data Immersion Method; MPCDM: Multiparticle collision dynamics model.

attached to a flexible panel [183–185]. These experimental results shows that there exist complicated interactive effects of both the frequency and stiffness on fish swimming performance. Tytell utilized a neuromechanical model to examine the role of body stiffness and found that fish can tune its body stiffness by appropriately

timed muscle contractions to achieve maximum speed [186]. Furtherly, he put forward a nondimensional effective flexibility (see Eq. (4)) to study the comprehensive effect of scaling flexibility and consequently to estimate the relevant resonant frequency.

Table 3 Fin research types and corresponding contents

Fin research types	Research contents
Caudal fins	Computational model [150, 151]; Stiffness [50, 145, 152]; Leading edge [153]; Trailing-edge [154]; Sweep angle [155]; Motion Planning [156]; Effects of St and Re [157]; Optimal kinematics [158]
Non-caudal fins	
Pectoral fins	Computational model at high Re and fin kinematics [147]; A structure design of pectoral fins [159, 160]
Median fins	Linear Acceleration [161]; elongated fin and dorsal fins [102]
Finlets	The wake structures and the flow around the finlet [162]; The hydrodynamic performance and vortex dynamics [148]
Comprehensive research	Biorobotic models of multi-fin systems [163]; The propulsive forces produced by multiple fins [149]; Numerical approach [164]
Interactions	Body-fin and fin-fin interactions [165]; The structure relationships between body and caudal fin [166]; Interactions between caudal fin and pectoral fin [146]

Note: Finlets are some small non-retractable fins and locate on the body margins between the caudal fins and the dorsal/anal fins.

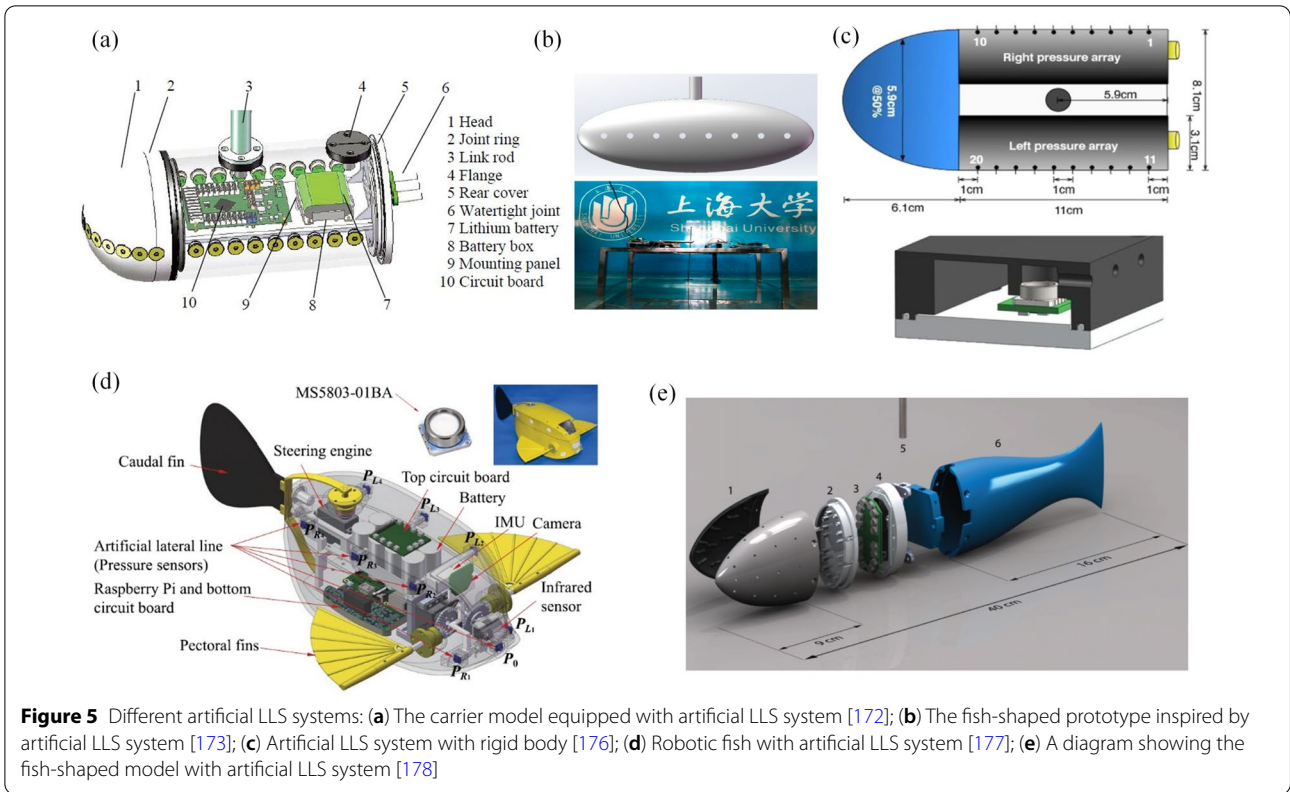


Figure 5 Different artificial LLS systems: (a) The carrier model equipped with artificial LLS system [172]; (b) The fish-shaped prototype inspired by artificial LLS system [173]; (c) Artificial LLS system with rigid body [176]; (d) Robotic fish with artificial LLS system [177]; (e) A diagram showing the fish-shaped model with artificial LLS system [178]

$$\Pi = \left(\frac{\rho h l^2 f^2}{EI} \right)^{1/2}, \tag{4}$$

where ρ is the fluid density, h is the average height of fish, l is the length, f is the tail-beat frequency and EI is the bending modulus.

