# Fish-Inspired Swimming Simulation and Robotic Implementation

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## Abstract

This paper describes our efforts to develop a Digital Fish Simulator (DFS), particularly aiming at creating a controlled kinematic centered environment to further shed light on how to design and control artificial fish robots. Compared to a 3D simulator for autonomous robotic fish by Liu and Hu, an improved body wave equation capable of multimodal swimming motions is adopted in our simulator and artificial swimming data can be further imported enabling various fictive swimming patterns. Furthermore, the swimming data generated from the simulator can directly be fed into the fish robots for verification, and vice versa. Finally, a series of fishlike robots with different mechanical design have been built to validate our well-formed ideas and to reach a new level of performance close to actual fish for real applications.

## 1 Introduction

It is well known that fish can perform very efficient locomotion and maneuvering in the water. With over 28, 0000 species and half a billion years of evolution, in particular, aquatic swimmers including fishes and cetaceans are endowed with a variety of morphological and structural features for moving through water with astonishing efficiency, speed, maneuverability, and stealth, which are further superior to current manufacturing technology of ships or autonomous underwater vehicles (AUVs) [1-4]. Fortunately, biomimetics (also referred to as bionics) initiated in the 1960's has brought bio-inspired technology in AUVs design. Specifically, attracted by the fish's remarkable swimming feats and also driven by mimicking such performance to update the existing AUVs technologies, extensive theoretical and practical research has been carried out to advance this interdisciplinary subject. So far, much effort has been devoted to the design and development of fishlike robots (also referred as robotic fish), mainly involving kinematic and hydrodynamic analysis, mechanical design, control methods, as well as physical tests. It is expected that the robotic fish with powerful motion capability will be more competent for aquatic-based applications such as underwater exploration, oceanic supervision, military detection, and the like.

In general, the propulsion modes of swimming fish can be categorized into two modes according to means of used propulsion part: body and caudal fin (BCF) propulsion, and median and paired fin (MPF) propulsion [1]. The latter can further be subdivided into pectoral fin (PF) propulsion and undulation fin (UF) propulsion. A mainstream view on fish swimming is that there exists no absolutely superior model in these modes in that each species of fish has well evolved for its own habitat. More recent evidence has suggested that fish actually relies on multiple control surfaces including caudal fin, pectoral fin, pelvic fin, dorsal fin, anal fin as well as body to achieve fast and maneuverable propulsion [5]. This well-integrated, configurable multiple control surfaces provide an excellent paradigm to create and control high-performance underwater vehicles. However, it is unrealistic to totally replicate a natural fish due to the tremendous difference between the biological system and the engineering counterpart. One of the reasons is that tradeoffs in engineering practice will have to be made between biological mechanism, engineered method, feasibility, cost/gain, etc. The existing robotic fish, at the same time, has been predominately used BCF, or PF, or UF for coordinated propulsion and maneuver. There have been few or limited studies related to simulating and constructing a robotic fish with many different fins, i.e., multiple control surfaces, which are desirable for enhanced maneuverability and controllability. In addition, from the viewpoint of artificial life, artificial fish and fish school have been devised in the form of 3D animation. For example, Tu and Terzopoulos designed a framework for behavioral animations featuring an artificial fish model yielding realistic individual and collective motions [6]. Although behavior guided fish agent in 3D virtual world is compatible with the behaviour based robotics, robotic fish and artificial fish and share little in common in locomotion mechanism and control method.

The objective of this paper, on the basis of our previous research, is to build a fish-inspired simulation platform, Digital Fish Simulator (DFS), which is beneficial in creating and controlling robotic prototypes. In contrast to a 3D simulator for autonomous robotic fish by Liu and Hu [7], an improved body wave equation capable of multimodal swimming motions is adopted and a two-way swimming data exchange interface is established enabling both fictive swimming patterns simulation and practical patterns recurrence. With the aid of the built DFS, a series of robotic prototypes have been successfully developed.

