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Locomotion Planning of Biomimetic Robotic Fish with Multi-joint Actuation

Chunlin Zhou and K. H. Low

Abstract—**This paper discusses the implementation of the biological fish swimming motion onto the biomimetic fish robots. The mechanism designs and the control methodologies might vary as the fundamental knowledge is learnt from different species of fish. However, all those systems can be divided into two major types in general, namely: serial open chain design and parallel mechanism design from an engineering viewpoint. The general solutions to the swimming motion planning for the type with parallel mechanism are discussed by using the kinematics equations, followed by the derivation of analytical gait control functions. The application of these solutions on a manta fish prototype and an eight-joint MPF (media and/or paired fin) fish prototype shows the good agreement with the proposed modeling in the steady swimming and forward/backward swimming.**

I. INTRODUCTION

Fish generates thrust through different ways of body motions [1]. The anatomy and morphology of real fish shed a light on the design of biologically inspired underwater vehicles for different specifications. Such underwater vehicles make use of the philosophy of fish swimming by simulating their morphological structure and swimming patterns [2]. Different communities in science and engineering are involved in the study of fish-like robots. For the robotics community, the research on the robotic fish has a straightforward objective: to transform the conceptual design of the biomimetic fish into practical swimming machines that can serve humans [3]. To achieve this aim, several issues in different levels are involved: the mechanical design of the fish robots, new materials involved in underwater propulsion, practical actuation and actuator design, the sensory and electronic system for underwater measurements, control of swimming for highly efficient locomotion, swam control and design of intelligent control strategy for autonomous manipulations, etc. The categories of the research interests are shown in Fig. 1.

This paper is dedicated to the implementation of fish steady swimming motion onto the biomimetic fish robots. In the study, the body motion function from the biological literatures is applied to derive the gait functions that serve as the control inputs for robotic fish. The general solutions provided in this paper can be applied to those multi-joint robotic fish. According to the fish morphology and swimming mode, the mechanism of fish robot design is summarized in two types as mentioned: serial and parallel mechanisms. In this paper, only the locomotion planning for the type with parallel mechanism is conducted, followed by the derivation of analytical gait control functions.

II. MECHANISM OF BIOMIMETIC FISH BODY/FIN

Breder [4] presents a set of nomenclatures classifying fish into several basic types according to the body structure and swimming pattern. The classification of fish is based on two main factors: (i) the extent to which propelling process is based on undulatory motion versus oscillatory motion and (ii) the body structures or fin segments that are most active in generating propulsion. Under the criteria, fish swimming is divided into BCF (body and/or caudal fin) locomotion and MPF (media and/or paired fin) locomotion. Although the classification is questioned for being oversimplified in biology area, the nomenclatures are widely accepted by researchers in engineering areas [5]. For biologically inspired underwater vehicle, Berder's classification is sufficient to provide information for the design of the bionic propulsor.

A. Design of Robotic Fish with Serial Chain Mechanism

Most of fish families obtain propulsion through BCF swimming. From mechanical design viewpoints, it is feasible to model vertebras of slender fish body or bones of its flexible fins as short rigid links. Subsequently, the body or fin of a robotic fish can be schematically represented as an open kinematic chain of those mechanical vertebras/bones (links) connected by revolute joints. A robotic fish contains limited number of such links, which provides an approximation of real fish. As an example of multi-actuated robotic fish, Fig. 2 shows a sketch that models the flexible fish body (or fin) with five rigid links that fit the segment of fish body (or fin). This structure shares the same idea with the design of robotic arm. The difference lies in that one end of the chain is designed as the fish head and the other end, the so called end-effector commonly seen in robotic arm, acts as the tail or caudal fin of robotic fish.

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Chunlin Zhou is a Ph.D. student in the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore (phone: 65-67905568, e-mail: zhou0095@ntu.edu.sg)

K. H. Low is a Professor of the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore (phone: 65-67905755, e-mail: mkhlow@ntu.edu.sg)

