SWIMMING SIMULATION AND SYSTEM IMPLEMENTATION
OF A MULTILINK ROBOTIC FISH

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Abstract. This paper is devoted to the development of a multilink Digital Fish Simulator (DFS), with the emphasis on creating a controlled kinematic centered environment to further shed light on how to design and control artificial fishlike robots (i.e., robotic fishes). 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 robotic fish for physical verification, and vice versa. More importantly, a series of robotic prototypes with different functions have been built to validate our well-formed ideas and to attain a new level of performance close to real fish.

Key Words. Kinematic simulations, System implementation, Fish swimming, Body wave, Robotic fish.

1. Introduction

As is well known, fish can perform very efficient locomotion and maneuvering in the water. With over 28,000 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, 5, 6, 7, 9]. 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 (i.e., 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 pollution detection, water quality monitor, underwater exploration, oceanic supervision, and the like.

In general, the propulsion modes of swimming fish can be categorized into two modes according to means of utilized propulsion part: body and caudal fin (BCF) propulsion, and median and paired fin (MPF) propulsion [6]. 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 [3]. 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 [8]. Although behavior guided fish agent in 3D virtual world is compatible with the behavior 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 [9, 10, 11], is to build a fish-inspired simulation platform, Digital Fish Simulator (DFS), which is beneficial in creating and controlling robotic prototypes. The simulated swimming features practically set the baseline for the further robotic design. Notice that the fish is assumed to adopt a multilink configuration in this work. In contrast to a 3D simulator for autonomous robotic fish by Liu and Hu [4], 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, various 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.

2. Review of bio-inspired fish swimming

2.1. Ichthyology basis. Generally speaking, as shown in Fig. 1, there exist two distinct propulsion modes for technical inspiration in developing robotic fish: BCF mode and MPF mode. 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 standpoint, 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 via coordination among segmental CPGs [2].

**Figure 1.** Propulsion modes in fish swimming. Adapted from [6].

**Figure 2.** Illustration of the skeleton of a common bony fish.
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 [3].

- 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 stressed is the 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 replicating the fundamental locomotion capability of real fish, we should not blindly copy animal structures and control mechanics, but entirely absorb the advantages of several biological creatures in a hybrid way. In this paper, we focus our attention on the radical problem of fishlike swimming generation and modulation, as well as their robotic implementation.

3.1. Functional design. Consider a multilink configured robotic fish, the key to this high-quality biomimicry is how to simplify the mechanism and generate the reasonable control data. That is, to quantify the lateral body motions of swimming fish, kinematic and anatomical data of vertebral column and tail should be paid much more attention. Typical of steady swimming is the contraction from head along the midline of the fish body. A widely used body wave is described by (1):

\[ y_{body}(x, t) = (c_1 x + c_2 x^2) \sin(kx + \omega t) \]

where \( y_{body} \) represents the transverse displacement of moving tail unit, \( x \) denotes the displacement along the head-tail axis, \( k \) indicates 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 (\( \omega = 2\pi f = 2\pi/T \)).
As illustrated in Fig. 3, the oscillatory part of the robotic fish is commonly discretized as a multilink (or N-link) mechanism made up of several oscillating hinge joints actuated by motors in bio-inspired fish-swimming engineering. It can be modeled 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 purpose, we consider the following discrete form of (1):

\[
y_{\text{body}}(x, i) = (c_1 x + c_2 x^2) \sin(kx \pm \frac{2\pi}{M} i)
\]

where \( i \) denotes the \( i \)th variable of the sequences \( y_{\text{body}}(x, i) (i = 0, 1, \ldots, M - 1) \) in one oscillation period, \( M \) indicates the discrete degree of the traveling wave, and the signs “+” and “−” represent different initial moving directions, which are dependent on different initial values. For more details on link-based body-wave fitting, please refer to [9].

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

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

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.

When changing the swimming direction, the real fish usually uses the tail in collaboration with pectoral fins. We remark that the pectoral fins of the carangiform swimmer have minimal effects on propulsion and steering, which are neglected in the current robotic model. For the multilink robotic fish, various turning modes can be implemented by commanding specific deflected angle in each oscillation cycle to the part or all of moving links. So a corrected turning body-wave is hypothesized to be yielded as follows:

\[
y_{\text{body}}(x, i) = (c_1 x + c_2 x^2) \sin(kx - \frac{2\pi}{M} i) + \sqrt{\frac{1}{4} D'^2 - x^2} - \frac{1}{2} D'
\]

where \( D' \) is the diameter of the curved tail axis, having a bearing on the turning diameter \( D \). An example of corrected turning body-wave is shown in Fig. 4, where \( c_1 = 0.05, c_2 = 0.09, k = 2\pi/3, M = 9, D' = 8 \). In this sense, fishlike movements,
either forward propulsion or turning maneuvers, can be generated within a well-integrated body wave framework.