The rest of the paper is organized as follows. Section 2 gives a brief review of fish-inspired biomimetic research. Design scheme and procedure for the DFS is presented in Section 3. Robotic prototypes and corresponding control framework are provided in Section 4. Finally, Section 5 concludes the paper with an outline of future work.

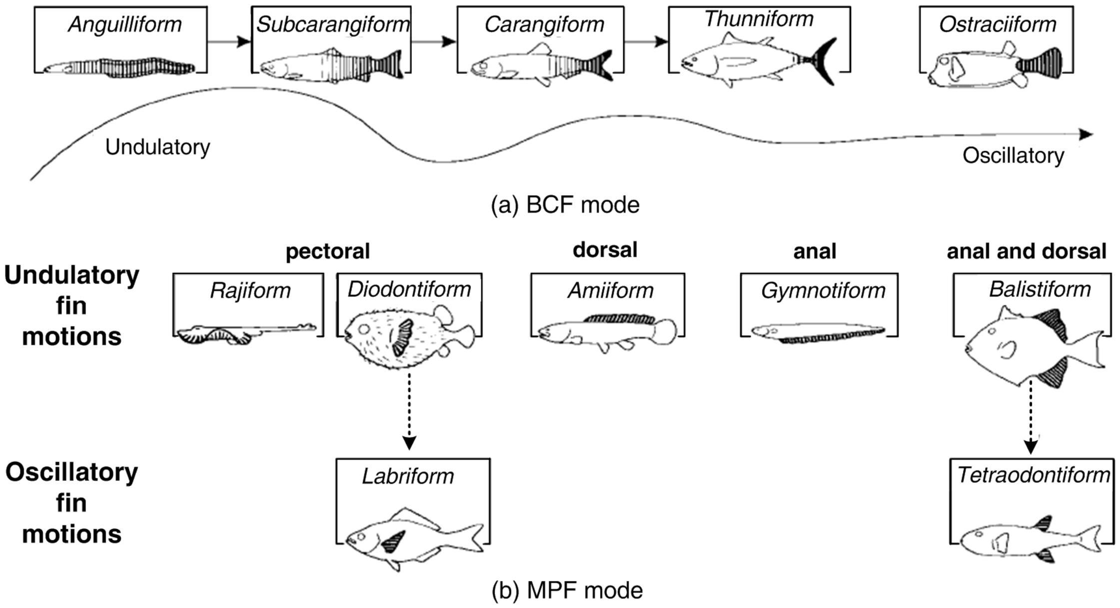


**Figure 1** Fish propulsion modes

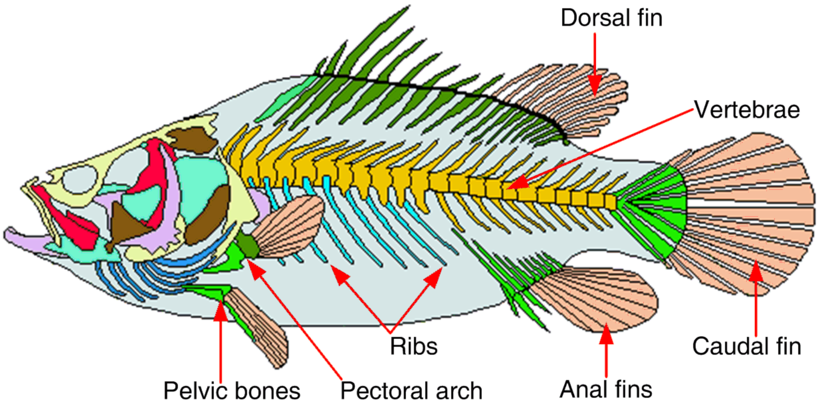


**Figure 2** Skeleton of a generalized bony fish

## 2 Review of Bio-inspired Fish Swimming

Prior to describing the detailed simulator design and implementation on fishlike swimming, we first review some of the relevant results in both biological and biomimetics literature.