Floryan obtained the optimal flexibility distribution along with the body of simmers through a linear inviscid model [187]. They discovered that significant thrust gain can be made and a resonance can be triggered by tuning the stiffness. The stiffness of their model are characterized by Eq. (5). Using this scaling stiffness, Luo studied the effect of stiffness of both fish body and caudal fin [188].

$$S = \frac{Eh^3}{\rho U^2 l^3}, \tag{5}$$

where E is the Young’s modulus and U is the swimming speed.

The biological principle and the effect of stiffness on swimming performance have been described above. Then, the stiffness adjustment mechanisms are introduced (see Figure 6). Xu Dong proposed a variable stiffness mechanism based on the negative work. He adopted a fuzzy controller to mimic this mechanism and describe

the relationship between stiffness and negative work [189]. The result shows that energy consumption during fish swimming is reduced and the propulsion efficiency is improved. Hongzhou Jiang applied a variant of redundant planar rotational parallel mechanisms—a variable stiffness decoupled mechanism based on mechanically adjustable compliance and controllable equilibrium position actuator (MACCEPA) to develop a robotic fish with large stiffness variation [190, 191]. Moreover, he fabricated a tensegrity robotic fish, which is composed of a series of rigid segments connected with tensegrity joints. The stiffness of each segment of which can be altered in theory [192].

3.3 Bionic Robotic Fish

Some bionic robotic fishes for specific research purposes have been mentioned above. Generally, robotic fish development has experienced three periods: rigid robotic fish, compliant robotic fish and soft robotic fish. This section deals mainly with the actuation, material and motion control of robotic fish.

3.3.1 Actuators and Materials

Almost all the robotic fish can be tracked back to Robo-Tuna designed by Triantafyllou. The development of rigid