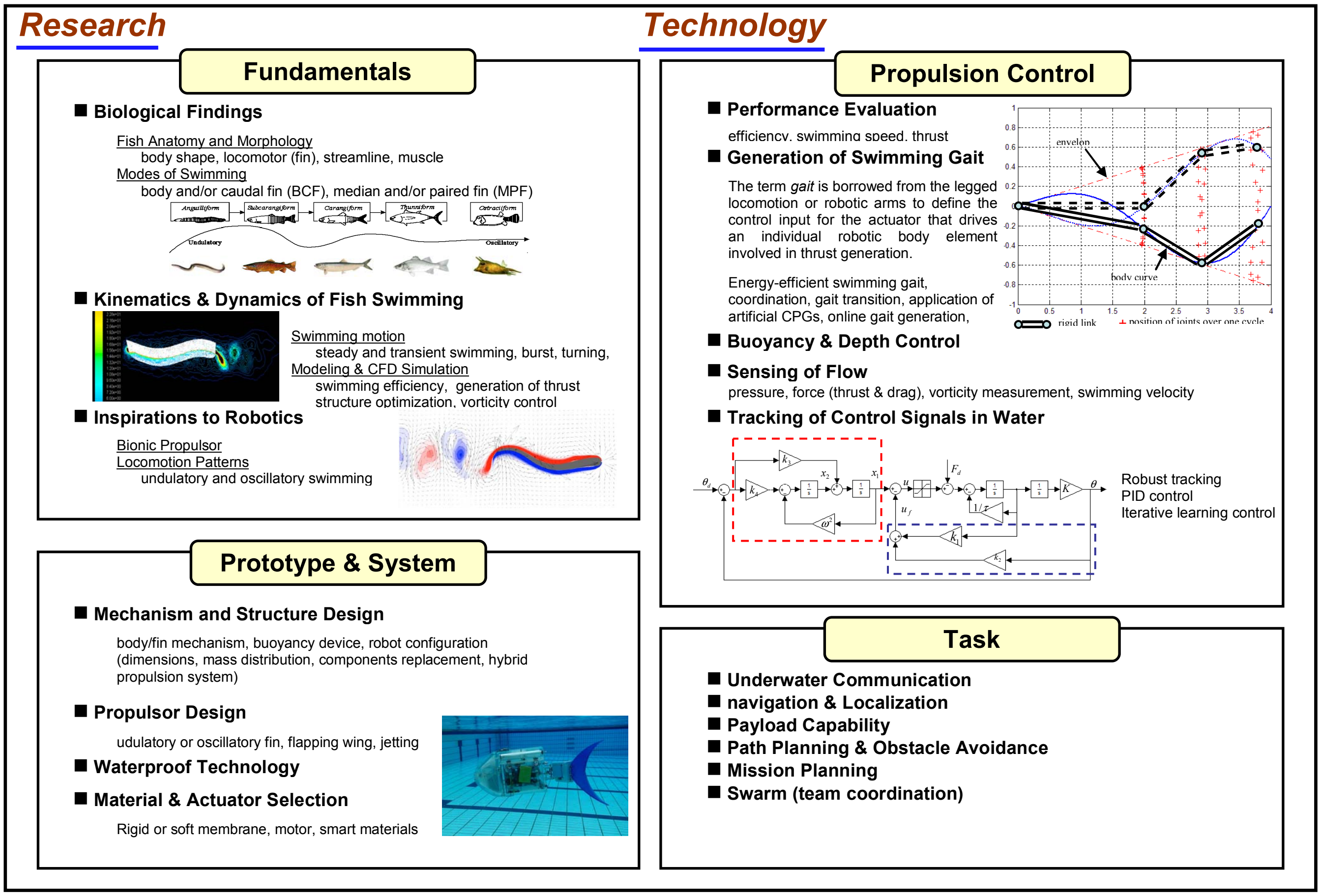


Fig. 1. Current research focuses in different levels of study on biologically inspired underwater propulsors (pictures are adopted from [6-8]).

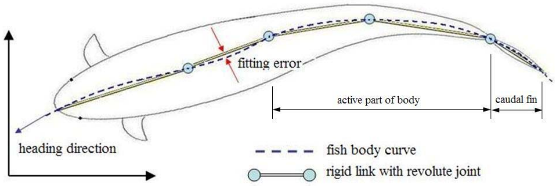


Fig. 2. Serial chain of links used to fit the body/fin of BCF swimmers.

B. *Design of Robotic Fish Based on Parallel Mechanism*

Undulatory swimming modes are also the major way of propulsion in steady swimming used by many fish [9]. Among those types of fish, a significant number of MPF swimmers obtain thrust through the purely undulatory fin motions. Such a fin consists of a set of muscles and bones that can produce backward traveling wave toward the opposite direction of heading during steady forward locomotion. The mechanical fin rays replace the bones of real fish in undulatory machines to provide thrust by biomimetic fins. Fin rays oscillate alternately with specific amplitude and frequency, which generate a traveling wave along the long fin (see Fig. 3). Nearly all the current prototypes of undulatory MPF fish [10, 11] adopt this scheme as the design model.

