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Review

Recent Progress in Modeling and Control of Bio-Inspired Fish Robots

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Abstract: Compared with traditional underwater vehicles, bio-inspired fish robots have the advantages of high efficiency, high maneuverability, low noise, and minor fluid disturbance. Therefore, they have gained an increasing research interest, which has led to a great deal of remarkable progress theoretically and practically in recent years. In this review, we first highlight our enhanced scientific understanding of bio-inspired propulsion and sensing underwater and then present the research progress and performance characteristics of different bio-inspired robot fish, classified by the propulsion method. Like the natural fish species they imitate, different types of bionic fish have different morphological structures and distinctive hydrodynamic properties. In addition, we select two pioneering directions about soft robotic control and multi-phase robotics. The hybrid dynamic control of soft robotic systems combines the accuracy of model-based control and the efficiency of model-free control, and is considered the proper way to optimize the classical control model with the intersection of multiple machine learning algorithms. Multi-phase robots provide a broader scope of application compared to ordinary bionic robot fish, with the ability of operating in air or on land outside the fluid. By introducing recent progress in related fields, we summarize the advantages and challenges of soft robotic control and multi-phase robotics, guiding the further development of bionic aquatic robots.

Keywords: bionic robotics; fish swimming; flapping foil; flow sensing; soft robotics; amphibious robotics

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1. Introduction

The ocean accounts for 71% of the earth's total surface area and is also a critical resource pool for humankind. The vast amount of water, mineral, and biological resources in the ocean are essential to modern society, and their potential value is much more sufficient compared to the land resources [1,2]. Therefore, how to explore and exploit the ocean safely and efficiently has become one of the leading research interests of the scientific community.

The human development of ocean vehicles can be traced back to ancient times, and the initial ocean explorer mainly sailed on the water surface [3]. However, since the 1930s, scientists and engineers have made tremendous progress in underwater vehicles. After two generations of underwater vehicle iterations [4], the current multi-species and multi-functional submersibles can already work effectively at different depths, from shallow to full ocean depth [5–11]. The new development goals have shifted to performance optimization involving complex hydrodynamic effects, such as swimming efficiency and noise control, inspired by aquatic animals.

Unlike traditional submersibles that obtain mobility from propellers and rudders, fish have evolved over millions of years to use oscillatory motion to swim and maneuver. Studies have found that such an oscillatory motion could lead to a high propulsion efficiency, super-maneuverability, low noise, and minor disturbance to the flow field [12–15]. In addition, aquatic animals have evolved to obtain various flow sensing abilities to perceive the complicated underwater environments [16–18]. Inspired by nature, the learning of the fish bionics and the design of the robotic fish are of great interest and importance for developing next-generation submersibles.

In more detail, via biological observation, fluid and structure experimentation, and numerical simulation, research has shown how fish use their soft bodies and specially evolved sensory systems to swim, maneuver, and navigate in the complex underwater environment in a highly efficient and agile manner. In addition, many researchers have also made solid progress on the design, fabrication, and control of bio-inspired aquatic robotics. As a matter of fact, since the birth of the "Robo-Tuna" by Triantafyllou et al. [19], over the last 30 years, we have witnessed a significant number of bionic swimming robots of different shapes and sizes, and the creature they mimic varies from fish (listed in detail in the following article) to all kinds of aquatic organisms, such as frogs [20,21], octopuses [22–24], jellyfish [25,26], etc. Their performance and the techniques involving various disciplines are aligned with continuous progress and innovation in material science, fluid mechanics, and control theory.

Despite extensive research in related fields, many scientific and technological bottlenecks still remain. First of all, understanding the complex fluid–fish–body interaction phenomenon is a significant challenge, especially within unsteady flow conditions. Computational fluid dynamics (CFD) has become a major tool to assist the experimental investigation but still suffers problems, such as the extensive computation resources required [27]. The second is the difference in the driving structure of natural fish compared to its robotic counterpart. The propulsion ability of fish comes from the coordination between muscle groups [28], which gives its body uniform weight distribution and a more space-saving motion structure. A body that has evolved over billions of years also has an excellent hydrodynamic shape and a reasonable structural elastic modulus. At the same time, the organic combination of movement between muscle groups is also the reason to improve the overall efficiency of movement [29]. Finally, fish have unique fluid sensing systems, such as the lateral line system in satin fish and the bioelectric system in sharks [17,18]. These fluid perception systems allow the foil to perceive the perturbation information of the flow field and efficiently utilize the energy in the flow field to enhance efficiency.

In the past decade, researchers have made more progress in the above problems, including the understanding and control of the physics of rigid and flexible foils [30–32] (as a simplified model of swimming fish), and shedding some light on the complex interaction between fish fins and their moving bodies. Meanwhile, tremendous advances based on materials science and computer science also breathe new life into the robotic fish design. New flexible materials and actuators have laid the foundation for the soft bionic shape of the robot fish [33–35]. Artificial intelligence algorithms and the extraction and analysis of big data have also greatly enhanced the robot's overall optimization, fine control, and information perception capabilities [36,37]. The addition of these new technologies leads the research of robot fish toward an interdisciplinary approach and makes the research field considerably broadened.

However, all these progresses are reported in various and diverse sources, and a timely overview would be helpful for those who are interested in carrying out research and development in this direction. Therefore, in our review, we would like to focus on the following two aspects of the problems:

1. How to identify and extract the extraordinary characteristics of fish, in order to establish effective physics models and explore the mechanisms;
2. How to imitate the structure and control characteristics of fish in engineering design, and manufacture robot fish with high-performance parameters.

The remaining of the paper is organized as follows. Section 2 introduces the theoretical and practical development of bio-inspired propulsors and sensors. In Section 3, we present various bio-inspired swimming robots based on their swimming forms and functionality. Before concluding, the last section focuses on the recent pioneering directions of the new generation of robot fish.

2. Bio-Inspired Propulsor and Sensor

2.1. Swimming Dynamics

Using oscillatory motion, natural fish have achieved both highly efficient and maneuverable propulsion. In this section, we provide a brief review of the recent key progress in understanding and hydrodynamic modeling of the oscillatory propulsion of the fish, from rigid and flexible flapping foil to fin–body interaction.

2.1.1. Rigid Flapping Foil

Due to the computational difficulties of hydrodynamics, a standard treatment of fish physics modeling is to simplify the swing of the fishtail into a model of a rigid flapping foil [38,39]. Several key parameters govern the fluid dynamics, including the Strouhal number *St* [38,40], Reynolds number *Re* [41,42], non-dimensional amplitude [41,43], etc., shown in Figure 1. Moreover, the relationship between the quantitative combinations of these motion parameters and the dynamic characteristic parameters, such as thrust and power, satisfies the scaling law [41,44,45], which can be regarded as a system that includes the dynamic principles of the flapping airfoil model on specific assumptions. When the kinematic parameters are input into the system, the output dynamics of the flapping airfoil characteristics can be obtained directly. Figure 1a implies that, with increasing frequencies and motion amplitudes, the enlarged experimental results are pretty close to the scaling law predictions based on the results on smaller parameter sets [45]. In Figure 1b, the curves consisting of the data points show that the mean thrust coefficient increases with *Re* under constant *St* and are convergence to constant values, which indicates that there is a functional relationship between the mean thrust coefficient and Re under the same Strouhal number [42].

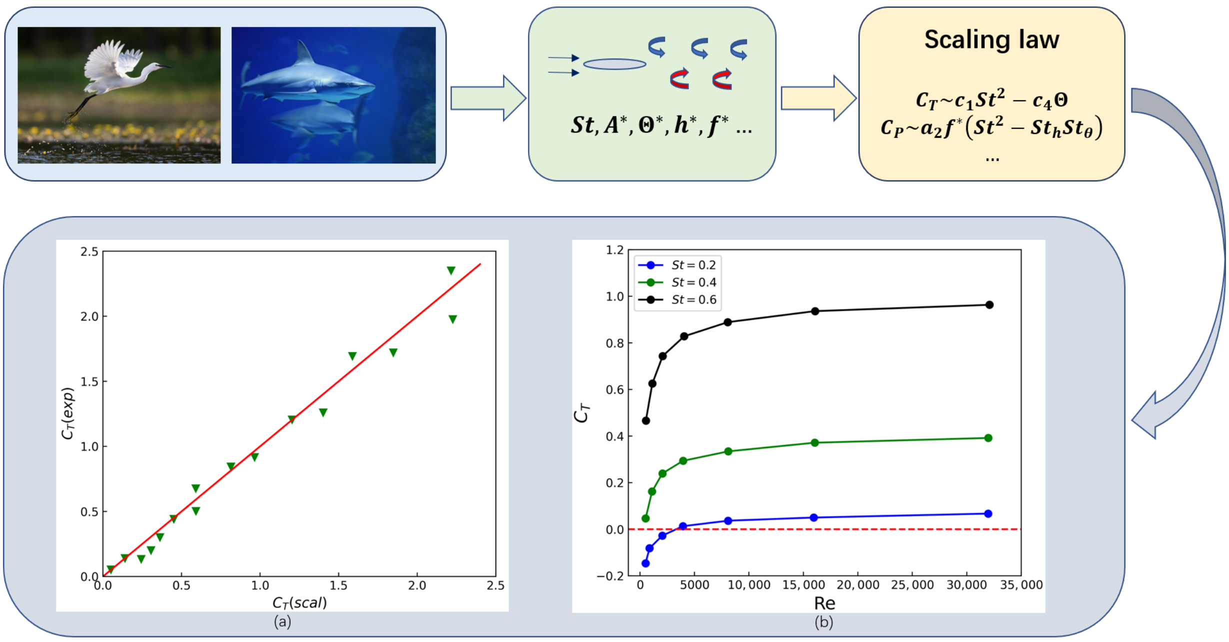


Figure 1. Scaling law, as a bridge connecting dynamics and kinematics, quantifies dynamic parameters and reveals the principle of flapping wing power generation. (**a**) Comparison of the average thrust obtained by experiment and scaling law. The points in (**b**) represent the average propulsive coefficient of the NACA0012 airfoil under different Re and St.