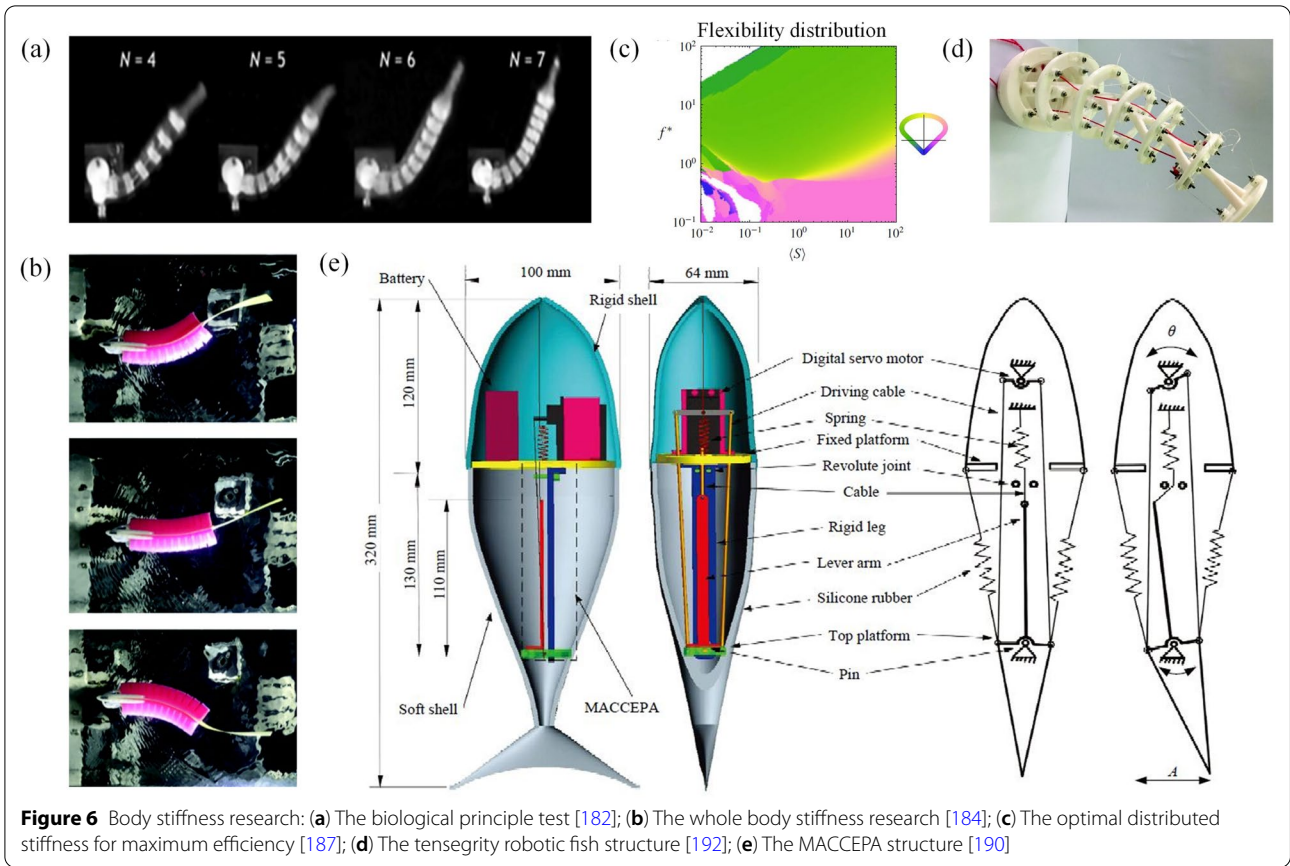
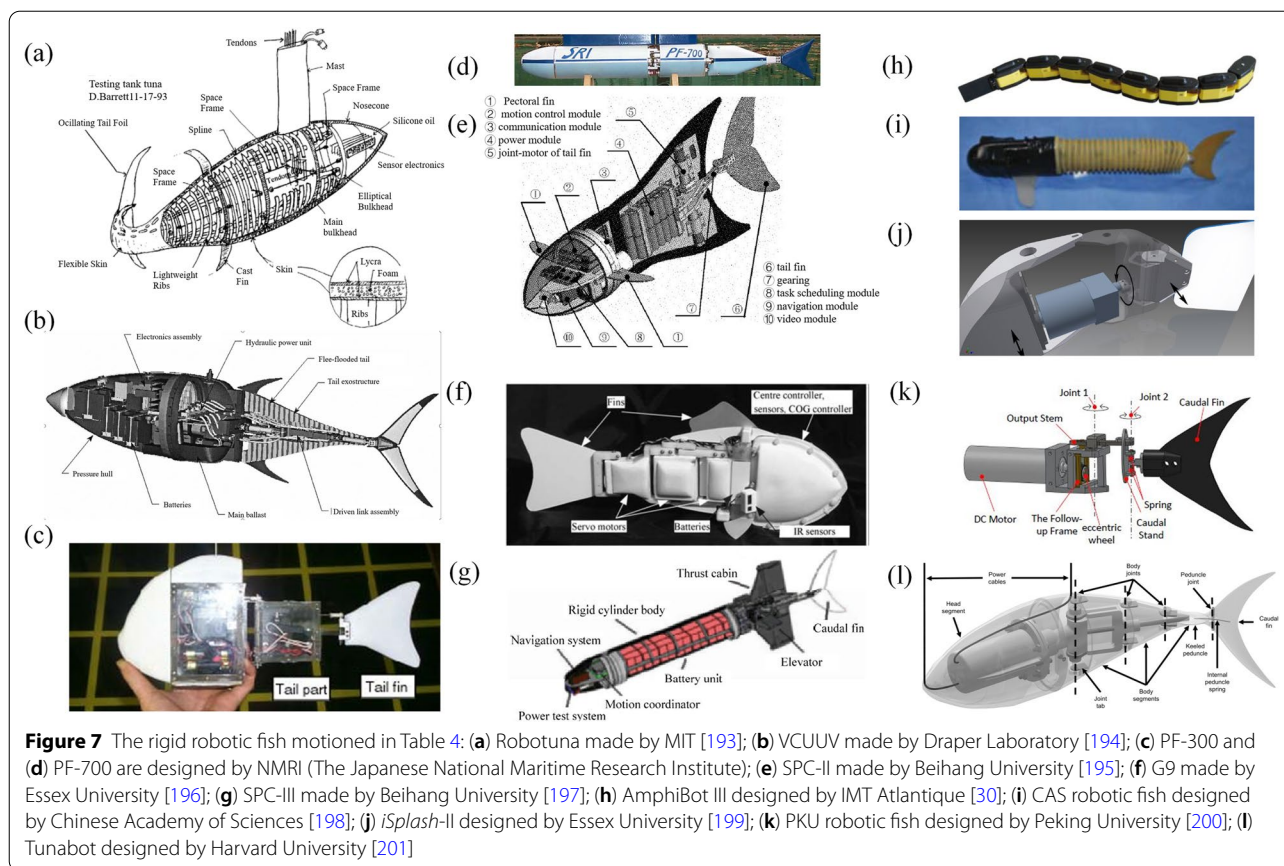