The actual machine design may be different for various prototypes. Epstein *et al.* [9] and Toda *et al.* [10] use cam-driven mechanism to produce the up-and-down oscillation motion of fin rays. The fin-ray configuration is different from the model by the crank-slider four-bar fin mechanism developed by Low *et al.* [11], in which the rotational axis is perpendicular to the longitudinal wave direction. For another comparison, in Epstein and Toda's models, the base longitudinal axis of the fin segments and the tip longitudinal axis of the fin segments can be formed in an inclining straight line, depending of the rotation angle. On the other hand, the base longitudinal axis of the fin segments in Low and Willy's model [11] is moving in the same horizontal plane of the tip's longitudinal axis of the fin segments, as shown in Fig. 4.

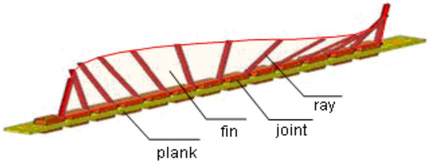


Fig. 3. Parallel mechanism of undulatory fin with fixed base design [12].

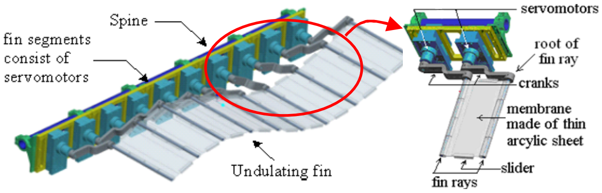


Fig. 4. Modular design of undulatory fin with free base design [11].

It is also worth mentioning that, by virtue of modular and scalable design, various types of biomimetic can be modeled by different number and arrangement of the undulatory fin(s). Fig. 5 shows the basic topology of such parallel mechanism design inspired by the MPF undulatory swimming modes. Although there are great variations among actual fish prototypes, all designs share the same mechanism topology. The gait planning and control for these prototypes are similar.

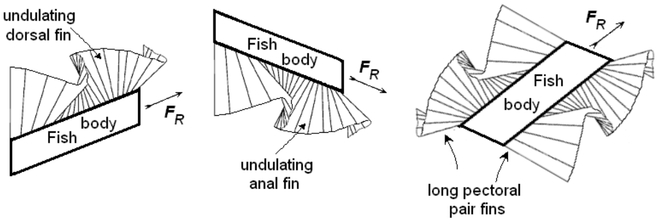


Fig. 5 Fundamental structures of undulatory fins found in amiiform, gymnotiform, or rajiform [6].

III. GAIT PLANNING FOR STEADY SWIMMING OF BIOMIMETIC FISH ROBOTS

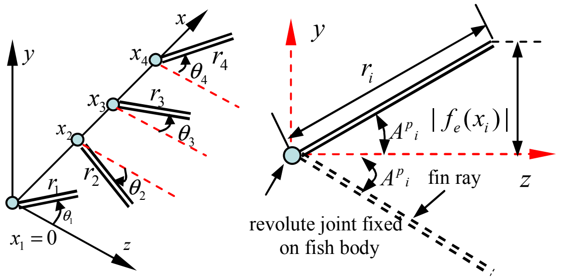
Here the term "gait" is borrowed from the legged locomotion defining the control input of the actuators used to drive the body/fin linkages. The main aim of gait planning is to find out an appropriate time-dependant functions for the control implementation. For the planar serial open chain design, this function describes the relative angles of links with respect to the adjacent link. For the parallel mechanism, the function describes the absolute angle of those links, because the linked fin rays are controlled independently within its workspace. The body motion function suggested by Lighthill [13] is adopted, as given by

$$y = f(x,t) = f_e(x,t)\sin(2\pi f t + \frac{2\pi}{\lambda}x) \tag{1}$$

where $f(x, t)$ is a wave function that describes the position of fish body along its central line (x-axis is the central line) of spinal cord at a specific time instance t, $f_e(x_i, t)$ is the envelop function, f is the oscillation frequency of body segment related to the speed of the wave generated by fish, and λ is the wave length. The function describes the transverse displacement of the slender fish body under steady forward swimming. It is applied to many different modes of fish models [14, 15]. In the following text, how to implement this function to control a swimming robot with parallel mechanism is discussed.