The following task is then deciding how to choose and tune control parameters. Continuous modulation of multiple parameters will bring tremendous burden to produce multimodal swimming gaits. Under such circumstances, 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 the DFS primarily include the following three aspects:

- Comparison between multilink oscillations and the body wave: The graphics of the moving multilink and the 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, one 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 also be loaded and tested on site.

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. 5). 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 mainly includes link number (ranging from 2 to 10), discrete degree in one oscillation (ranging from 8 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 [10] for more geometric optimization details. The latter 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 directly 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.
Figure 7. Comparison of different swimmers in the DFS. (a) Anguilliform swimming. (b) Carangiform swimming. (c) Snake-like swimming.

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 [11], 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. As shown in Fig. 6, a controlled simulation environments with static and dynamic obstacles are created. Different obstacle avoidance approaches can then be loaded and tested in the DFS repeatedly.

3.3. Some simulation cases. With the well-integrated DFS, many kinematics studies can be emulated 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 predominant kinematic feature. According to the obtained simulation results, $P_1 = \{0.2, 0, 2.0, 0\}$, $P_2 = \{0.05, 0.09, 0.5, 0.1\}$ and $P_3 = \{0.35, 0.3, 0, 0\}$ are representative of anguilliform, carangiform, and snake-like swimmers, as depicted by Fig. 7. It implies carangiform, anguilliform, 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 robotic fishes.

![Figure 8. Prototypes of various robotic fishes. (a) A three-link robotic fish for the Robofish Water Polo. (b) A four-link multimodal robotic fish swimming in the lake. (c) A marsupial robotic fish system including a mother fish and a daughter fish [12]. (d) An amphibious robotic fish moving on the wet grassland.](image-url)
4. Development of robotic fish and control framework

To evaluate the conceived design ideas and control framework, we try to build different physical robots serving as a repeatable testbed. A conceptual design of robotic fish with multiple control surfaces entirely consists of several elements: a head and anterior body, a multilink 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 multilink soft body is composed of four servomotors connected in series with aluminum 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 duroplastics. In order to contribute to more thrust, the caudal fin is made of partly compliant material. In addition, two winglike pectoral fins are symmetrically placed at the rear lower position of the rigid shell. Meanwhile a dorsal fin and a pelvic fin are located the anterior top and the posterior bottom of the fish shell, respectively. It is preferable to the robot that a neutral buoyancy maintains. Unfortunately, for any set density, the robot only has neutral buoyancy at a single depth. So an artificial swim-bladder may be created to alter the average density of the robot so that a neutral buoyancy is attained at any given depth.

To date, as shown in Fig. 8, a series of robotic fish prototypes have been developed in our laboratory. These robots have the same multilink structure but serve different purposes. Through extensive simulations and experiments, robotic fishes have achieved vivid swimming and even performed some simple mobile sensing tasks. We remark that two control methods: reverse kinematics control and CPG-based control, have been adopted in our robotic fishes capable of multimodal swimming. The swimming control data derived from the DFS is used for the reverse kinematics control.

In particular, as illustrated in Fig. 9, we have proposed a two-phase CPG-based control architecture to implement the autonomous swimming control. Specifically, the whole control process is divided into two phases: upper decision-making and

![Figure 9. A two-phase control framework for CPG-based multimodal swimming control.](image-url)
automatic adjustment. According to the upper command from the controller and the sensory input, algorithms based on the CPG model determine locomotion gaits such as straight forward/backward, turning left/right, submergence, and so on, and modify the coupling forms and controlling parameters accordingly. The CPG model with sensory feedback will then take charge the autonomous control before new upper commands change the robot’s movements.

During implementation, each mode is encoded with a standardized “template” essentially corresponding to a set of CPG parameters. As a first step, according to the sensory input in conjunction with the upper command, a fuzzy finite state machine capable of smooth switching and easy programming will determine a suitable swimming mode. At the second stage, some control policies will be taken to finely tune template parameters. Hence the robotic fish achieved steady but flexible 3D swimming even disturb occurred.

5. Conclusions and future work

This paper has described an overall design for fish-inspired simulation and robotic implementation. In the multilink based fish swimming framework, an improvement on the widely used body wave equation has been made to produce multimodal swimming motions. A bidirectional 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 applicable control framework have been developed. However, only simplified kinematical model and minimal hydrodynamic information were utilized to achieve fishlike swimming. The obtained swimming performance of the robotic fish is inferior to that of the biological counterpart. Much more effort should be devoted to breaking through the performance bottlenecks and tuning characteristic parameters in a relatively optimum fashion.

The ongoing and future work will concentrate on continuing to learn from fish and improve both the DFS’s simulation performance and the robotic fish’s mechatronic structure. This is the key to enhanced propulsion performance and should be given top priority.

References


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