Table 4 A summary of rigid robotic fish

Year	Name	Speed (BL/s)	f (Hz)	Joints	Actuators	Turning radius (BL)	Turning rate ((°)/s)
1994	Robotuna	0.65	—	6	DC servomotors	—	—
1999	VCUUV	0.61	1	4	Hydraulic piston	2	75
2000	PF-300	0.59	2.3	2	DC servomotors	0.8	36
2001	PF-700	1	10	2	DC motor+ DC servomotor	—	—
2005	SPC-II	1.2	2.5	2	DC servomotors	—	30
2006	G9	1.96	—	3	DC servomotors	0.3	120
2010	SPC-III	1.17	2.5	2	DC servomotors	0.75	—
2014	AmphiBot III	0.67	—	8	DC motors	0.28	—
2014	CAS robotic fish	1.04	—	4	DC servomotors	0.23	670
2015	iSplash-II	11.6	20	4	Electric motor	—	—
2016	PKU robotic fish	2.6	12	2	DC motor	—	—
2020	Tunabot	4.64	8	4	DC motor	—	—

robotic fish is shown in Table 4 and Figure 7. The main driving mode includes motor drive and hydraulic drive. The motor can be further divided into three types: steering engine, servomotor, DC (Direct current) motor. The advantages of motor drive are that it can achieve precise

predefined motion and high-frequency oscillation and can provide high power, while this kind of drive has large noise, high power consumption and complex structure. Hydraulic drive can bring about large driving torque, but the shortcoming is that it needs a complete hydraulic

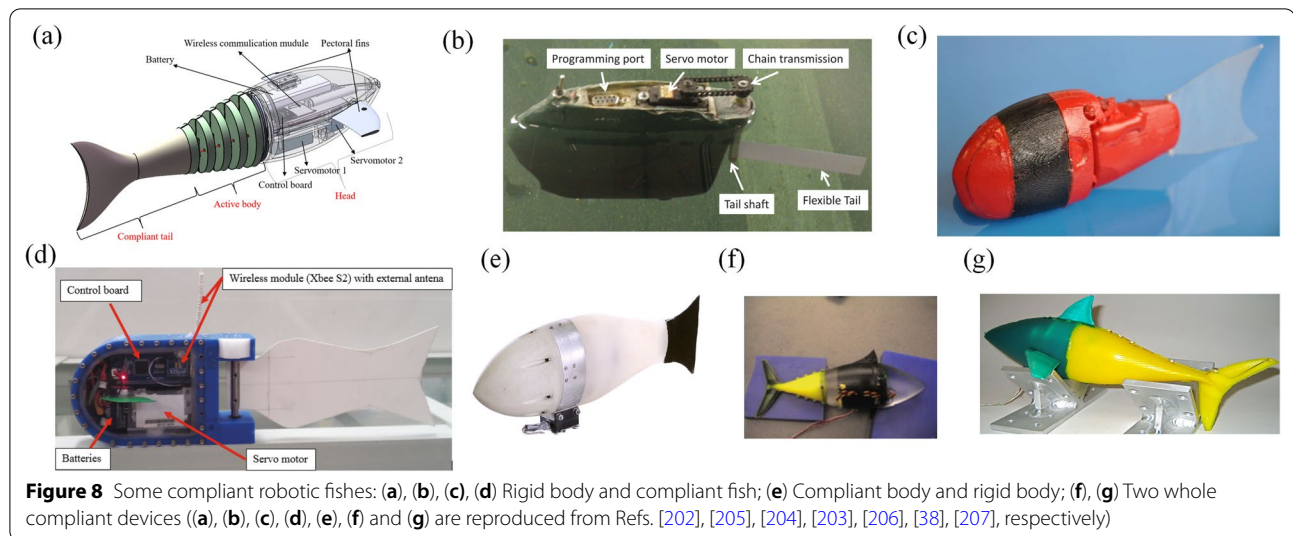


system. Both of the above drive modes need large space. To mimic the body wave of real fish, rigid robotic fish always is composed of rigid links and rotation joints. Single link is the simplest design that uses a single motor to drive the caudal fin. By contrast, multiple links can imitate the fish skeletons better and gives the robotic fish a higher degree of freedom. However, this multiple-link structure is difficult to control. As for the material of rigid robotic fish, it does not have high elastic deformation capability due to high stiffness. There are three types of material usually used: metals like aluminum and steel, plastic like polystyrene, PVC and plexiglass and composite like carbon fiber.

Compliant robotic fish is a transitional stage between rigid robotic fish and soft robotic fish, which is typical featured by soft materials and traditional drive mode. Therefore, deformation can happen passively. Soft materials have a large elastic deformation and can recover to original shape. Rubber like silicone and latex and metals like spring steel and cables are usually applied in compliant robotic fish. On the other hand, soft materials can be used to protect actuators and waterproof. There exist three kinds of research types on compliant robotic fish (see Figure 8): (1) robotic fish composed of rigid body

and compliant tail [202–205]; (2) robotic fish composed of rigid tail and compliant body [206]; (3) a whole compliant device [38, 207]. Zhong designed a novel robotic fish with wire-driven active body and compliant tail, which outperforms many rigid robotic fish [202]. The maximum swimming speed is up to 2.15 BL/s, the highest Froude efficiency to 97% and the average turning rate to 63°/s. Interestingly, some researchers found resonance phenomenon in swimming speed, thrust and efficiency [38, 203, 206].