A. Generating Simple Harmonic Waveform

A simple parallel mechanism used to construct undulatory fin/body is depicted in Fig. 6. Generation of an undulatory waveform by fins can be regarded as a process that the fin rays of fish oscillates alternately in a certain sequence. They drive the membrane of the fin to stretch or retract, which forms an undulatory wave along the fin. As a result, the gait planning for generation of undulatory motion is a problem of finding the sequence and oscillation functions of biomimetic fin rays. The basic gait function remains a sinusoidal form.



(a) (b)

Fig. 6 Parallel linkage mechanism used in the fish robots: (a) the parallel connection of fin rays and (b) the structure of single fin ray (rigid link).

The successful implementation of undulatory swimming depends on the determination of oscillation amplitude of fin rays and the phase lag between adjacent links. As depicted in Fig. 6(a), we set the position of first link joint as the origin, the longitude of fin as the x axis. For a simple harmonic waveform, the amplitude of oscillation $A^p{}_i$ can be derived from the following equation:

$$A^p{}_i = \arcsin\frac{|f_e(x_i)|}{r_i} \tag{2}$$

where r_i is the length of fin ray and x_i is the longitudinal position of the ith joint (see Fig. 6). The phase difference between two adjacent links depends on the wave number, the wavelength, the distance between two adjacent links, and the number of links used to simulate the undulatory wave. Their relationship is given by:

$$\varphi^p{}_i = \varphi^p{}_1 - \frac{2\pi}{\lambda}x_i \quad i = 1,2,\ldots,n \tag{3}$$

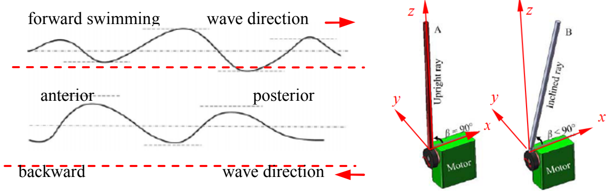
where $\varphi^p{}_i$ is the phase lag of the first fin ray. The gaits can then be governed by a set of time-dependant sinusoidal functions:

$$\theta_i = A^p{}_i\sin(2\pi f t + \varphi^p{}_i) \tag{4}$$

For the control of robotic fish, the bi-directional swimming locomotion can be obtained by changing the sign of the phase lag, $\varphi^p{}_i = -\varphi^p{}_i$ [16].

B. Generating Non-harmonic Waveform Motion

Usually, the biomimetic undulatory fin motion is modeled by simple harmonic waves. However, a non-harmonic waveform of Gymnotiform swimmers was reported and simulated by swimming machines [12]. As shown in Fig. 7(a), the waveform shows asymmetry features when swimming forward or backward. This phenomena is assumed having connection with the swimming efficiency.



(a) (b)

Fig. 7 A non-harmonic waveform generated by Gymnotiform swimmers and the mechanical fin rays that generate such wave: (a) waveform at forward/backward swimming and (b) the fin rays with different inclined angles. The left unit with β=90° is named the upright ray, while the right unit with β< 90° is called the inclined ray (adopted from [12]).

The asymmetry waveform is observed in the steady swimming of Black Ghost Knifefish, a Gymnotiform swimmer. The fin rays bend toward the direction of water flow. It is not clear now whether this phenomenon is related to the swimming efficiency or is only an effect of the natural compliance of flexible fin rays to the oncoming flow. Since this fin motion exists in nature, we also consider it on biomimetic fish with appropriate gait sequence. The gait function of the single fin ray developed by Hu *et al.* [12] is a harmonic function because of the inclination of fin rays the wave generated by the undulatory fin is asymmetrical. Once the angle β is decided, the wave shape cannot be changed (see Fig. 7(b)). We derive gait functions for general designs with straight (upright) fin ray, which has the same effect. By changing the wave shape parameters, the proposed fish prototype can simulate waves with different shapes.