Floryan et al. [44] simulated a pure pitching or pure heaving foil with various small amplitudes, and they found that fluid forces acting on the foil can be decomposed into two parts: the lift and the added mass. Later, they established the scaling law for the propulsive performance of the flapping foil with a small amplitude based on Theodorsen's lift theory [46] and Sedov's added mass model [47] as follows:

$$C_T = c_1 St^2 + c_2 St^2 f^* U^*, \tag{1}$$

$$C_P = c_3 St^2, \tag{2}$$

where C_T is the thrust coefficient, C_P is the efficiency coefficient, and f^* and U^* are the reduced frequency and the reduced velocity, respectively. In addition, c_1, c_2 and c_n are the scaling constants. The meanings represented by the symbols of all equations in this article can be found in the abbreviation page.

It was interesting to note that the thrust contribution of the airfoil with pure pitch motion was the added mass, while the thrust of the airfoil with pure heave motion was only the lift. Derived from Equation (1), it was concluded that f^* would lead to a significant thrust increase with constant St, and the flow speed has no major effect on the propulsive performance. Floryan et al. [44] defined the reference velocity as the relative velocity between the moving foil and the surrounding fluid, as follows:

$$C_T = 2F_T / \rho f^2 A^2 sc \tag{3}$$

Based on the the aforementioned scaling law proposed by Floryan et al. [44], various studies have been conducted to extend the theory to include combined pitching and heaving motions [45] and large amplitude motion [41]. In addition, several experiments [38,43,48] were later conducted, demonstrating the validity of the theory.

One of the major disadvantages of the model is that the influence of the separated shear layer produced by the airfoil under large-amplitude motion was not considered. Based on the Garrick model [49], Moored et al. [38] proposed an inviscid flow theory, incorporating the effect of the separated shear layer as well as the wake shedding vortices. However, it needs to be pointed out that the viscosity will have an effect on the flapping foil performance, as some preliminary result [41,44] has shown that viscosity would worsen the propulsion efficiency. In particular, when St is very small, the offset drag caused by a large motion amplitude is the key factor that makes the foil unable to obtain thrust, quantified by the performance factor η (shown in Figure 2) as follows:

$$\eta = \frac{A^*[St^2 - b_1 g(\theta)]}{St^3(1 - h^*\theta^*)} \tag{4}$$

In summary, the establishment of the scaling law not only sheds light on the physical mechanism of the flapping foils, but also has been an effective tool to optimize the motion control of the bionic aircraft/underwater vehicle [39] and to accelerate the design cycle. In addition, the scaling law of the dynamic characteristics of the two-dimensional rigid flapping airfoil can be extended to other relevant directions, such as the dynamic characteristics of the ground effect of flapping wing [48,50], the study of the dynamic characteristics of non-sinusoidal flapping [51], the intermittent swimming of fish [52], and the flexible flapping foil dynamic [53].

2.1.2. Flexible Flapping Foil

By simplifying marine animal fins to flapping foils, many experimental and computational analyses were conducted on the hydrodynamic performance of rigid foils [54]. However, there is a large discrepancy between the research findings of rigid foils and actual fins since they are subjected to deformation actively or passively during the movement of marine animals in practice [55–57]. For this reason, it is necessary to consider the effect of flexible deformation on the swimming performance of the flapping foil.

Although both the rigid foil and flexible foil can generate propulsive force through pitching and heaving motions in the current, it should be noted that flexible foil has greater effective flapping amplitude [58] and more complex tail vorticity [59], which leads to the difference in hydrodynamic performance. Figure 3 presents the profile deformation of rigid foil and flexible foil in different motions. Katz and Weihs [60] adopted potential flow theory to illustrate that the flexible foil could provide up to 20 percent greater propulsive effectiveness with only a slight drop in overall thrust.

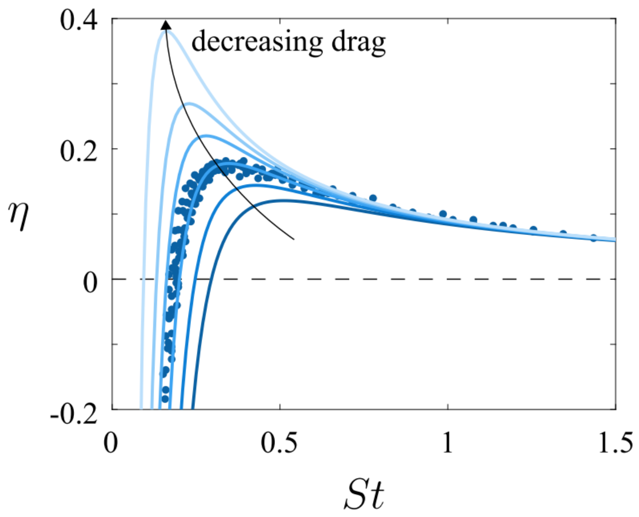


Figure 2. Propulsive efficiency η relationship between St. Solid lines are generated according to Equation (4). The color of the line from dark to light indicates the offset drag from large to small. Adapted from [41], with permission from PNAS, 2018.

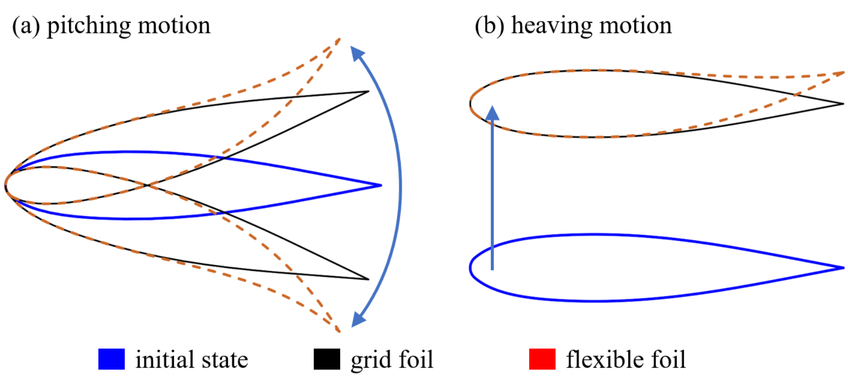


Figure 3. Profile deformation of rigid foil and flexible foil in different motions: (**a**) pitching motion; (**b**) heaving motion.

However, the influence of the foil flexibility on the mechanism of the thrust generation remains unclear. To evaluate the performance of flexible foils sufficiently, numerous computational models have been developed to investigate the propulsive characteristics in the published lecture. Miao and Ho [61] simplified the flapping motion of flexible foils as a continuous deformation model of time-varying flexure amplitude. They introduced the consumption power rate and the thrust power coefficient to calculate the propulsive efficiency. The results indicated that a satisfactory thrust performance could be delivered by providing an appropriate combination of chord length and flexure amplitude. Alben et al. [30] presented a theoretical and experimental study of the performance of freely swimming flexible foils. The thin, flexible foil was modeled as a one-dimensional body moving in a two-dimensional viscid fluid. Results showed that the foil speed is a nonlinear function of foil length and bending rigidity. Paraz et al. [62] performed a systematic test to explore the effect of flexibility and flapping amplitude on thrust generation and swimming efficiency. A weakly nonlinear model was developed to predict a flexible foil's kinematic and dynamic responses actuated in heave at its leading edge. These models provided the theoretical basis for subsequent research into the propulsion performance.

To analyze the effects of flexibility, respectively, either heave-only or pitch-only actuation is usually considered the movement mode of flapping foils. Alben [63] presented a formulation of the motion of a flexible body with a vortex-sheet wake and used it to study propulsive forces generated by a flexible body pitched periodically at the leading edge in the small-amplitude regime. Quinn et al. [64] studied the propulsive performance of heaving flexible panels by kinematic analysis and direct force measurements. The results indicated that the thrust production was dominated by the motion of the leading edge, and the propulsive efficiency reached the local maxima near resonant frequencies when the trailing edge amplitude was maximized.

When considering combination of heaving and pitching, more additional input parameters need to be taken account in. Alben [65] established a numerical model with a phase difference between the heaving and pitching motions to investigate the dynamics of a flexible foil driven periodically in uniform stream. Maximum thrust was obtained when heaving was combined with pitching to generate a larger trailing edge deflection, and maximum efficiency occurred when heaving and pitching were nearly canceled in their effect on the trailing edge displacement. Quinn et al. [66] combined grid search and experimental gradient-based optimization to maximize the efficiency of a flexible panel with heave and pitch motions, which found that optimum pitch and heave motions produced nearly twice the efficiencies of optimal heave-only motions.

Additionally, the material properties of the flexible foil have a significant effect on its hydrodynamic performance. David et al. [67] investigated thrust production from a pitching flexible foil in a uniform flow. Comparing with the results of rigid foils, with flexible foils, it was found that the material flexibility raised the possibility of resonance between the actuating motion and the natural frequency of the structure. Dewey et al. [53] utilized rectangular flexible panels undergoing pitch oscillations at the leading edge to examine the influence of flexibility on propulsion generation. It was observed that the flexible foil achieved a significant enhancement of thrust production and propulsive efficiency simultaneously when the oscillation frequency controlled by flexibility reached a certain range. Anevlai et al. [68] numerically studied the relationship between propulsive performance and elastic parameters, giving typical configurations of the un-deformed and deformable camber line for a purely heaving foil. The results showed that the propulsion efficiency rose with the decreasing of Young's modulus.