Soft robotic fish with a continuously deformable body can exhibit continuum motions that conventional rigid-bodied robotic fish cannot achieve, which has become a new hotspot. The soft materials have been introduced above. The biggest difference from the above two kinds of robotic fish is the soft actuation. Soft actuators applied in robotic fish are summarized and listed in Table 5 and Figure 9. All the actuators except FEA belong to functional material actuations. FEA plays a key role in soft robotics field and was used to robotic fish first by Marchese [10]. The high complexity and nonlinearity of FEA make the dynamics modeling challenging. Zhou established a theoretical model to predict the bending angle of a bi-directionally FEA [208]. Tao Wang developed a universal

**Table 5** A summary of soft actuators used in robotic fish

Actuator	Description	Mechanism
FEA (Fluidic Elastomer Actuators)	Pressure input leads to bending constrained by an inextensible layer; Stress < 5 MPa, strain < 15%, typical frequency \approx 2 Hz, efficiency < 20%, work density \approx 0.5 J/kg	See Figure 10
DEA (Dielectric Elastomer Actuators)	Maxwell stress results in compression in one side and extension in the other; Stress < 7.2 MPa, strain < 380% (area), typical frequency \approx 1–10 Hz, efficiency < 90%, work density < 3.5 J/kg	
SMA (shape memory alloy)	Deformed at low temperatures and recovered to original shape at high temperatures; long time delays; Stress > 300 MPa, strain > 4%, efficiency > 3.8%	
IPMC (ionic polymer-metal composite)	When an electric field is applied, swelling on the cathode side and shrinking on the anode side cause bending; Stress < 5 MPa, typical frequency \approx 5 Hz, efficiency < 3%, work density < 4 J/kg	

Note: (1) As a reference, the performance metric of mammalian muscle is listed here. Stress \approx 0.1–0.35 MPa, strain \approx 20%–40%, efficiency \approx 40%, work density \approx 8–40 J/kg. (2) The relevant data in Table 5 are gathered from Refs. [223, 224].

model for FEA based on constant curvature assumption and Lagrangian approach and further proposed a non-linear robust control model based on system identification [209, 210]. Optimizations aiming to improve the FEA performance have also been made. Hu evaluated the effect of structure parameters such as input pressure, the wall thickness and the gap between chambers to optimize the performance of FEA [211]. Yang adopted a new form of free bottom of FEA and thus improved the bending capacity of FEA [212]. Li proposed a fiber-reinforced FEA that can bear high pressure up to 400 kPa [213]. Consequently, some FEA variations are applied in robotic fishes. Feng used a fiber-reinforced FEA array to generate body wave of anguilliform fish [214]. Frame manufactured jellyfish robot with eight FEAs extending radially from its center [215]. Joshi replaced FEAs of jellyfish robot with soft pneumatic composite actuators which consists of FEAs and thin steel springs [216].

3.3.2 Motion Control

Motion control can be roughly divided into two classes: open-loop control for body wave generation and close-loop control based on dynamic models. Open-loop control always fits the body wave by designing predefined multiple-link kinematics or using functional material actuators. In another way, central pattern generator (CPG) method can generate periodic signals for joints directly without sensory feedback. Inspired by the biological neural network, CPGs are analogue to an array of coupled neurons that produce oscillatory signals [226]. Although it lacks enough theoretical basis, CPG control has been widely used in bionic engineering [227–231]. Due to no feedback in open-loop control, it cannot reach the desired motion compared with close-loop control. As for close-loop control, speed control, depth control, attitude control, path following and target tracking are emphatically introduced below (see Table 6).