It is assumed from Fig 7(a) that this kind of wave is formed by oscillations of particles with more than one frequency component in a continuum of media. We also assume that this asymmetry waveform is generated by similar non-harmonic oscillations of successive fin rays. Fig. 8 shows a curve of non-harmonic oscillation for a biomimetic fin ray. The non-dimensional parameter m is defined as

$$m = \frac{t_m}{0.5T - t_m} \tag{5}$$

$$t_m = t[\max(\theta_i)] = \frac{mT}{2(m+1)} \tag{6}$$

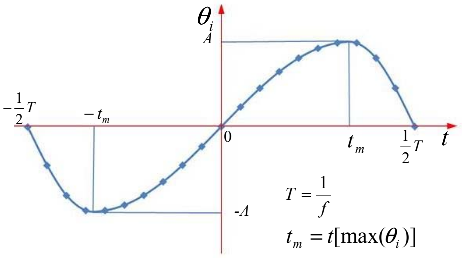


Fig. 8. A curve of non-harmonic oscillation for the ith fin ray.

According to (6) and Fig. 8, if m=1, the curve becomes symmetrical; if m>1, the oscillation of fin rays will cause a forward swimming waveform depicted in Fig 7(a) and a backward swimming waveform is obtained, if m<1. Next, we apply cubic spline to fit this curve in time domain [0, T/2]. The general form of the fitting function is

$$\theta_i(t) = B_3 t^3 + B_2 t^2 + B_1 t + B_0 \tag{7}$$

By virtue of Fig. 8, we obtain the conditions (by assuming unit amplitude, A=1) and

$$\begin{pmatrix} B_3 \\ B_2 \\ B_1 \\ B_0 \end{pmatrix} = \begin{pmatrix} -\dfrac{2t_m + T/2}{{t_m}^2 (t_m - T/2)^2} \\ -1/{t_m}^2 - 2t_m B_3 \\ 2/t_m + {t_m}^2 B_3 \\ 0 \end{pmatrix} \tag{8}$$

The gait function $\theta_i(t)$ within [0, T/2] has now been obtained. Because of the periodicity of gaits, the gait function should be odd expanded in the region of [-T/2, T/2] as:

$$\theta_i(x,t) = \begin{cases} B_3 t^3 + B_2 t^2 + B_1 t & t \in (0, T/2] \\ B_3 t^3 - B_2 t^2 + B_1 t & t \in (-T/2, 0] \end{cases} \tag{9}$$

It should be noted that the gait function given by (9) is coupled with the position of fin rays implicitly. To control the separate actuators, we must find time-dependant control functions. Since the wave is non-harmonic which contains more than one frequency component, it is desired to express this wave as

$$y = f(x,t) = f_e(x) \sum_{j=1}^{\infty} b_j \sin[2j\pi f t + \varphi_j(x)] \tag{10}$$

where $\varphi_j(x)$ is the phase lag of different fin rays and b_j is the coefficient of components with different frequencies. Note that the coefficient b_j can be derived from (9). According to the property of a wave equation, if we use Fourier series to expand (9), b_j equals the amplitude of Fourier series with different frequencies. In addition, it can be proved that the wave shape is irrelevant to the oscillation frequency of links, and it is only determined by the shape parameter m. The phase difference $\varphi(x)$ is related to the position of fin rays and the frequency component it belongs to. Here, we adopt the coordinate system as depicted in Fig. 7(a). By using one-dimensional wave equation, $\varphi_j(x_i) = j\varphi^p{}_i$, where $\varphi^p{}_i$ is determined by (3). Therefore, the planned gait for separate fin rays should be

$$\theta_i(t) = f(x_i, t) = f_e(x_i) \sum_{j=1}^{\infty} b_j \sin(2j\pi f t + j\varphi^p{}_i) \tag{11}$$

We can also obtain a backward swimming gait by changing the sign of $\varphi^p{}_i$. In actual applications, a finite number of frequency components are used. In our experiments, a smooth swimming can be achieved by only three components, which will be discussed next.

IV. EXPERIMENTAL RESULTS

The gait functions obtained from the previous sections are used in our experiments to control the fish prototype by simulating different swimming modes. The robotic ray is chosen in the simulation. This system contains both classes of the mechanisms discussed in the previous sections.