Just as the flexibility of real fins is typically non-uniform, flexibility distribution is also one of the defining characteristics of foil propulsion. Floryan et al. [69] explored the relationships between the distributed flexibility and propulsive performance by a linear inviscid model of a passively flexible foil. Simulation results revealed that the maximum thrust could be obtained by triggering a resonance between natural and actuation frequencies or concentrating the stiffness toward the leading edge. Furthermore, Melike Kurt et al. [70] took a pitching hydrofoil system with a pair of three-dimensional non-uniformly flexible foils to simulate the fin–fin interactions during fish locomotion. Data from experimental works identified that the collective efficiency of the system can be improved by adjusting the position of foils and setting the correct phase difference between foils.

Due to the flexible deformation of fish fins under the action of hydrodynamics, flexibility is one of the crucial factors in determining the fish swimming locomotion. Therefore, the studies on the flexible foil are helpful to understand the fish swimming mechanism and lay a solid foundation for the development of bio-inspired fish robots.

2.1.3. Fin–Body Interaction

Numerical simulations of large-scale deformation in hydrodynamic simulations are highly complex and technically challenging to implement, and studies are generally simplified to model the physics of fish. For example, most fish studies do not consider the structures attached to the fish, such as the pectoral and anal fins (as shown in Figure A1), and only consider the propulsive role of the caudal fin following the body oscillation. Some studies have even simplified the fish body to a two-dimensional NACA wing shape to accommodate the large deformation of the fish body [45,71–73].

However, the rapid development of image capture technology and the in-depth understanding of the physics mechanism of the fin–body interaction in recent years, have corroborated from different perspectives that additional fins have multiple degrees of improvement on the overall propulsion efficiency and maneuverability of the fish. Moreover, the fin structures also play a vital role in the fish's swimming pattern. We mainly focus on the different fin structures of fish to introduce the fin–body interaction in the following part. The different kinds of fins of a typical fish are illustrated in Appendix A Figure A1.

The flows associated with a swimming fish are dominated by unsteady mechanisms. Generally, the flow/vortices patterns are posterior body vortices (PBV), leading-edge vortices (LEV), and trailing-edge vortices (TEV) [74]. The fin plays an essential role in all the vortex pattern control of fish, and the effect of all kinds of fins varies according to multiple conditions.

In 2017, Dong et al. [75] conducted 3D simulations and water tunnel experiments to analyze the vortex dynamics and performance enhancement of fin–body interactions. It is found that the fin–body system is crucial in undulatory swimming patterns. The fin–body interactions produce high propulsion and alleviate drag, as the body–caudal fin system captures the PBVs to strengthen the LEVs, which produce the most thrust to the fish [75–77]. Apart from the caudal fin, the other fin structures also have irreplaceable functions. The median fins, except for the caudal fin (the dorsal and anal fin), strengthen the PBVs of the fish [75], and their flapping phase affects the collision time between the PBVs and the LEVs, which eventually results in caudal fin performance optimization [78,79]. Even the tiny pitching finlets create constructive forces to facilitate posterior body flapping [80].

In recent decades, with the establishment of the new theoretical model, the development of the novel experimental approach, and the increase in the computational resource, researchers have made significant progress in understanding the fundamental principle of bio-inspired oscillatory propulsion. Primarily, we have seen an increasing interest in studying the complex fluid–structure interaction of the flexible bodies with an unsteady incoming flow, which helps shed light on the primary mechanism of fish's high efficiency and super maneuverability and guides the design and control of new bio-inspired underwater robots.

2.2. Underwater Sensing

After million years of evolution, fish are capable of surviving in various underwater environments. This may be owed to various organs in fish, such as rod and cone cells, otoliths and weberian organ, lateral line, chemo-reception and electroreception. To be more specific, rod and cone cells are capable of assisting the fish in seeing its surrounding environments, which can provide the vision for fish and help them in localization and detecting unwanted obstacles [81]. For the otoliths and weberian organ, they can provide proper hearing in fish. In particular, otoliths are found in the inner ear of the fish, and weberian organ transfers vibrations in the swim bladder to the inner ear [82], which can help fish in finding prey and escaping from danger.

Robotic fish have integrated multiple sensors to mimic the biological functions of real fish. In particular, the vision part of fish-inspired robots are always implemented through the charge-coupled device (CCD) or a complement metal oxide semiconductor (CMOS) camera [83,84]. By adopting these sensors, the robotic fish are capable of performing various operations, such as goal recognition, and detecting and avoiding obstacles [85,86]. Although the hearing sensors are not widespread as vision sensors in robotic fish, there are still various sensors designed to provide the fish-inspired robot the hearing function, such as sonar, ultrasonic proximity sensor and ultrasound range sensors [87,88]. Through these seniors, the robotic fish are able to detect threats and perform navigation [89].

Thanks to the lateral line as a common mechanosensory system in various species, fish are capable of navigating in the dark or turbulent water. The lateral line consists of neuromasts made up of a number of hairy cells and a cupula, which connects the hairy cells to the surrounding water masses [90], and perceive the change of water flow in the surrounding water environment. To ensure that underwater robots can complete complex underwater tasks, the artificial lateral-line system has been designed [91–93], which can provide important environmental information for robotic fish and enable them to avoid obstacles effectively. Moreover, various different sensors are also adopted to mimic the flow and pressure sensing and achieve precise attitude control, such as water sensor, pressure sensor and depth meter [89,94,95].

Finally, fish also have the organs or tissues to provide chemoreception and electroreception. These organs or tissues are capable of detecting different substances or weak bioelectric fields, and hence the fish react accordingly [96], while the sensors related to these aspects are relatively few indeed. However, there are also some sensors that cannot be found as corresponding functions in real fish, such as a compass [97], proximity sensor [98] and GPS [99]. These sensors are designed and integrated with the aims of further exploration and experiment around the fish-inspired robots, as there is still a huge gap between real fish and the robots.

The biological system has provided more elegant solutions to navigate in complicated circumstances than current state-of-art manufactured underwater sensors. Studies show that fish acquire a more precise, compact, and energy-saving sensory system, which provides vital research interest for the future integration of bio-inspired MEMS sensors. Meanwhile, we would like to point out that sensors, such as LIDAR, sonar, etc., may also be implemented in bionic robots, providing advanced functions without biological equivalence to reach or even surpass the fish's environmental sensing capability.

3. Classification of the Fish Inspired Robots

As there are several methodologies to define the locomotion characteristics of fish, this paper adopts the method of the swimming propulsor to classify the fish motion categories [14]. A body and (or) caudal fin (BCF) swimmer bends its body into a backward propulsive wave that extends up to its caudal fin, while median and paired fin (MPF) swimmers use the median and paired fins to gain thrust. Similar to the classification of the biological systems, fish-inspired robots can also be divided into BCF-based and MPF-based robotic fish with a series of subcategories [28]. Here, we only focus on parts of them named anguilliform, subcarangiform, carangiform, thunniform, ostraciiform, labriform, rajiform, amiiform and gymnotiform, which are most popular in the research of fish-inspired robots in recent years [100–102]. Different subcategories of fish-inspired robots are described in Figure 4. Furthermore, the characteristics of each robot are also reviewed and compared in the figures below.

3.1. Robots in Anguilliform

The anguilliform caudal fin category represents animals that are highly flexible (due to a large number of vertebrae) and have a small turning radii [103,104]. Snake-like robots show the full body undulation as anguilliform and, hence, are concluded in this section. Moreover, some amphibious robots, which include Salamandra Robotica II [94] developed by Crespi et al., Series Elastic Actuated Snake [105], Mamba Waterproof Snake Robot [106], and amphibious snake-like robot developed by Yu et al. [107] also belong to this category, as they also perform anguilliform locomotion.

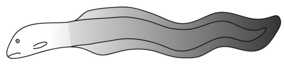
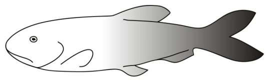
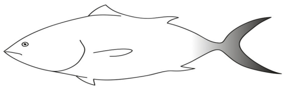
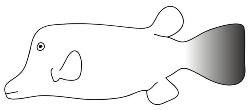
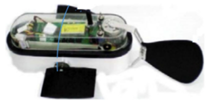
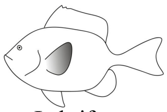
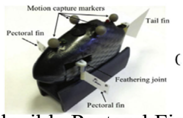
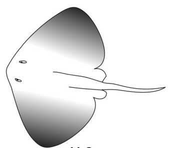
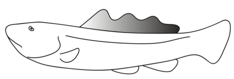
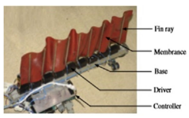
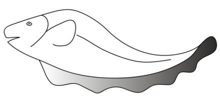
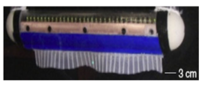
	Fish Subcategories	Representative Robot Fish	Performance description
BCF based fish inspired robots	 Anguilliform	 LAMPETRA (Stefanini et al. 2012)	1) High maneuverability and flexibility 2) Low speed 3) Low hydrodynamic efficiency
	 Subcarangiform & Carangiform	 G9 Fish (Hu et al. 2006)	1) Lower maneuverability than anguilliform 2) Higher speed than anguilliform
	 Thunniform	 MIT RoboTuna (Tolkoff et al. 1999)	1) Lower maneuverability than carangiform 2) Higher speed than carangiform
	 Ostraciiform	 Boxfish-like Robot (Wang et al. 2014)	1) High maneuverability with little flexibility 2) Low speed 3) Low hydrodynamic efficiency
MPF based fish inspired robots	 Labriform	 Flexible Pectoral Fin Joint Labriform Robot (Behbahani et al. 2016)	1) Low maneuverability 2) Low speed
	 Rajiform	 Manta Ray Robot (Gao et al. 2007)	1) Low to medium maneuverability 2) High stability 3) Low speed
	 Amiiform	 RoboGrilos (Hu et al. 2009)	1) High maneuverability 2) Low to medium speed
	 Gymnotiform	 Robotic Knifefish (Curet et al. 2011)	1) High maneuverability 2) Higher speed than labriform

Figure 4. BCF- and MPF-based fish and representative fish-inspired robots are listed in the above figure. The second column presents main subcategories of fish classified by propulsion methods [108–115]. The third column consists of representative robot fish in each subcategory. The last column describes the hydrodynamic characteristics of each subcategory.