### 2.1 Ichthyology basis

As illustrated in Fig. 1, there exist two distinct propulsion modes for technical inspiration in developing robotic fish: BCF mode and MPF mode [1]. The former is favorable for the cases requiring greater thrust and accelerations, while the latter for the cases requiring higher maneuverability. Meanwhile, in terms of movement's temporal features, swimming locomotion can be categorized into periodic swimming characterized by a cyclic repetition of the propulsive movements and transient movement involving rapid starts, escape maneuvers, and turns. Meanwhile, studies into the dynamics of fish locomotion show that most fishes synthetically use multiple control surfaces (e.g., tail plus caudal fin, pectoral fins, pelvic fin, dorsal fin, anal fin) to accomplish efficient and effective propulsion. Fig. 2 shows the skeleton of a bony fish, which involves functionally complementary control surfaces. From the structural design standpont, the vertebrae, cranium, jaw, ribs, and intramuscular bones make up the bony fish skeleton. Basically, the skeleton provides a foundation for the body and the fins, encases and protects the brain and the spinal cord, and serves as an attachment for muscles. Meanwhile, the tail is laterally compressed and corresponding tail vertebrae become smaller distally. Namely, the lengths of skeleton elements, from the skull to the last caudal vertebra, tend to be smaller and smaller, providing some clues to the structural optimization.

Moreover, regarding the locomotion control of fish swimming, neutral and mechanical feedback play critical roles. As biologists suggest, fishes swim using multiple body segments and organizing left-right alternations in each segment so as to produce the body wave that propels them through water. These rhythmic motor patterns are internally produced by central pattern generators (CPGs), i.e., central neuronal circuits whose activation can produce rhythmic patterns in the absence of sensory or descending inputs that carry specific timing information. Thus neural system can generate and control a variety of motor behaviors by coordinating each segmental CPG [8].

## 2.2 Biomimetic principles

As an efficient and effective underwater propulsive system, fish is of some technological interest in developing novel AUVs. Typically, it involves the following aspects:

- **Hydrodynamics:** Fish in natural environments vary greatly in body shape with significant hydrodynamic consequence. An important and intriguing mechanism associated with high-performance swimming is shedding of vortex rings and recycling of vortex energy exploited by fish. For instance, a pair of abducted pectoral fins cause the formation of a drag wake, and the fish tail will recycle the energy of the pectoral-fin vortices. Vortex interaction among different control surfaces (e.g., pectoral fins and tail) facilitates the generation of thrust. The caudal fin shape, of course, has certain effect on vortex formation patterns [5].
- **Propulsive mechanism:** As mentioned previously, fish are propelled through the water by fins, body movement, or both. A fish can swim even if its fins are removed, though it usually has difficulty in controlling direction and balance. During swimming, the fins are driven by muscles attached to the base of the fin spines and the rays. In particular, fish with fairly rigid bodies depend mostly on fin action for propulsion. Notice also that fish fins are flexible and move in a complex 3D manner.
- **Locomotion control:** So far, the control mechanism of fish body and fins are not fully understood. Though patterns of body undulations are very similar in steady swimming, fishes apply more maneuvering swimming than steady swimming. Another point to be emphasized is stability, a significant issue in real-world applications. With the center of buoyance lies below the center of mass, fish is statically unstable. Other forces are needed to make up the lift so that a well-balanced state is achieved, even worse at low-speed swimming.

After briefly reviewing the ichthyology basis and biomimetic principles of fish swimming, the next step is to develop a simplified simulator helpful to propulsion mechanism and control methods.

# 3 Development of DFS

With the purpose of simulating the fundamental locomotion capability of natural fish, we should not blindly copy animal structures and control mechanics, but entirely absorb the advantages of several biological creatures in a hybrid form. In this paper, we will focus our attention on the main problem of fishlike swimming generation and modulation, as well as their robotic implementation.