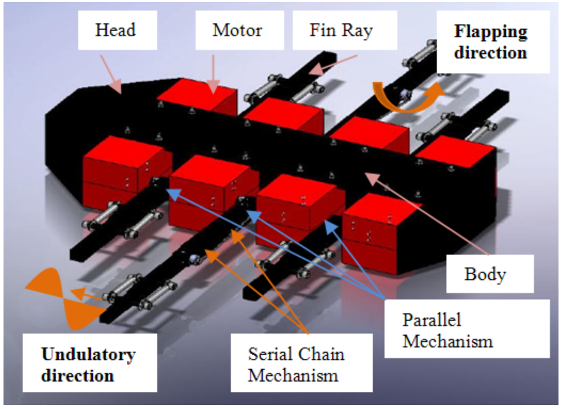
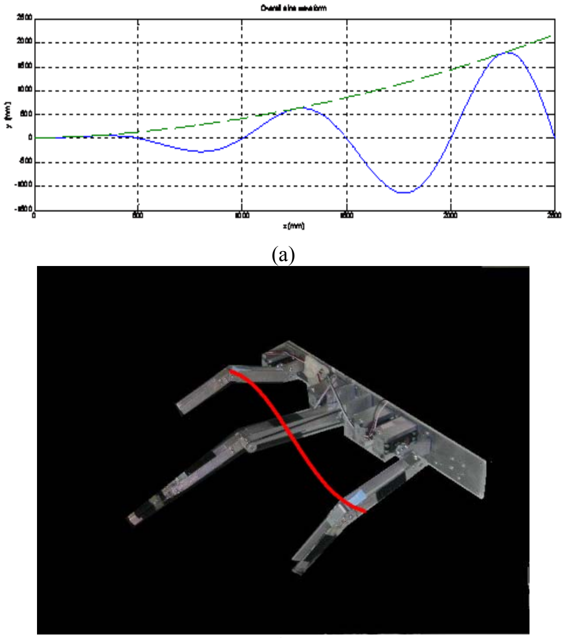


Fig. 9. Design layout of the robotic manta ray [17].

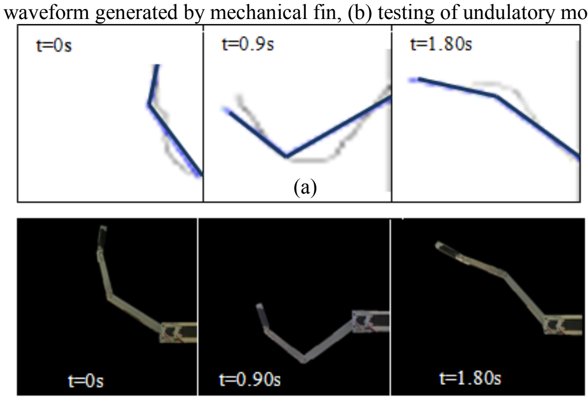
In the first example, a system with the three fin rays is driven by three individual servo motors which are in parallel mechanism as shown in Fig. 9. As for the middle fin ray, one more degree of freedom is added onto the first link in order to simulate the flapping motion. Thus, the second fin ray is a typical 2-DOF serial open chain mechanism. The ray fish swims by using elongated, paired pectoral fins that have evolved to extend from opposite sides of a generally flat body. They use these fins to swim in *rajiform* motion, which includes two distinct modes. The first mode is oscillatory motion, which is similar to bird flapping. Unlike most birds, however, the fin is not held as a rigid hydrofoil, but rather a standing wave pattern is created on the fin. The second mode is undulatory motion, in which a periodic waveform (a "ripple") travels along the fin from front to back, producing a net velocity aft. Rajiform motion may include either mode exclusively or a combination of the two [18].



(a)

(b)

Fig. 10. Undulatory motion generated by parallel mechanism (a) waveform generated by mechanical fin, (b) testing of undulatory motion.



(a)

(b)

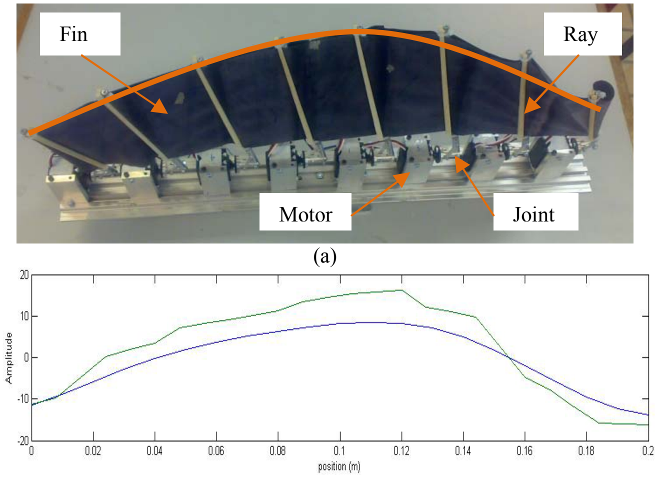
Fig. 11. Oscillatory motion generated by serial open chain mechanism (a) simulated fin waveform generated, (b) testing of oscillation motion.