Due to the hyper-redundant design comprising multiple serially connected links, anguilliform robots obtain relatively high maneuverability as the high degree of freedom of the robot. While the early efforts in this category are considered to be the Amphibot [116], which the actuators only allow for one degree of freedom, Stefanini et al. created the LAMPETRA [108], which has a more flexible body thanks to smaller sections and actuators. After that, Salamandra Robotica I [117] and II [94], as amphibious snake-like robots, were created with 18 and 20 degrees of freedom (DOF), respectively. However, the pseudo-rigid nature of the links leads to the maneuverability loss of the robots, compared with their biological counterparts.

3.2. Robots in Subcarangiform and Carangiform

The subcarangiform and carangiform classifications are highly similar and can be distinguished by a slightly different initiation point along the body. In particular, subcarangiform fish utilize slightly more back and forth head movement [118], while carangiform fish utilize one-third of their posterior body for undulation [119].

Due to the difficulty of discerning the robot's variation in body undulation initiation between subcarangiform and carangiform, the robots in these categories are grouped based on their actuation mechanism. In this subsection, we divide them into four parts: the three-link systems, four-linked systems, multi-linked systems, and the outliers [28]. Considering the three-link actuation robots, the G9 fish [109] is the most famous, which has a rigid body unit that houses components. For the four-link systems, Yu et al. proposed three different robots, namely Four-Joint Robotic Fish, Four-Link Robotic Fish Large Pectoral Fin Control Surfaces [84] and AmphiRobot-II [120] with a rigid body. Koca et al. [121] created a robot that has a small rigid body, where the caudal peduncle actuation unit is a majority of the body length. This robot has fixed pectoral fins and a sizable rigid tail.

In 2005, multiple robots were created through the work of Essex MT1 Robotic Fish [122] for which the actuation mechanism is multi-linked peduncle units, where rigid components are used. Information on the construction of these robots is limited, but the Essex C-turn Robot [123] has a small head unit and a large peduncle section, where a multi-sectioned skin covers the peduncle section. Ichikizaki et al. [124] created a Carp-inspired robot, where the robot structure was contained within a mimetic body shell. Furthermore, Clapham et al. [125] created iSplash, which showed promise in body undulation mimicry.

There are also a few robots that do not belong to the three- or four-link systems. For instance, a wire-driven shark was constructed by Lau et al. [126], with a multi-segmented tail, providing the capability for good peduncle flexion. Furthermore, a hydraulic actuated peduncle was created by Katzschmann et al. [127], of which the peduncle is made of soft materials. Katzschmann et al. [128] proposed an acoustically controlled soft robotic fish to explore underwater life.

In a word, major robots in this category maintained rigidity during the locomotion, and therefore the body undulation is localized in the posterior portion, which causes an enhanced propulsive force [96]. Therefore, carangiform and subcarangiform locomotion robots are more likely to have higher speeds than those that are anguilliform.

3.3. Robots in Thunniform

With a very limited body undulation to the last quarter of the body, thunniform fish are usually very streamlined and extremely efficient fish, as they sustain top speed for a long duration to either pursue prey or avoid even larger predators [129,130].

The thunniform robots use a peduncle actuation unit and different actuation mechanisms to achieve a more concentrated tail actuation. An early effort in Thunniform robots was the RoboTuna created by MIT [110]. Thereafter, a robot mimicking a mackerel called Mackerel Robot [131] was created in 2012. These two robots were both equipped with a flexible, streamlined skin and fixed to a strut. Furthermore, inspired by the RoboTuna, a large vorticity control unmanned undersea vehicle (VCUUV) was created by Anderson et al. at the Draper Laboratory [132]. This design is capable of high-speed swimming; however, this is also a weighty hydraulic design. Chen et al. created an ionic polymer–metal composite (IPMC) peduncle-driven robot, where the body and pectoral fins are rigid structures with no complacent movement [133]. Moreover, a miniature robotic fish was created by Marras et al., where the body and peduncle could be considered two separate units controlled by a single motor and joint [134]. A relatively simple single-motor-actuated robotic fish called Single-Motor-Actuated Robotic Fish, was created by Yu et al. [86], in which the motor gives motion to an eccentric wheel that drives a connecting rod. In 2011, a multi-linked robotic dolphin was created by Shen et al., which has a polymer–metal peduncle unit composited of three links that allow for vertical flexion and a fourth for a smaller horizontal flexion [135]. In addition, a slider-crank robotic dolphin was created that gave actuation to two vertical pitch units and one yaw unit, which realizes a tail flexion with three degrees of freedom, and the pectoral fins are fixed surfaces [136]. Through efforts to increase the endurance, a gliding mode was conceived for a mechanical design by Wu et al., in which the robot incorporated a single joint for the movement of the peduncle with another joint for the movement of the caudal fin [137]. Yu et al. [138] created a dolphin robot that was capable of fast speed and leaping out of the water.

3.4. Robots in Ostraciiform

The ostraciiform is a unique class because it uses an oscillatory thrust-generating mechanism. These fish gain propulsive power through the low hydrodynamic efficient, pendulum-like oscillations of the stiff caudal fin. However, these fish have good maneuverability in the tiny crevasses as their habitats [139].

Ostraciiform robots utilize fewer actuators because only the tail fin needs to oscillate. Moreover, these robots mainly have a rigid body with high maneuverability. For instance, the BoxyBot created by Lachat et al. [140] is a rigid component-based robot, and the body was separated into two sections. Kodati et al. [141] created a robot named the microautonomous robotic ostraciiform (MARCO). Wang [111] and his consultants created the Boxfish-like robot, which was slightly smaller but had the same capabilities. Mainong et al. [142] used their design to invest different aspect ratios and shapes for the pectoral fins. The body is a mimic of the boxfish, of which the caudal fin has 1 DOF, while the pectoral fins have 360° movement spaces.

3.5. Robots in Labriform

The species of labriform tend to be found in reefs and areas of coverage in which fish use a caudal fin occasionally when their pectoral muscles are at maximum endurance or when performing a burst acceleration [143]. Moreover, these fish may have low endurance when solely utilizing the pectoral fins [112].

As it is challenging to create a stable robot that solely uses fin oscillation, there are few robots belonging to this subcategory. Sitorus et al. [144] created the early labriform robot, called Wrasse robot, in 2009. Thereafter, by efforts by Behbahani et al. [145], a labriform swimming robot was proposed with flexible pectoral fins which could perform both the rowing and flapping motions. Moreover, a cross-over robot that drives its pectoral fins and a dual caudal fin for swimming was proposed by Zhang et al. [146]. The robot used a hybrid fin mode; the pectoral fins have 3 DOF, while the dual caudal fin has 1 DOF, and the whole kinematic system compresses the water when their strokes come together.

3.6. Robots in Rajiform

The body of individuals in rajiform comprises cartilage, which gives their whole body great flexibility. Furthermore, the fin ribs extend from the body into the pectoral fin [147].

In practical robot fish design, there are a variety of robots belonging to this class due to the advantage in efficiency and maneuverability. Here, we divide them into two parts, namely leading-edge rib-based robots and multi-ribbed-based robots. For the leading-edge rib-based robots, one crucial early effort to note is the manta ray robot, with a rigid unit as the body and fixed control surfaces as horizontal and vertical tails [113]. This robot was then upgraded into the Robo-Ray III, where the fixed control surfaces were replaced by functioning ones that increased stability and depth control [148]. Furthermore, a rigid encased skeleton design called flexible pectoral foil cownose ray was created by Cai et al. [149]. The skeleton was encased in a mimetic body resembling the manta ray. A soft material leading edge design called IPMC manta ray was created by Chen et al. [150], using the elastomer membrane fin as the front part of the body. Alvarado et al. [151] proposed a similar design called the soft body single–dual actuator ray with a body that contains more than 70% soft materials. In addition, Chew et al. [152] created a leading edge design named the bionic fin manta ray in 2015, which gave flapping actuation to a rigid, leading edge in the pectoral fin.