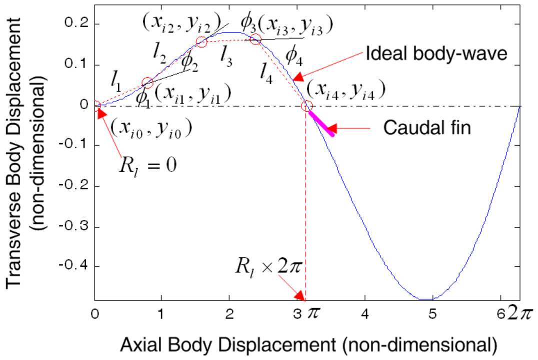


**Figure 3** Multi-link based fishlike swimming design

## 3.1 Functional design

Since our previous propulsive mechanism for fishlike propulsion is multi-link based configuration, how to simplify the mechanism and generate the reasonable control data is the key to high-quality biomimicry. Specifically, to quantify the lateral body motions of swimming fish, kinematic and anatomical data of vertebral column and tail are paid more attention. Typical of steady swimming is the propulsive wave (hereafter referred to as body wave) resulting from the progression of muscular contraction from head along the midline of the fish body. A widely used body wave is described by (1):

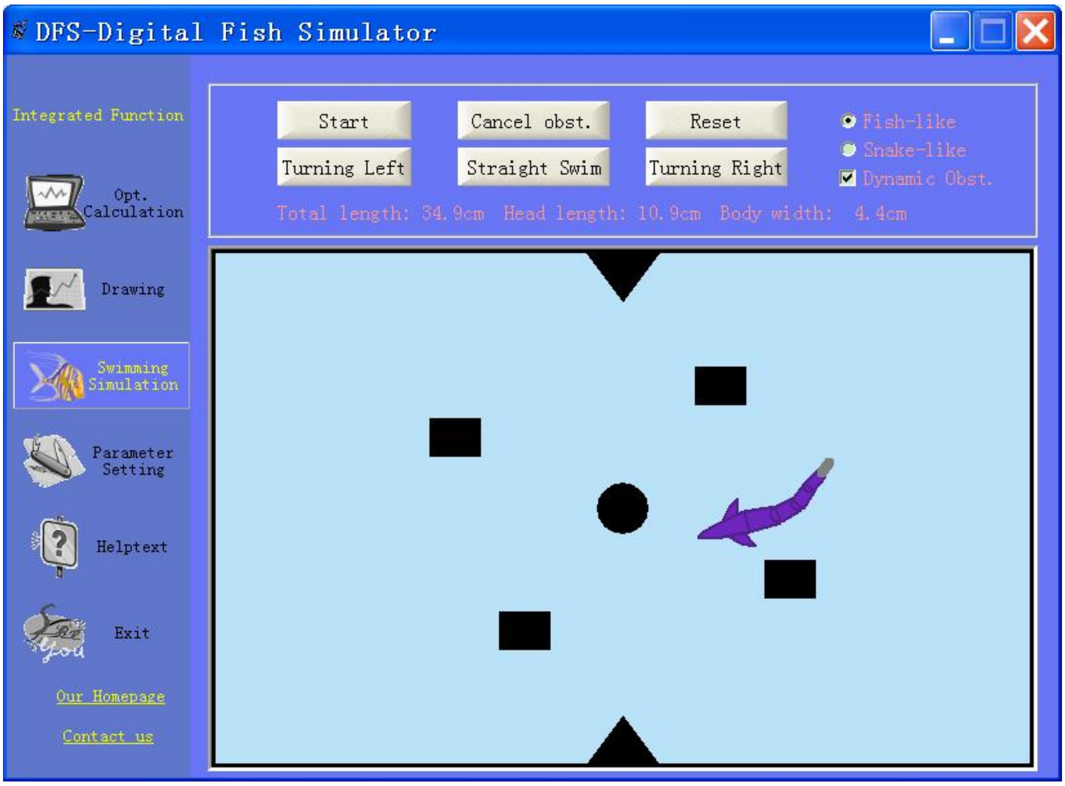
$$y_{\text{body}}(x,t) = (c_1 x + c_2 x^2)\sin(kx + \omega t) \tag{1}$$