As the literature states, the undulating motion is achieved by three servo motors with parallel mechanism [17]. The designated waveform is a harmonic sinusoid waveform with a quadric envelop (as shown in Fig. 10(a)). Usually, the rajiform swimmer can only generate 0.4 waveform in one fin length. Fig. 10(b) shows the undulating motion of the three fin rays and the waveform formed.

There are two links involved into the flapping motion, the geometry parameters for the planar open chain mechanism are outlined: the lengths of the rigid body links $\{r_i\}=\{170, 120\}$ and the active body length R = 300 mm. If we consider the flapping motion as a quarter of the quadric enveloped sinusoid waveform, the wave number is then taken as k = 0.25 and the wavelength $\lambda \cong 1200$ mm. Therefore, the body motion function is selected as

$$y = f(x,t) = (0.001x^2)\sin(2\pi ft + \frac{2\pi}{1200}x) \qquad (12)$$

from which we can obtain the gait functions for this six-link robotic prototype. The parameters are $\{A^s_i\}=\{7.59°, 48.59°\}$ and $\{\varphi^s_i\} = \{7.53°, 21.84°\}$. Fig. 11 shows the comparison of the simulated waveform and the real output at t = 0 s, 0.9 s, and 1.8 s.



(a)

(b)

Fig. 12. An example of non-harmonic waveform generated by mechanical fin at different time instances.

Fig. 12(a) shows the result of the gait planning that generates a non-harmonic waveform on the undulatory fin. The computed gait functions have been tested on our undulatory fin platform in the laboratory environment. A smooth and flexible locomotion is achieved as expected. As shown in Fig. 12(b), the spline line (in green) stands for the real waveform obtained from the visual study of the knifefish and the smooth curve (in blue) is the expected waveform, which is a non-harmonic periodical wave. Such a waveform comes from the biomimetics and its actual effects, especially on swimming efficiency, need to be investigated in future works.

V. CONCLUDING REMARKS

This paper has discussed the mechanism design and the gait study of the two major classes of the biomimetic fish robot: planar *serial* open chain mechanism and *parallel* mechanism. The kinematic equations for the latter mechanism are derived and tested on a rajiform fish prototype. By applying those solutions and control functions onto the multi-joint testing platforms, a smooth and flexible aquatic locomotion is achieved. It is shown that the proposed gait functions are also applicable to other fish prototypes, or even other multi-joint robots with similar mechanism topology.

As for the control inputs, the derived gait functions have explicit mathematical structures, which are useful for the design of feedback control algorithms. As those steady swimming gait control functions can be decomposed into superposition of sine functions, as given in (11), a robust gait control system can be designed for actuators to track the desired inputs in the underwater environment, which is discussed more in [8].

The aim of the present work is to explore an analytical method to gait planning problem. Therefore, this paper does not discuss the swimming performance, in terms of dynamics and energy-efficiency. The optimal values of these parameters will be investigated in future. Currently, many different methods have been proposed and implemented to address this issue. One method is the so-called biomimetic approach, which is also used in this paper: record the motion of real animal and playback the similar motion on robots. However, it does not guarantee a swimming machine achieves the same high efficiency as animals, even if the machine swims like a real fish [2]. This is an off-line based approach because the swimming control does not take the real-time fish-water interaction into account. Other off-line based approach includes the computational fluid dynamics simulation, the voticity control theory and the use of Particle Image Velocimetry (PIV) technology, etc [19, 20]. Although these methods show great progress for control of robotic fishes, they exhibit a common problem: a closed-loop control scheme for swimming machines is not available yet due to the absence of feedback of water flow information around the fish body [21]. Without this closed-loop control, the swimming gait cannot be adaptive to the water flow.

In future work, we will develop a feedback method, which acquires the flow information around the fish body. With this method, an on-line gait planning and a closed-loop swimming control are possible to enhance the swimming performance, including the swimming efficiency [22]. Swimming gaits adaptive to water flow according to sensory feedback for multi-DOF fish robot can also be generated through this control scheme. Futhermore, the swimming patterns will not be determined by the prescribed kinematic equations, but by the real-time feedback information.

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