There are also various bionic prototypes for the actively excited multi-ribbed rajiform category. The first robot to be considered is the cow-nosed ray-I created by Yang et al. [153] with an actuation skeleton that excites multiple ribs in a flexible membrane. Zhong et al. [154] designed RoMan-I with interlimb coordination of 14 DOF involved in the thrust generation, which can perform swimming and gliding locomotion in water driven by servomotors. Rowan-II was developed by Zhou et al. [155,156], which can perform diversified locomotion patterns in water by using a model of artificial central pattern generators (CPGs) constructed with coupled nonlinear oscillators. After that, a larger version called RoMan-III was proposed by Low et al. [148] based on RoMan-II; the size of the third version is much more compact while maintaining the velocity. Punning et al. [157] and Takagi et al. [158] designed relatively similar IPMC robots called IPMC chain ribbed ray and multi-ribbed IPMC, respectively. Moreover, Krishnamurthy et al. [159] created a RayBot which is a rajiform robot that uses a caudal fin for propulsion. The smallest robot considered is a soft-robotic ray combined with tissue engineering, which was created by Park et al. [160] with a metallic skeleton that transports electrical excitation to multiple ribs.

Although rajiform fish have high maneuverability, the same ability of the robots inspired by rajiform locomotion varies from low to medium. The difference in performance should be attributed to the flexibility deficiency of the broad fins used in the robots compared to the fins of real fishes, resulting in lower degrees of freedom [96].

3.7. Robots in Amiiform

The fish in amiiform are not extremely fast, but they can move forward and backward by switching the direction of the wave motion in the fin, which shows decent agility [161].

Compared to the subcategory above, the robots designed in amiiform are relatively few. Hu et al. [114] proposed the RoboGrilos with a very slender rigid body that contains the necessary actuation mechanisms to carry the translational undulation wave. Moreover, a remarkably similar dorsal undulation fin design called the Dorsal Undulation Fin Robot was implemented with a rigid shell encasement akin to the torpedo by Xie et al. [162].

3.8. Robots in Gymnotiform

Gymnotiform fish are experts in complex maneuvering. In particular, fish in this subcategory bend the body at a significant angle, allowing the fin even to be in a vertical axis, which can permit them to move with a higher degree of freedom [163].

Similar to amiiform, the gymnotiform class has few robot systems to be classified. Siahmansouri et al. [164] incorporated a knifefish robot with pitch and yaw actuation joints that connect to the multi-ribbed propulsion fin. Curet et al. [115] created a robot that has an actuation mechanism encased in a rigid tubular shell. Furthermore, Liu et al. [165] proposed a robot that uses a passive fin design, where a rib on the nose and tail of the robot gives excitation to the flexible fin membrane stretched between them.

3.9. Summary

From the above introduction, it is obvious that each swimming mode of fish has its unique characteristics, advantages, appropriate flow field environment, and the corresponding designs of fish-inspired robots often make trade-offs in these different properties.

It should be noted that the caudal fin-propelled BCF swimming mode is still the dominant driving mode in this period for high-speed fish and bionic fish, but researchers have also paid attention to the synergy between different fins and the hydrodynamic effects generated by the overall flexible deformation of the fish. However, most bionic attempts at this stage are still relatively crude imitations, rarely supported by quantitative and complete hydrodynamic theories, and are hard to be further optimized. It is foreseeable that future bionic fish should consider the characteristics of flexible deformation and the design introducing artificial intelligence to achieve better hydrodynamic performance.

4. Advanced Topics and Pioneering Directions

The above sections reviewed the critical progress in understanding, modeling, and constructing new bio-inspired swimming robots in the last decades. This section identifies two key advanced topics, including the recent development of soft robot control techniques and the amphibious robot that can swim, fly, and walk.

4.1. Soft Robotic Control

Compared with traditional robots, soft robots have several advantages: high safety, strong adaptability to wearable devices, etc. [33] Due to their unique features and advantages, soft robots have a wide range of applications. However, unlike traditional rigid robots, soft robots have the characteristics of high material elasticity and novel driving methods, which also leads to new difficulties in control system, shown in Figure 5. In particular, for the increasing number of soft swimming robots in recent years, researchers have summarized the following key control challenges;

1. Soft robots are naturally underactuated systems, which leads to difficulty in predicting their kinematics and dynamics [166].
2. The fluid environment is complex, and the external force is difficult to quantify [167].

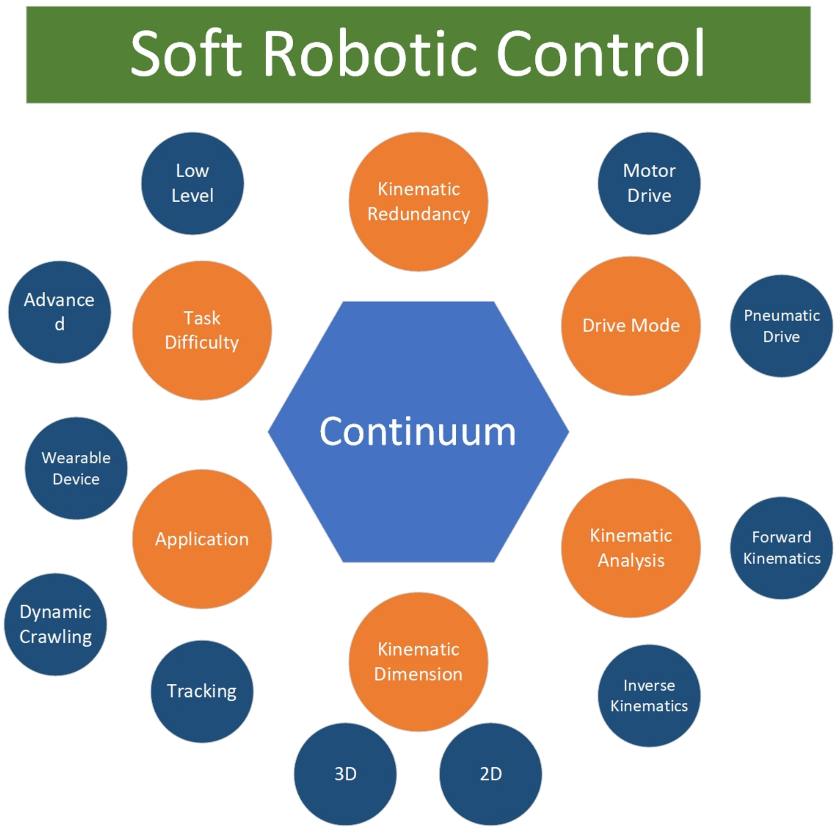


Figure 5. The elements of soft robotic control.

The state-of-the-art methods can mainly be divided into analytical and numerical methods to address the aforementioned issues. The analytic methods use simplified theory, which is not accurate enough to meet the precise control requirements. On the other hand, numerical simulation provides accurate prediction with extensive computational resources, which is not suitable for the real-time control of the robotic fish [167]. Similarly, the problems of underactuation and complex environmental coupling prevail in every aspect of the soft robotic system. In the last five years, researchers have emphasized improving and even providing destructive control methodology in the following three aspects: the traditional model-based control, the data-driven model-free, and the hybrid method.

4.1.1. Model-Based Dynamic Control

The traditional dynamic control methods of flexible bodies are similar to rigid ones, mainly based on various physical models, such as central pattern generators (CPG). Lee et al. [33] reviewed the latest research on soft robots and their application areas and introduced an adaptive controller based on a linear model. Since conventional control techniques are insufficient to handle soft robots, the paper also discussed open–closed loop relationships for robotic fish control and suggested the need for new control concepts. Thuruthel et al. [168] argued that model predict control (MPC) is ideal for controlling these continuum/soft robots, theoretically allowing for accurate control.

Santina et al. proposed an alternative formulation of soft robot dynamics based on the common assumption of piecewise constant curvature (PCC) [169] that relates the behavior of soft robots to that of rigid robots with joint flexibility, enabling the dynamic control of soft robots and interaction between soft robots and their environment. After that, the team extended the soft robot dynamics formulation from 2D to 3D, and this new closed-loop control method enables soft robots to track trajectories in 3D space [170]. Based on the previous studies, the Santina team [171] completed the development of a closed-loop dynamic controller for continuous soft robots for the first time. Additionally, the group designed a novel underactuated mechanical system [172], a soft inverted pendulum, that proposed nonlinear feedback regulation based on partial feedback linearization and derived the complete control equations for this scheme.

For a higher standard of quantitative soft robotic research, Thieffry et al. [173] completed an algorithm for model simplification by solving the equations of continuous medium mechanics using the finite element method, while comparing existing methods, including model-free control, the PCC hypothesis-based model and FEM model-based controller. Wang et al. [174] designed a new strategy for the trajectory control of a multi-sectional continuum robot in 3D space, constructed and utilized the inverse kinematic and dynamical equations, and its transformation to achieve the modeling and control of the continuum robot.

Up to this point, the modeling and continuum control methods for flexible robots have been developed considerably, and more systematic and summarized work has emerged. Santina et al. [175] described the similarities between rigid, flexible, and soft robots by introducing the concept of discretization in infinite-dimensional space using a generic terminology inspired by classical robotics and robot control; based on this research, it is possible to transfer the controller from the rigid domain to the soft continuum domain. Schegg et al. [176] outlined the modeling approach for soft robots and the available methods to calculate the mechanical flexibility and implemented a dynamic control algorithm based on the mechanical model for the stable control of the robot's positioning.

Overall, the traditional model-based methods provide a balance between accuracy and complexity, yet they still face many issues, such as poor environmental adaptive ability, high correlation between control and model accuracy. Therefore, machine learning (ML), i.e., the data-driven model-free method, has attracted more attention, given its capability in solving highly nonlinear and strongly time-variant problems.

4.1.2. Model-Free Dynamic Control

Compared to the model-based control methods, the development of model-free methods based on ML has also received considerable attention, with the potential of performing more advanced tasks. In the review by Lee et al. [33], they summarized the future directions of soft robotic control: autonomous behavior, high-level tasks, cognition, and interaction with the environment. The authors further proposed that online learning may help to configure models or perform tasks in unstructured environments with many uncertainties. In the same year, Zhang et al. [177] introduced a new method to achieve soft robot control, and the team achieved an abstract representation of soft robot states and a reinforcement learning method to obtain efficient control Strategy.