where $y_{body}$ is the transverse displacement of tail unit, $x$ is the displacement along the head-tail axis, $k$ is the body wave number ($k$=2$\pi/\lambda$), $\lambda$ is the body wave length, $c_1$ is the linear wave amplitude envelope, $c_2$ is the quadratic wave amplitude envelope, and $\omega$ is the body wave frequency ($\omega$=2$\pi f$= 2$\pi/T$).

In bio-inspired fish-swimming engineering, the oscillatory part of the robotic fish is discretely designed as a multi-link (or $N$-link) mechanism composed of several oscillating hinge joints actuated by motors. It can be modelled as a planar, serial chain of links along the axial body displacement, and the end points of the links in the chain can be achieved by numerical fitting to a discretized, spatial- and time-varying body wave. For simplification purposes, we consider the following discrete form of (1):

$$y_{\text{body}}(x,i) = (c_1 x + c_2 x^2)\sin(kx \pm \tfrac{2\pi}{M} i) \tag{2}$$

where $i$ denotes the $i$th variable of the sequences $y_{body}(x; i)$ ($i$ =0, 1,. . ., $M$–1) in one oscillation period, $M$ indicates the discrete degree of the traveling wave, and the signs “+” and “–” represent different initial moving directions, which are determined based on different initial values. Refer to [4] for more details on link-based body-wave fitting.



● Fish-like
○ Snake-like
☑ Dynamic Obst.

Total length: 34.9cm Head length: 10.9cm Body width: 4.4cm

**Figure 4** A snapshot of DFS

Taking more diverse sinusoidal motions exhibited in fish-like or snake-like locomotion into consideration, a generalized body wave that facilitates engineering realization is proposed as below:

$$y_{\text{body}}(x,t) = (c_1 x + c_2 x^2)\sin(k_1 x + k_2 x^2 + t) \qquad (3)$$

where $k_1$ denotes the linear body wave number and $k_2$ indicates the quadratic body wave number. The determination of $k_1$ and $k_2$ depends on the desired oscillation type and function.

The next task is deciding how to acquire suitable control parameters. Continuous modulation of multiple parameters will bring tremendous burden to produce multimodal swimming gaits. In such cases, the trial-and-error method based on simulation technology is often adopted to modulate the parameters, further meeting the requirements of control tasks.

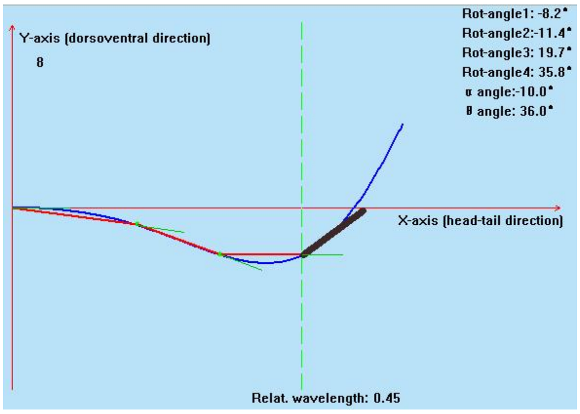
## 3.2 Design scheme and simulator development

The desired functions of DFS primarily include the following three aspects:

