# Classification of the Fish Inspired Robots

Subjects: Engineering, Marine

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Compared with traditional underwater vehicles, bio-inspired fish robots have the advantages of high efficiency, high maneuverability, low noise, and minor fluid disturbance. The propulsion ability of fish comes from the coordination between muscle groups, 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. Finally, fish have unique fluid sensing systems. 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.

Keywords: Classification ; Fish Inspired Robots ; fish swimming

## 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][6][7][8][9][10][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][13][14][15]. In addition, aquatic animals have evolved to obtain various flow sensing abilities to perceive the complicated underwater environments [16][17][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, human have witnessed a significant number of bionic swimming robots of different shapes and sizes, and the creature they mimic varies from fish to all kinds of aquatic organisms, such as frogs [20][21], octopuses [22][23][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][31][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][34][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.

## 2. 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 [38][39]. Snake-like robots show the full body undulation as anguilliform and, hence are concluded. Moreover, some amphibious robots, which include Salamandra Robotica II [40] developed by Crespi et al., Series Elastic Actuated Snake [41], Mamba Waterproof Snake Robot [42], and amphibious snake-like robot developed by Yu et al. [43] also belong to this category, as they also perform anguilliform locomotion.

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 [44], which the actuators only allow for one degree of freedom, Stefanini et al. created the LAMPETRA [45], which has a more flexible body thanks to smaller sections and actuators. After that, Salamandra Robotica I [46] and II [40], 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. 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 [47], while carangiform fish utilize one-third of their posterior body for undulation [48].

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. Researchers 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 [49] 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 [50] and AmphiRobot-II [51] with a rigid body. Koca et al. [52] 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 [53] 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 [54] has a small head unit and a large peduncle section, where a multi-sectioned skin covers the peduncle section. Ichikizaki et al. [55] created a Carp-inspired robot, where the robot structure was contained within a mimetic body shell. Furthermore, Clapham et al. [56] 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. [57], with a multi-segmented tail, providing the capability for good peduncle flexion. Furthermore, a hydraulic actuated peduncle was created by Katzschmann et al. [58], of which the peduncle is made of soft materials. Katzschmann et al. [59] 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 [60]. Therefore, carangiform and subcarangiform locomotion robots are more likely to have higher speeds than those that are anguilliform.

## 4. 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 [61][62].

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 [63]. Thereafter, a robot mimicking a mackerel called Mackerel Robot [64] 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 [65]. 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 [66]. 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 [67]. A relatively simple single-motor-actuated robotic fish called Single-Motor-Actuated Robotic Fish, was created by Yu et al. [68], 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 [69]. 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 [70]. 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 [71]. Yu et al. [72] created a dolphin robot that was capable of fast speed and leaping out of the water.

## 5. 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 [73].

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. [74] is a rigid component-based robot, and the body was separated into two sections. Kodati et al. [75] created a robot named the microautonomous robotic ostraciiform (MARCO). Wang [76] and his consultants created the Boxfish-like robot, which was slightly smaller but had the same capabilities. Mainong et al. [77] 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.

## 6. 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 [78]. Moreover, these fish may have low endurance when solely utilizing the pectoral fins [79].

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. [80] created the early labriform robot, called Wrasse robot, in 2009. Thereafter, by efforts by Behbahani et al. [81], 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. [82]. 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.

## 7. 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 [83].

In practical robot fish design, there are a variety of robots belonging to this class due to the advantage in efficiency and maneuverability. Here, researchers 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 [84]. 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 [85]. Furthermore, a rigid encased skeleton design called flexible pectoral foil cownose ray was created by Cai et al. [86]. 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. [87], using the elastomer membrane fin as the front part of the body. Alvarado et al. [88] 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. [89] 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. [90] with an actuation skeleton that excites multiple ribs in a flexible membrane. Zhong et al. [91] 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. [92][93], 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. [85] based on RoMan-II; the size of the third version is much more compact while maintaining the velocity. Punning et al. [94] and Takagi et al. [95] designed relatively similar IPMC robots called IPMC chain ribbed ray and multi-ribbed IPMC, respectively. Moreover, Krishnamurthy et al. [96] 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. [97] 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 [60].

## 8. 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 [98].

Compared to the subcategory above, the robots designed in amiiform are relatively few. Hu et al. [99] 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. [100]

## 9. 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 [101].

Similar to amiiform, the gymnotiform class has few robot systems to be classified. Siahmansouri et al. [102] incorporated a knifefish robot with pitch and yaw actuation joints that connect to the multi-ribbed propulsion fin. Curet et al. [103] created a robot that has an actuation mechanism encased in a rigid tubular shell. Furthermore, Liu et al. [104] 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.

## 10. 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.

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