Since 2017, there have been many attempts in the field of model-free control. Thuruthel et al. [178] introduced a machine learning-based approach, proposing a unique formulation that integrates end-effector feedback and learns the inverse kinematics of a continuous manipulator. They demonstrated the applicability of this model-free approach to kinematic control for nonlinear continuum robots. Furthermore, they discussed the shortcomings and development prospects of model-free methods [168]. Although this method provides a relatively simple way to develop dynamic controllers, its practical applications have certain limitations due to training time or stability issues. Their research suggested that a hybrid controller incorporating model-based and model-free approaches may also be a feasible approach. Based on previous work, Thuruthel et al. [179] proposed a novel variable diameter continuous robotic arm and a general control strategy for closed-loop task space control. The robotic arm is composed of an inverse kinematics-based feedback component, a forward kinematics-based feedforward component, and a low-level velocity controller; the team also introduced two neural networks to learn forward and inverse kinematic models of the manipulator.

For the applications of deep learning algorithms, Zhou et al. [180] proposed a new strategy for controlling soft robots with elastic behavior. The main contribution of this work is the use of neural networks to obtain an approximate model soft robot, and then a controller is proposed on this basis to control a real soft robot made of silicon. Bern et al. [181] introduced a way to use machine learning methods for soft robot control by learning a differentiable model of the quasi-static physics of the soft robot and then performing gradient-based optimization to find the best open-loop control input. This approach provided an efficient framework for learning the physical properties of soft robots. Wang et al. [182] introduced particle swarm optimization (PSO) and genetic algorithm (GA) optimization to solve the endpoint coordinates derived from a piecewise constant curvature model. They proposed that the effectiveness of interactive data collection also hinders the further development of model-free control, and a sim-to-real transfer method [183] was introduced to address this issue.

As algorithms and modeling of the continuous control body are increasingly sophisticated, more powerful ML methods have been implemented for the control of soft robots. Li et al. [184] introduced a data-based control framework for solving the underwater motion problem of soft robots using deep reinforcement learning (DRL). This framework includes a soft robotics simulation method that collects data to train neural networks, a neural network controller for swimming robots trained in a simulated environment, and a computer vision method that uses cameras to collect spatial information from real robots. Their research realized the linear motion of a soft robot in turbulent water. This team also investigated the feasibility of using model-free multi-agent reinforcement learning (RL) [185], i.e., multi-agent deep Q-network (MADQN), to control a 2-DOF cable-driven continuous surgical manipulator. Their research enabled robots to perform trajectory tracking with sub-millimeter error under external loads, soft obstacles, and rigid collisions.

In summary, the model-free control method has had a gratifying advance in recent years and has taken control of underactuated systems to new heights. Needless to say, it also has crucial implications for the design of robotic fish that are naturally underactuated in fluids. However, despite its large success, the model-free method still faces many problems, such as low efficiency, poor accuracy, huge noise, intense data requirement, and difficulties in convergence guaranteed. One feasible solution proposed by the community to address the problem is to combine the model-based and model-free methods to form a hybrid control scheme, as shown in Figure 6.

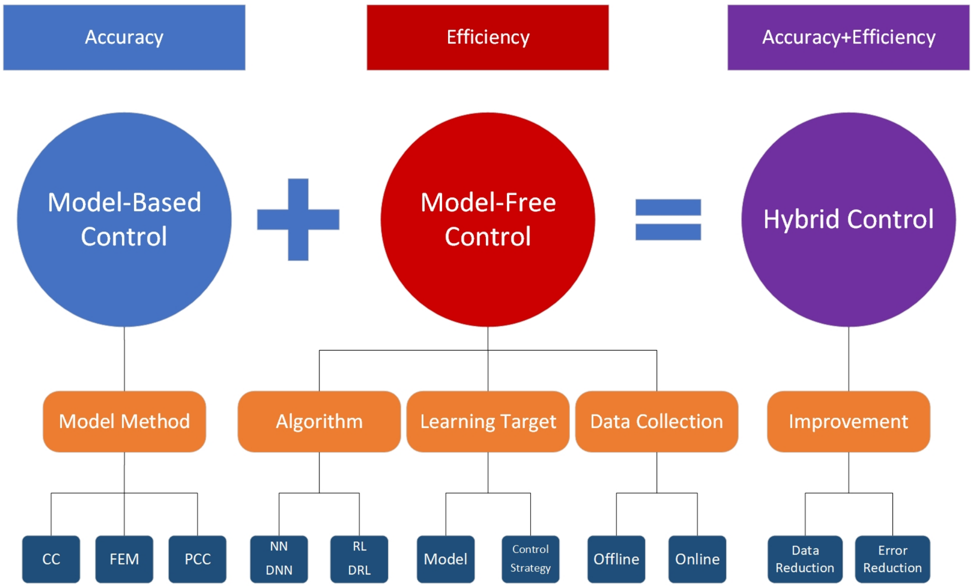


Figure 6. The composition of hybrid control. Both model-based and model-free control have unique benefits along with certain limitations. Based on all the previously mentioned, the hybrid control methods that combine their advantages have been continuously developed and accepted by the community in recent years.

4.1.3. Hybrid Dynamic Control

In order to combine the accuracy of model-based control and the efficiency of model-free control, researchers started to introduce machine learning algorithms to optimize the classical control model, referred to as the hybrid control method. Thuruthel et al. [186] proposed a model-based policy learning algorithm, which consists of three stages: learning a forward dynamic model, generating trajectories as samples for policies, and a final policy learning stage. The forward dynamic model is represented using a recurrent neural network, and the closed-loop policy is derived using trajectory optimization and supervised learning. Li et al. [187] used graph neural networks to encode the state into object-centric embeddings and a block-wise linear transition matrix to regularize the shared structure across objects. The obtained dynamics models can quickly adapt to new environments of unknown physical parameters and produce control signals to achieve specified goals. Phillip et al. [188] introduced a neural network-based method for representing system states and gradients associated with inputs and outputs with a linearized discrete state space of the system. Using the MPC method, they built a first-principles-based model with high performance in steady-state error, rise time, and overshoot.

In 2020, Jiang et al. [189] proposed a novel structure called the honeycomb pneumatic network (HPN) and a finite element method (FEM)-based parameter optimization method for the design parameters of the HPN arm. An open-loop controller is implemented based on the accurate model by combining PCC modeling and machine learning methods. Therefore, a feedback controller using the estimated Jacobian is implemented in 3D space based on the inaccurate model. Based on this study, Li et al. [190] proposed a Q-learning controller for soft robotics by using a pre-trained model to improve the controller's performance, and the training data came from a simulator-based on a piecewise constant curvature model. Their model reduced the amount of real-world training data and greatly improved its accuracy and convergence speed. Fang et al. [191] conducted a learning-based approach to solve the inverse kinematics problem of soft robots with highly nonlinear deformations in real time. They use a neural network to learn a forward kinematics mapping function and the Jacobian of that function and solve the IK problem based on Jacobian iterations. The method is helpful in the control of pneumatically actuated soft robots for path tracking and interactive localization.

As the hybrid dynamic control model has matured, more applicational works have emerged. Tang et al. [192] designed a soft robotic glove based on a soft elastic composite actuator (SECA) and proposed a model-based online learning adaptive control algorithm. The hybrid controller enables the soft robotic glove to adapt to different hand conditions for reference tracking. Wang et al. [193] successfully applied the continuum robot for natural orifice endoscopic surgery by designing a hybrid adaptive control framework that combines offline-trained robotic inverse kinematics with neural networks. The online adaptive adjustment of PID controller parameters is combined with another neural network to compensate for the positioning error caused by external disturbances.

4.1.4. Summary

In summary, soft robotic control is a fast-evolving research area with many exciting challenges and achievements. Soft robot control urgently needs to solve some of its unique problems, such as underactuation, and complex interaction with the environment, which are also critical for bio-inspired aquatic robots.

Model-based control is a traditional method with the control core based on existing physical laws, such as the N–S equation. This method has high accuracy (accuracy), but it is complex and generally takes a long time to solve with a high dependence on control theory.

Model-free control is a new mainstream method in recent years based on computer technology. The existing research uses different machine learning methods, such as NN, DNN, and RL, to learn motion models or control strategies. The method is more straightforward with low dependence on control theory. However, as this method puts higher requirements on the required data, it becomes a new challenge to collect a suitable and sufficient amount of data. In addition, the problem of non-convergence of the solution may occur with this method.

The hybrid control method is a highly cutting-edge research method that combines the advantages of both aforementioned methods. The method can be considered an improvement of model-free control while absorbing the strength of physics models. By incorporating the existing physical equations into the neural network, hybrid control methods achieve data streamlining and error reduction, and the convergence of the solution process is guaranteed. One thing to note is that the research on this method is still in the preliminary stage, and the existing studies are more focused on relatively simple tasks. It is foreseeable that this method may become a new hot spot in this field in the near future.

4.2. Multi-Mode Robot

The multi-mode robot is the class that can achieve the multi-domain motion with the multi modes. The different modes allow the robot to adapt to different environments flexibly [194]. The transition from aquatic to terrestrial or aerial locomotion was crucial in vertebrate evolution. In addition to working on a more efficient and faster robot in the water, the roboticists also expect the underwater robots to have multi-mode amphibious locomotion capabilities for special missions, such as emergency rescue, coastal harvesting, and military uses. According to the hybrid class, we divide these robots into air–aquatic and ground–aquatic amphibious underwater robots to introduce them separately in the following sections.