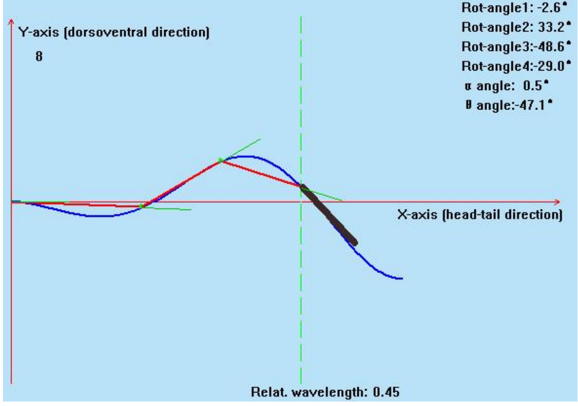
- **Comparison between multi-link oscillations and body wave:** The graphics of moving multi-link and theoretical body wave can be comparatively displayed in one oscillation period, which provides an instructive guide to observe approximation degree.
- **Dynamic status display:** Through sequentially display the motion states of moving links in one oscillation period, we can visually observe oscillatory amplitude and swimming trajectory.
- **Motion simulation:** Motion animation embodies the most direct manifestation of swimming effect. A rendered fish body and a virtual swimming pool with obstacles, static or dynamic, will be devised. Motion control methods such as turning, obstacle avoidance, and other maneuvering controls can then be loaded and online tested.

As a final step, the proposed fish-inspired steady and maneuvering swimming mechanisms, together with conceived control methods, are blended into the DFS via an Object Oriented software engineering methodology (see Fig. 4). That is, we developed a custom-built executive routine to account for both theoretical and experimental factors based on a WINDOWS XP operation system with a compiler of Microsoft Visual C++.

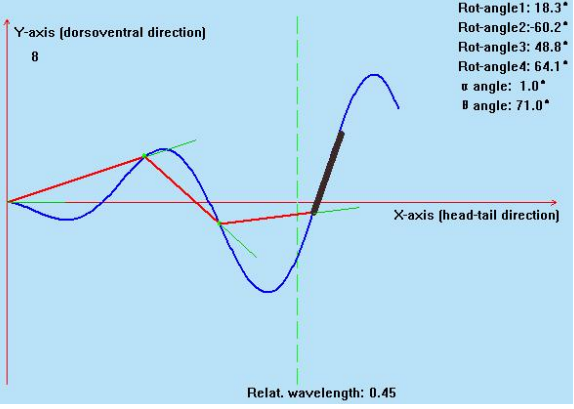
In the DFS, basic input parameters involve fish body wave part and motor control part. The former part mainly includes link number (ranging from 2 to 10), discrete degree in one oscillation (ranging from 28 to 72), relative wave length (ranging from 0.3 to max. 1.0), phase difference (ranging from 75 to max. 90 degrees), and link-length ratio. We remark that a strategy that is based on the geometric optimization of relative link lengths to approximate a given smooth, spatial- and time-varying body-wave curve for enhanced swimming performance has been added to the DFS. Please refer to [9] for more geometric optimization details. The latter part comprises maximum rotary angle of used motors, left rotary limit (LA), right rotary limit (RA), minimum link length, etc. Through body-wave fitting based optimal calculation, the swimming data is automatically generated from the simulator, which can di-



(a) Carangiform swimming



(b) Anguiform swimming



(c) Snake-like swimming

**Figure 5** Comparison of carangiform, anguiform, and snake-like swimmers with same parameters in DFS

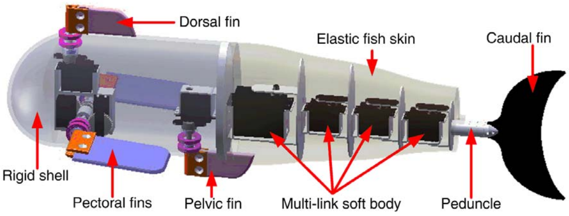


**Figure 6** A conceptual design of the robotic fish

rectly be fed into the fish robots for control purpose. The supposed data in a specified form, in turn can directly fed into the simulator for visual verification. Hence, a two-way swimming data exchange interface is achieved, facilitating subsequent development.