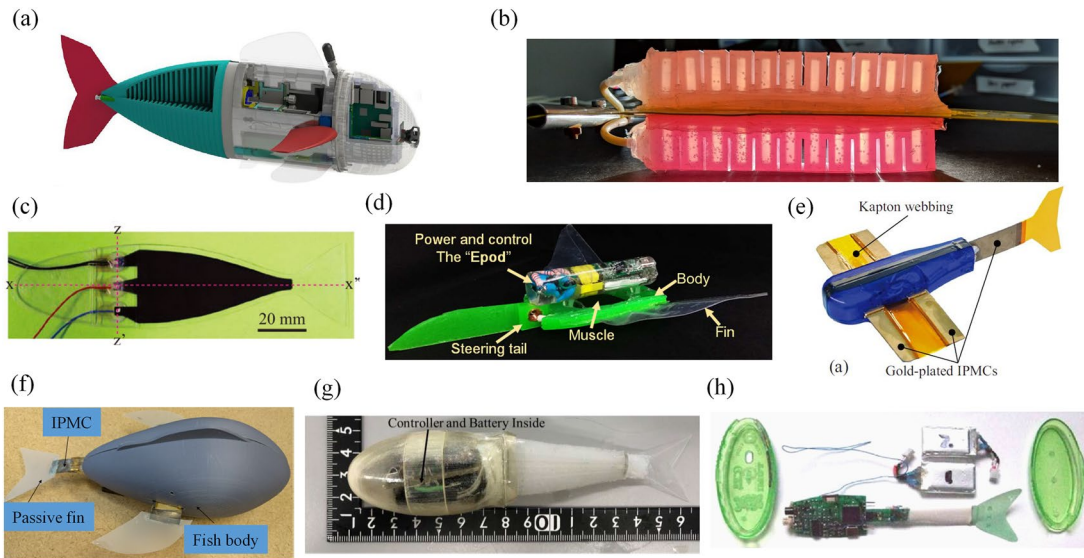


Figure 9 Some typical soft robotic fish: (a), (b) Actuated by FEA; (c), (d) Actuated by DEA; (e), (f) Driven by IPMC; (g), (h) Driven by SMA ((a)–(h) are reproduced from Refs. [3], [185], [217], [218], [219], [220], [221] and [222], respectively)

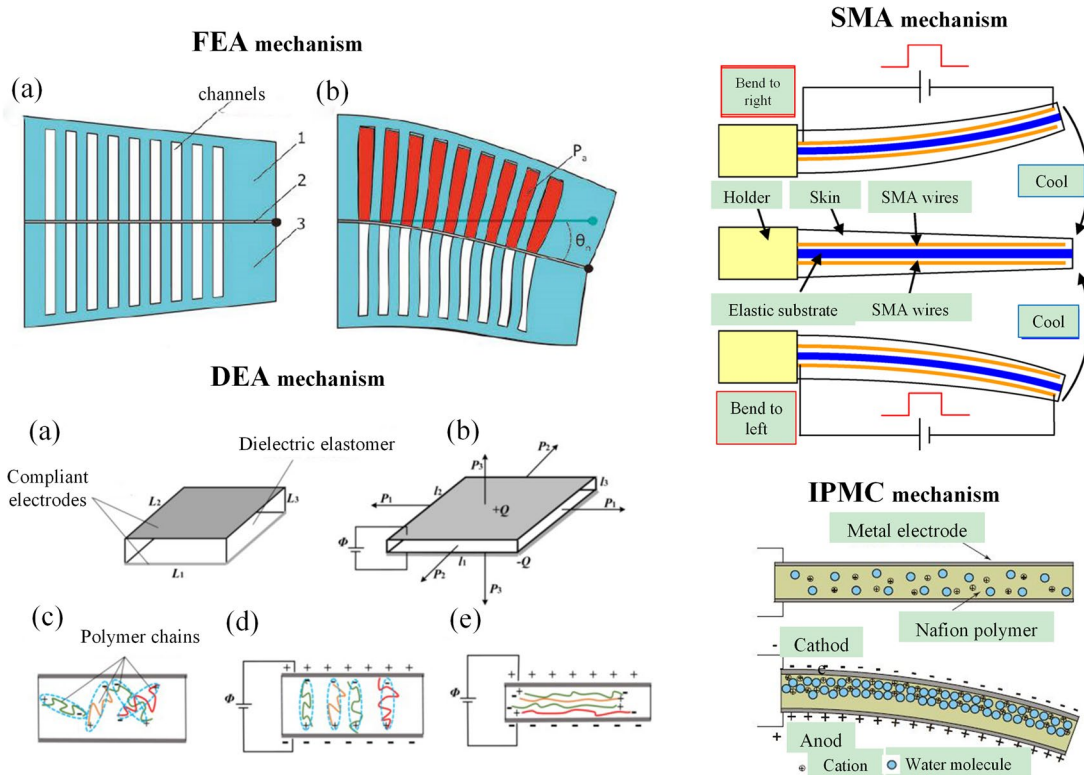


Figure 10 Soft actuator mechanisms (The figures of FEA mechanism, SMA mechanism, DEA mechanism and IPMC mechanism are reproduced from Refs. [10, 222, 225] and [219] respectively)