4.2.1. From Swimming to Flying

Plenty of works have been conducted on traditional fixed-wing amphibious robots [195–201] and rotor-wing robots [202–205]. However, the traditional amphibious robots have shortages in flexibility and efficiency compared with bio-inspired ones. Moreover, traditional ones suffer more drag to gain the lift force.

Eons of natural selection have given birds in the sky and fish in the water the ability to explore each other's space for survival or resources. Flying fish, for example, can jump out of the water and glide at speeds of up to 16 km per hour for distances of more than 400 m to avoid predators; the gannets can dive into the water at 40 m/s and hunt by flapping their wings and distorting their lenses. Roboticists believe that bio-inspired ones have more potential to be amphibious, and various bio-inspired air–aquatic prototypes are designed following these two trends, as shown in Figure 7.

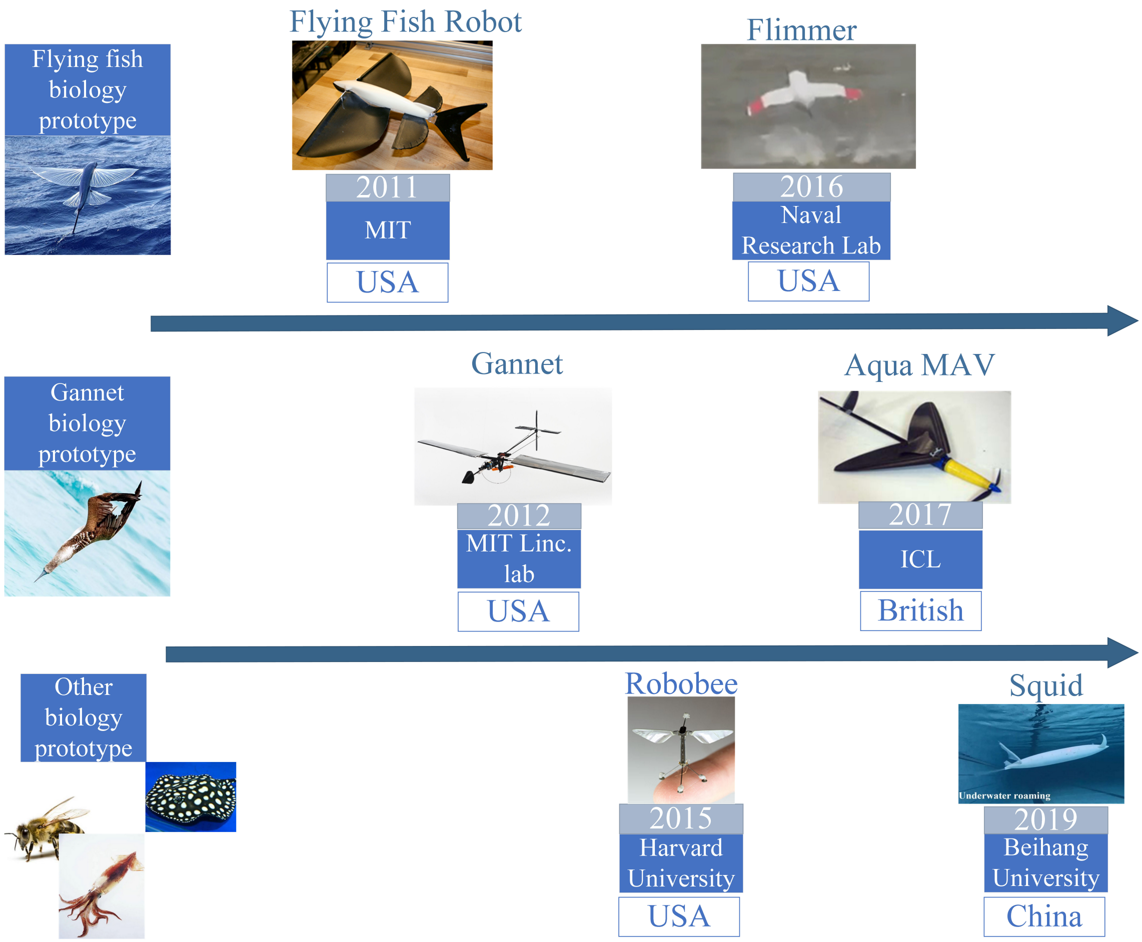


Figure 7. The timeline of bio-inspired aerial–aquatic prototypes; the related works are distinguished by their morphological structure and are divided into fish-like, bird-like, and other biology prototypes.

A. Flying fish-like Robots

To build up a database, Fish et al. [206] analyzed the wing morphology, body length, fin area, fin span, wing load, and aspect ratio of six species of flying fish ranging in size from 0.003 to 0.53 kg, and concluded that the aerodynamic design of flying fish is closer to that of birds and bats, but unlike all other vertebrate gliders. The wing load, high aspect ratio, and relatively flat glide trajectory of flying fish indicate that the wing configuration has a high lift-to-drag ratio, can operate at high speeds, and has aerodynamic performance similar to that of birds' gliding flight. Their research laid the foundation of theoretical basis data for future amphibious flying fish robots research.

For a beforehand prototype research project, Gao et al. [207] from MIT built the first amphibious prototype that mimics a flying fish using a clever spiral rod to drive the differential phase swing of the fish in a single degree of freedom. Although the project demonstrated the difficulty of achieving the ideal exit velocity of 10 m/s underwater under current conditions, the team continues to investigate the possibility of further acceleration following this principle in the air at a lower exit velocity.

Based on research in the early stage, Geder et al. [208] conducted the UUV test, and further developed an amphibious robot called Flimmer (flying-swimmer). Its underwater performance [209] and surface landing performance [210] were studied respectively. Fins act like wingtips in the air to reduce induced drag and act as hydrodynamic propulsion in the water. The effects of fin material and shape on underwater and air were verified through simulation and experiment, but the model can only be one-directionally amphibious. In 2020, they intended to optimize the design and performance of prototypes with bionic fins in tandem systems [211].

The flying fish-like robot is simple in transmission and elegant, with only one pair of actuators. However, a flexible buoyancy control system is still a critical challenge in design, and the trans-media procedure is also highly time consuming, causing compromise on operational flexibility.

B. Bird-like Robots

Compared with flying fish, the booby's direct and rapid access to water is more maneuverable, which is more suitable for special emergency operations in the military field. However, the impact load on the structure and the fluid stability always bring new challenges to the prototype design.

For a micro prototype, MIT's Lincoln Laboratory designed a gannet robot with folding wings [212]. They placed the folded center of buoyancy on the same vertical plane as the center of gravity, with the center of gravity lower, and the overall density was close to neutral buoyancy. For the test, the prototype entered the water at a speed above 7 m/s with the nose cone protecting the electronics and wings. The prototype survived multiple plunges and still entered the water smoothly.

Then roboticists began to challenge the large prototype. Siddall et al. [213] designed a gannet-mimicking UAV and produced a new scaled version in 2017. The aircraft completed the water–air transition through folding wings and catapulted out of the water with a high-pressure CARBON dioxide pump as the power supply. The speed can easily reach 11 m/s to meet the requirements of glide speed, but due to the imperfections of flight control and sensor, only the ejection test was carried out without the transition flight glide test. Subsequent work will focus on adding aerial propulsion, control surfaces and sensors so that the aircraft can continue flying [214].

The bird-like robots' direct and rapid access to water provides better maneuverability than fish-like robots. However, the strength of the material brings limitations to the robot's size. On the other hand, the relatively big head part of the prototype supports few trans-media operations.

4.2.2. From Swimming to Walking

The traditional ground–aquatic robot is the one that uses an improved propeller to fit the amphibious environment. However, based on the fundamental principles of nature, more bio-inspired prototypes have emerged in recent years, which have more potential for higher performance or other previously unexplored capabilities [215]. The traditional and bio-inspired ground-aquatic robots are summarized in Figure 8.

The bio-inspired ground–aquatic robot follows a trend from six feet to multi-feet, currently evolved into fins.

The six-foot prototype is a classical design. Gregory et al. [216] presented a prototype called AQUA. It is an amphibious robot that swims via the motion of its legs rather than using thrusters and control surfaces for propulsion. AQUA can walk along the shore, swim along the surface in open water, or walk on the bottom of the ocean. In 2013, based on AQUA, Dey et al. [217] proposed a single leg design with the advantages of both the walking legs and the swimming flippers to overcome the problem of AQUA's extremely poor thrust for swimming. Additionally, its flippers are entirely unsuitable for terrestrial operations. In 2020, Picardi et al. [218] in Italy reported a bio-inspired underwater legged robot, called SILVER2, that implements locomotion modalities inspired by benthic animals (organisms that harness the interaction with the seabed to move; for example, crabs).

For the multi-feet robot, Ijspeert et al. [219] in France presented a spinal cord model and its implementation in an amphibious salamander robot. It demonstrated how a primitive neural circuit for swimming could be extended by phylogenetically more recent limb oscillatory centers, and explained the ability of salamanders to switch between swimming and walking. In 2021, Rafeeq et al. [220] designed a spider-like four-legged robot, yet the system design and functional implementation are still in the early stage.