Besides steady swimming, fish in nature applies more maneuvering swimming. Typical maneuvering mechanisms include body-tail deflection, pectoral-fin stroke, stabilization control in pitch, fast-turn, backward swimming, and so on. Our current emphasis is limited to body-tail deflection based maneuvers. By add different deflections (i.e., dynamic offsets) to the straight, symmetric swimming gaits, various turns can be easily achieved. As investigated previously [10], the characteristic parameters associated with turning performance involve magnitude, position, and time of the deflections applied to the links. This turning control method now is employed to accomplish flexible obstacle negotiation with the aid of sensory perception. At present, as shown in Fig. 4, two controlled simulation environments with static and dynamic obstacles are created. Different obstacle avoidance approaches can then be loaded and tested in the DFS.

### 3.3 Some simulation cases

With the well-integrated DFS, many kinematics studies can be simulated and evaluated. For instance, specific parameter combination $P$={$c_1$, $c_2$, $k_1$, $k_2$} for diversified swimming motions can be defined as a key kinematic feature. According to the obtained results, $P_1$={0.05, 0.09, 0.5, 0.1}, $P_2$={0.2, 0, 2.0, 0} and $P_3$={0.35, 0, 3.0, 0} are representative of carangiform, anguiform, and snake-like swimmers, as depicted by Figure 5. It implies carangiform, anguiform, and snake-like swimmers share multi-segment mechanical attribute though their morphologies differ greatly. Further parameter optimization in conjunction with hydrodynamic analysis can be achieved and applied to the design of novel fish-like robots.

## 4 Development of Fishlike Robots

To evaluate the conceived design ideas and control framework, we try to build different physical robots serving as a repeatable testbed. Fig. 6 shows a conceptual design of robotic fish with multiple control surfaces. It entirely consists of several elements: a head and anterior body, a multi-link soft body, a caudal peduncle and caudal fin, a pair of pectoral fins, a dorsal fin, and a pelvic fin. Notice that each fin on a fish is intended to perform a specific function. The rigid shell of the head and anterior body is made of fiber reinforced plastics, offering a hollow and watertight space housing electronics and sensors, control components, batteries, and balance weight. The multi-link soft body is composed of four servomotors connected in series with aluminium link, whose outside is wrapped by a compliant, crinkled rubber tube functioning as fish skin. Considering the caudal fin, in its final lash, may contribute as much as 40 percent of the forward thrust, a crescent-shaped caudal fin is connected to the last link via a slim peduncle made of duroplasts. In order to contribute to more thrust, the caudal fin is made of partly compliant material. In addition, two wing-like pectoral fins are symmetrically placed at the rear lower position of the rigid shell. Meanwhile a dorsa