Table 6 Overview of close-loop motion control

Control objective	Representative	Control description	Control objective	Representative	Control description
Speed control	Verma [243]	SMC based on data-driven model	Attitude control	J Yuan [235]	SMO-based heading control
	X F Li [244]	Iterative learning control method	Path tracking	J Pan [247]; S Du [248]	Target point is first obtained by LOS method and is then transformed to an offset rotation angle by fuzzy-linear model
Depth control	T Yuan [245]	A Kalman filter based force-feed-back control		J Z Yu [239]	A point-to-point control algorithm and real-time visual feedback
	F Shen [233]	Fuzzy PID control		Kopman [204]	System input is the servomotor angle and a PID algorithm is implemented
	P F Zhang [246]	TSOV-NMPC algorithm		R Wang [249]	ADRC strategy is used to reduce the system uncertainty
	J Z Yu [234]	Sliding-mode fuzzy control		R Wang [250]	BS technique and LOS method are integrated
Attitude control	L Zhang [232]	Fuzzy logic control	Target tracking	Y H Hu [240]	Proportional feedback control
	R Y Tian [238]	ADRC strategy		J Z Yu [242]	A sliding-mode fuzzy control and a multiple-stage directional control are integrated
	C Meurer [237]	Nonlinear PD controller		S L Chen [241]	BS-based hybrid target tracking control
	Z Q Cao [236]	Self-tuning fuzzy strategy	Leaping control	J Z Yu [251]	AoA-based speed control and the hybrid closed-loop control are integrated

Note: LOS means line-of-sight; PID means proportional integral derivative; ADRC means active disturbance rejection control; SMC is sliding mode control; TSOV-NMPC means two-stage orientation-velocity nonlinear model predictive controller; PD means proportional derivative; SMO means sliding mode observer; AoA means angle of attack; BS means backstepping

Speed control: Precise speed control of robotic fish is essential for motion control and motion planning. Xu JX's team of National University of Singapore has done much work on the speed control and has proposed several control methods, including SMC, data-driven model and iterative learning method.

Depth control: Vertical movement is also important besides horizontal motion, which can help fulfill many tasks, such as seabed mapping, ocean exploration. As shown in Table 6, Zhang adopted fuzzy logic method to control depth by changing the angle of pectoral fin [232]. Shen applied fuzzy PID control to change the center of gravity for depth control [233]. In the work of Junzhi Yu, SMC and fuzzy control are combined to regulate the depth of robotic dolphin [234]. It can be seen that fuzzy control is often used in depth control.

Attitude control: Attitude includes three aspects: roll, pitch and yaw. Most relative studies researches focus on the single attitude control. Yuan and Cao designed SMO and self-tuning fuzzy strategy for heading control of robotic dolphin, respectively [235, 236]. Meurer used nonlinear PD controller for yaw control of compliant robotic fish [237]. Tian developed an ADRC strategy to track the target pose [238].

Path tracking: According to different targets, path tracking includes two aspects: way-point tracking, path

following. Junzhi Yu's team of Chinese Academy of Sciences has made many efforts in this field. As for way-point tracking, Yu successfully applied point-to-point control algorithm in four-link robotic fish [239]. Kopman implemented PID control for a two-link robotic fish [204]. As for path following, Yu's team developed a series of methods successively, including BS technique, LOS method, ADRC and fuzzy-linear model.

Target tracking: Target tracking faces the challenges of complex fluid environments such as weak light, limited field of view and obstacles. Hu gave a decentralized control methods for two vision-based robotic fish to fulfill the tasks of target tracking and collision avoidance [240]. Chen used BS technique to develop a target tracking control framework and Yu designed a target tracking control scheme that combines sliding-mode fuzzy control and multiple-stage directional control [241, 242]

4 Research Trend

4.1 Curvature Control

Theory Basis: Past studies always attempted to develop a comprehensive swimming model including muscle activity, passive viscoelasticity and fluid mechanics. Although much progress on muscle model has been made by EMGs, the neuro-musculo-mechanical model, owing to its complexity, is still far from perfect especially for

carangiform fish and thunniform fish. McMillen held that neuromuscular systems produce an intrinsic shape determined by its preferred curvature [14]. Therefore, the internal moment can be described in Eq. (6) based on linear constitutive relation. The hypothesis indeed treat fish swimming as a beam actuated by a preferred curvature. It is remarked that the curvature presented in swimming process does not equal the preferred curvature, which reflects the active/passive swimming mechanism.

$$M = EI(\varphi_s - \kappa) + \delta\varphi_{st}, \quad (6)$$

where κ is preferred curvature that is the function of time t and arc-length along fish body centerline s . φ is the local incident angle between tangent of centerline and the horizontal axis. The subscript denotes the derivative with respect to s or/and t . δ is viscoelastic damping coefficient.

The equations of fish locomotion can be thus obtained based on the conservation of linear and angular momentum. The question then arises naturally: which preferred curvature is appropriate? The problem can be solved by optimization once the optimization objectives are set. The preferred curvature distribution along fish body can be determined finally.