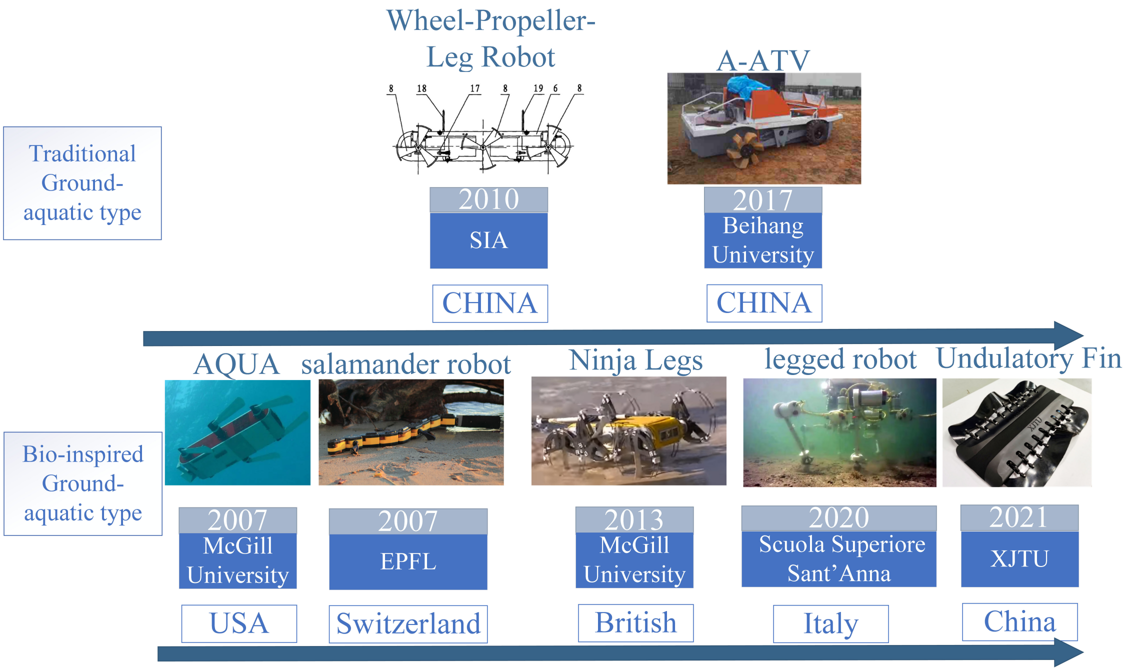


Figure 8. The timeline of ground-aquatic prototypes,divided into traditional and bio-inspired prototypes.

The fin robot has been a new trend in recent years. Chi et al. [221] designed a novel concept of an amphibious spherical robot with fins in 2021. The proposed amphibious spherical robot utilizes the rolling motion of a spherical shell as the principal locomotion mode in the aquatic environment. Meanwhile, they proposed a decentralized method of a spherical amphibious multi-robot control system based on blockchain technology [222] and carried out a set of experiments to evaluate the performance of on-land locomotion and underwater locomotion [223]. In 2021, Pliant Energy System developed the first undulatory fin robot in the world. Then Yin et al. [224] in XJTU proposed a novel amphibious robot inspired by Gymnarchus niloticus. The robot prototype is comprised of undulatory fins, shells and robot bodies. The undulatory fins are symmetrically placed on each side of the robot, enabling the robot to swim underwater and crawl on the ground. According to the performance of this prototype, we believe that the undulatory fin robots have the potential to become a research hotspot in the future.

The traditional ground–aquatic vehicle is more stable and reliable in locomotion on land, thus is suitable to be large in size for manned use. However, it is highly efficient on land but low in the water. On the contrary, the bio-inspired ground-aquatic robot has a trend to have multi-feet; thus, it is highly efficient in water but low on land. Additionally, the flexibility in turning makes it more suitable for crewless exploration operations.

4.2.3. Summary

In summary, the progress and challenges for each class of multi-mode robots in this subsection are listed in Table 1. The community has witnessed various genius designs of bio-inspired amphibious robots that can both fly and swim or walk and swim in the last decade.

However, it is important to note that in the procedure of developing future bionic aerial and underwater amphibious vehicles, many improved or even disruptive technologies are necessary for efficient locomotion in different media, such as multi-functional propulsors, lighter but stronger structures, and higher power density materials.

Table 1. Progress and challenges for each class of multi-mode robot presented.

Class	Subclass	Progress and Advantages	Disadvantages and Limitations
Air-aquatic	Fish-like [206–208,211]	The foundation of experimental data and theoretical basis [206]; Demonstration of the difficulty in achieving the ideal exit velocity [207] ; Multi-domain fin effects verification [208]	One-directional operation [207,208].
	Bird-like [212–214]	A new approach of trans-media operation[212]; Two-directional trans-media operation [213].	Incapable of complex missions or verifying the circumstance [212]; Conventional propeller propulsion increasing structural weight and system complexity [213].
Ground-aquatic	Traditional [215]	More stable and reliable in locomotion on land [215].	Low efficient in water and not flexible in turning [215].
	Bio-inspied: Multi-foot [216–220]	Redesign of a legged robot for amphibious environment [216,219]; Overcoming the weakness in swimming thrust [217]; Huge in size for complex mission [218];	The feasibility requires further verification [220]; Poor thrust in liquid [216]; Flippers unsuitable for terrestrial operations [217].
	Bio-inspied: Fin [221,224]	Combination of the spherical robot and fins [221]; A novel simple undulatory fin actuator that operates both on land and in water, with high adaptability and robustness [224].	Lack of experiments to determine coefficients in the empirical equations, so as to obtain a more precise mathematical model [221]; Inefficiency on land [224].

5. Discussion and Conclusions

The review attempts to present a comprehensive development of robot fish in recent years from both physics mechanisms and practical applications. Section 2 presents an overall conceptual introduction of a bionic propulsion system capable of closed-loop system precise control, from the physics of the bionic drive's propulsion mechanism to a brief description of fluid information perception. We adopt the science principle of simplicity to complexity for the introduction, starting from the scaling law governing a simple rigid-airfoil model's hydrodynamics, advancing to models considering the flexibility of the torso, and finally to the complex fin–body interactions and the flowfield perception of a highly bionic robotic fish. There has been a long research history and splendid progress in the mechanistic exploration and functional mimicry of bionic fish. However, it is also evident that many difficulties remain to be solved, such as more powerful computational methods and better quantitative theoretical models.

Section 3 enumerates the underwater bionic robotic applications with different forms and functions that have emerged in the last decade. Various fish in the oceans and rivers have distinguished forms and excellent performance properties, providing diverse guidelines for the design of corresponding bionic fish. Despite the fruitful achievements, all the current bionic fish are still far from our ideal model of the intelligent, flexible, and highly perceptive aquatic robot. Moreover, they have brought out even more challenges and future directions during the process.

As the design and manufacturing of bionic fish has progressed theoretically and practically in recent years, it has required an increasingly high multidisciplinary intersection level for further development. The last section includes some significant works on flexible robots and amphibious robots, representing the future directions of robot fish development. The hybrid control method of the soft system is a crucial technique to deal with the underactuated structure of the newest flexible bionic fish. The multi-mode ability of robots blurs the boundaries between the sea, land and the sky, raising their practicality and environmental adaptability to a new level. It is foreseeable that the continuous development of artificial intelligence algorithms and other related disciplines such as materials science will have further interaction with bionics. The design and manufacturing of robotic fish will tend to be more multidisciplinary and intelligent, thus requiring the collaboration of a worldwide cross-disciplinary academic community.

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Abbreviations

$c_n (n = 1, 2 \ldots)$	Constants
C_T	Thrust coefficient
C_P	Power coefficient
f	Flapping frequency
c	Chord length
U_∞	Free-stream velocity
f^*	Flapping reduce frequency; fc/U_∞
U_e	Effective velocity; $\sqrt{U_\infty^2 + \dot{h}^2}$
U^*	Dimensionless velocity; U_e/U_∞
h	Heave position
ρ	Fluid density
F_T	Thrust
A	Amplitude of the trailing edge
s	Wing span
θ	Pitch angle
ϕ	Phase angle between heave and pitch motions
h_0	Heave amplitude
St_h	Strouhal number defined by heave; $2fh_0/U_\infty$
St_θ	Strouhal number defined by pitch; $2f\theta c/U_\infty$
St	Strouhal number; $St_h^2 + St_\theta^2 + 2St_h St_\theta \cos\phi$
L	Characteristic length
A^*	Dimensionless trailing edge amplitude; A/L
$g(\theta)$	Function of offset drag

h^*	Dimensionless heave position; H/L
θ^*	Dimensionless pitch angle; $\theta L/A$
Re	Reynolds number
b_1	Coefficient related to Re

Appendix A

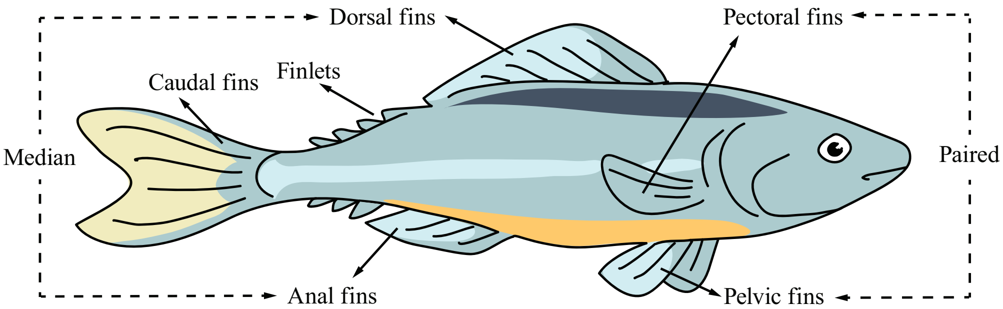

Figure A1. Fins of a typical fish.

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