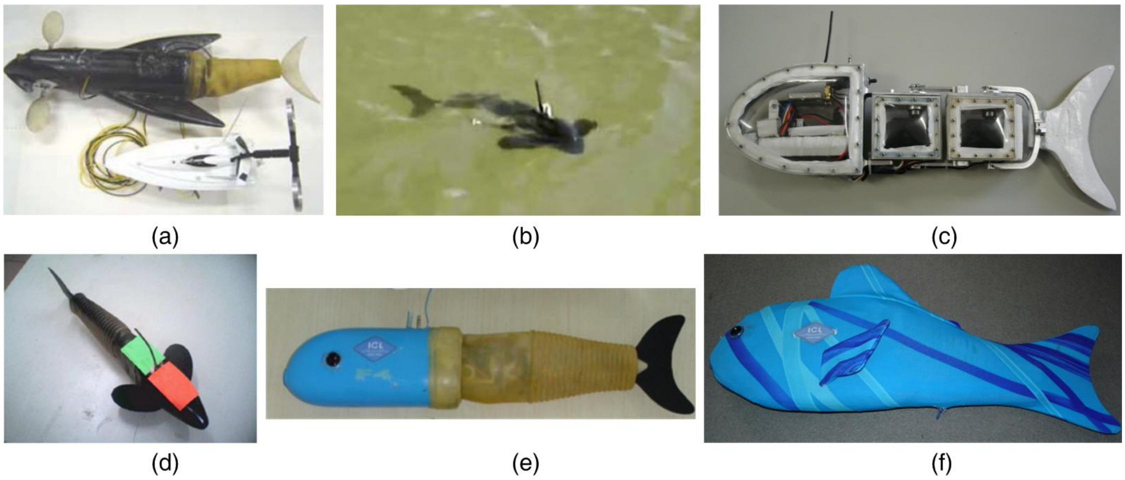


**Figure 7** Prototypes of different robotic fishes. (a) Robotic fish capable of 3D swimming for mobile sensing; (b) four-link multimodal robotic fish swimming in the Weiming Lake of Peking University; (c) two-module, reconfigurable robotic fish; (d) three-link robotic fish; (e) four-link robotic fish with three infrared sensor for obstacle avoidance; (f) two-link robotic fish decorated with waterproof clothing.

fin and a pelvic fin are located the anterior top and the posterior bottom of the fish shell, respectively.

For the moment, as shown in Fig. 7, a series of robotic fish prototypes have been developed in our lab. Through extensive simulations and tests, robotic fish is able to swim vividly and perform simple mobile sensing task in field tests. We remark that two control methods: reverse kinematics control and CPG based control, have been adopted in our robotic fishes capable of multimodal swimming. In particular, the swimming control data derived from the DFS is used for the reverse kinematics control.

## 5 Conclusions and Future Work

This paper has described an overall design for fish-inspired simulation and robotic implementation. In the multi-link based fish swimming framework, an improvement on the widely used body wave equation has been made to produce multimodal swimming motions. A two-way swimming data exchange has been well integrated into the DFS, enabling fish swimming data generation and testing. Accompanying with this software platform, various robotic fishes and their control methods have been developed. However, only simplified kinematical model and minimal hydrodynamic information were utilized to achieve fishlike swimming. The ongoing and future work will concentrate on continuing to improve both the DFS's simulation performance and the robotic fish's mechatronic structure. This is the key and should be given top priority.

## Acknowledgment

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## References

[1] M. Sfakiotakis, D. M. Lane, J. B. C. Davies. Review of fish swimming modes for aquatic locomotion. IEEE J. Ocean. Eng., 1999, 24(2): 237-252

[2] M. S. Triantafyllou, A. H. Techet, F. S. Hover. Review of experimental work in biomimetic foils. IEEE J. Ocean. Eng., 2004, 29(3): 585-594

[3]P. R. Bandyopadhyay. Trends in biorobotic autonomous undersea vehicles. IEEE J. Ocean. Eng., 2005, 30(1): 109-139

[4] J. Yu, M. Tan, S. Wang, E. Chen. Development of a biomimetic robotic fish and its control algorithm. IEEE Trans. Syst., Man Cybern. B, Cybern., 2004, 34(4): 1798-1810

[5] G. V. Lauder, E. J. Anderson, J. Tangorra, P. G. A. Madden. Fish biorobotics: Kinematics and hydrodynamics of self-propulsion. J. Exp. Biol., 2007, 210: 2767-2780

[6] X. Tu, D. Terzopoulos. Artificial fishes: Physics, locomotion, perception, behavior. Proc. of ACM SIGGRAPH'94, Orlando, FL, July, 1994, pp. 43-50

[7] J. D. Liu, H. S. Hu. A 3D simulator for autonomous robotic fish. International Journal of Automation and Comput-ing, 2004, vol. 1; pp. 42-55

[8] A. J. Ijspeert. Central pattern generators for locomotion control in animals and robots: A review. Neural Networks, 2008, 21: 642-653

[9] J. Yu, L. Wang, M. Tan. Geometric optimization of relative link lengths for biomimetic robotic fish. IEEE Transactions on Robotics, 2007, 23(2): 382-386

[10] J. Yu, L. Liu, L. Wang, M.Tan, D. Xu. Turning control of a multilink biomimetic robotic fish. IEEE Transactions on Robotics, 2008, 24(1), 201-206