Experimental Analysis: For simplicity, the preferred curvature distribution can be treated as approximate piecewise constant curvature (APCC). Cheng developed an APCC equivalent model: APCC 2L-5R model (L means links and R means rotation joints), which can be used in rigid robotic fish design [252]. In this way, the kinematics of rigid links is equivalent to the continuum robot. On the other hand, for soft robotic fish, we can utilize the idea of Luo Ming as a reference [253]. He first developed a dynamic model for soft robots actuated by FEA. The model contains soft bending segments and short rigid links. Second, he designed a variation of FEA, tested the relationship between curvature and pressure input and improved dynamic response. At last, he used a modular approach to fabricate each segment of soft robot and adopted open-loop control to achieve the desired motion. This framework has been applied in a pressure-operated soft robotic snake successfully. Yet, when this framework is ported to soft robotic fish, the slow dynamic response highly up to 1–2 s consequently induces the low tail-beat frequency. It can be solved by changing the structure parameter to improve the dynamic response of FEA. Moreover, the close-loop control should be considered if precise motion is required.

4.2 Machine Learning

At present, machine learning (ML) is deeply changing every aspect of scientific and technical field and fish swimming research is no exception. The advantage of ML is to address problems for which the optimal theoretical

solution method is unknown. Even though ML is computationally costly, especially when it involves FSI models, it develops rapidly in the aspects of fluid mechanics and robots. The methods used in ML include deep learning (DL), reinforcement learning (RL) and deep reinforcement learning (DRL). In the aspect of fluid mechanics, ML can extract information from a large amount of data and reveal the underlying mechanism of fluid mechanics. Petros's team of ETH Zurich used RL to study fish school problem in 2014 and gave an overview of research development and promising opportunities of ML for fluid mechanics [254, 255]. Raissi studied the application of DL in vortex induced vibrations [256]. Rabault studied the application of DRL in active flow control and shape optimization and Xu utilized DRL to find out the optimal control strategy for rotating cylinders [257, 258]. Jiao trained fish to learn how to swim in potential flow based on RL [259]. Still, the research on fish locomotion mechanism based on ML is not near enough. There are vast prospects in waiting for us to explore. As for robots, Liu discussed the application of RL in robotic fish [260]. Thuruthel introduced ML-based motion control for soft robot and Cho applied RL to generate a CPG-based motion control of a robotic salamander [261, 262]. For soft robotic fish, ML can improve the survival possibilities by adapting to complex underwater environment. In addition, robotic fish can learn various motion skills autonomously through ML.

4.3 Multiple Robotic Fish System

The coordinated planning and control of multiple robotic fish system has not been fully addressed in the past studies and still is a challenging task at present [226]. Compared with single robotic fish, multiple robotic fish system can deal with complex underwater tasks and save work time. There are two difficulties to overcome: interaction mechanism of real fish school and cooperative communication of multiple robotic fish system. The former can give insights into the active flow control mechanism to save energy and the latter can help to share collected information. Artificial intelligence (AI) will play a more important role in these two areas in the future. Both attitude adjustment in fish school and swarm intelligence strategy in coordinated control require the outstanding learning ability of AI.

5 Conclusions

Researchers hope to design an AUV with excellent capabilities like high speed, high efficiency and low noise through studying fish swimming mechanism. Thus, the relevant research can be generally divided into two classes: fish locomotion mechanism from a science perspective and bionic robotic fish from an engineering

perspective. Although much progress has been made, the gap between bionic robotic fish and real fish is still apparent. In this article, the research development on fish swimming is presented. Research methods, current research direction and future research trend are detailed. The internal biomechanics of fish is investigated by Vivo experiments and is treated as a beam or multi-body system in the mathematical model. The external fluid information is obtained by PIV or DPIV experiments and is simulated by CFD. The comprehensive study of fish swimming can be simplified to foil research that can provide qualitative analysis. For single fish, certainly, unsteady locomotor behaviors reflecting maneuverability such as fast start, turning locomotion and burst-and-coast swimming and steady swimming performance reflecting speed and efficiency are the focus of research. While the fish school research put emphasis on the active flow control and swarm energy saving. On the other hand, Robotic fish development has experienced three periods: rigid robotic fish, compliant robotic fish and soft robotic fish. Hence, the actuators and materials have been greatly changed. As for the motion control of bionic fish, the overview of the speed control, depth control, attitude control, path following and target tracking are introduced. In the future, AI will help researchers to understand fish swimming mechanism and design intelligent motion control strategies. With the development of soft robot on material and basic theory, curvature control in bionic robotic fish based on the preferred curvature hypothesis can be realized. We hope that this review can help scholars to understand the recent research development of fish swimming and provide a reference for the further research.

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Author Contributions

YL wrote the manuscript. HJ put forward the framework and content of the paper. All authors read and approved the final manuscript.

Authors' Information

Yanwen Liu, born in 1992, is currently a PhD candidate at *School of Mechatronics Engineering, Harbin Institute of Technology, China*. He received his master's degree from *Harbin Institute of Technology, China*, in 2017. His research interests include soft robotics and bio-inspired robotics.

Hongzhou Jiang, born in 1971, is currently a professor at *Harbin Institute of Technology, China*. He received his PhD degree from *Harbin Institute of Technology, China*, in 2001. His research interests include design and control of parallel mechanism, hydraulic control system, tensegrity robotics and bio-inspired robotics.

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Competing Interests

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