Parameter Optimization of Simplified Propulsive Model for Biomimetic Robot Fish*

Junzhi Yu and Long Wang

Intelligent Control Laboratory
Center for Systems and Control, Department of Mechanics and Engineering Science
Peking University, Beijing 100871, P. R. China
jzyu@mech.pku.edu.cn

Abstract - This paper is concerned with the parameter optimization for a simplified propulsive model of biomimetic robot fish propelled by a multiple linked mechanism. Taking account of both theoretic hydrodynamic issues and practical problems in engineering realization, the optimal link-length-ratio is numerically calculated by an improved constrained cyclic variable method. The result is successfully applied to the 4-linked robot fish developed in our laboratory. The comparative experiments on forward swimming speed of the robot fish before and after parameter optimization verify the effectiveness of our method.

Index Terms - Biomimetic robot fish, underwater robot, parameter optimization, mechanical design, constrained cyclic variable method.

I. INTRODUCTION

In recent years, there has been growing interest in robotic research where robots have either been used to address specific biological questions or have been directly inspired by biological systems. A variety of biomimetic robots ranging from flying, swinging to swimming have been constructed, see [1] for an overview of biorobotics research. In the category of swimming robots, biomimetic robot fish is motivated by a desire to create Autonomous Underwater Vehicles (AUVs) with the virtue of efficiency, maneuverability and noise-free. Moreover, it also provides essential insights into the mechanism and control of fish swimming [2].

A fish in nature, as is well known, propels itself by the coordinated motion of its body, fins and tail, achieving tremendous propulsive efficiency and excellent maneuverability, which is advantageous over conventional marine vehicles powered by rotary propellers with the same power consumption. On one hand, swimming efficiency of ordinary fish is over 80 percent, and fish in carangoid even up to 90 percent, while conventional screw propeller is only between 40 percent and 50 percent. On the other hand, dolphin can cruise at 20 knots following propeller is only between 40 percent and 50 percent. On one hand, swimming efficiency of ordinary fish is over 80 percent, and fish in carangoid even up to 90 percent, while conventional screw propeller is only between 40 percent and 50 percent. On the other hand, dolphin can cruise at 20 knots following marine vessels with ease. Meanwhile, during hunting for food, pike can burst to prey with a 20 g acceleration. Furthermore, fish can turn rapidly with the radius of 10 to 30 percent of Body Length (BL), whereas conventional ship turns slowly with three times BL [2]. From the viewpoint of engineering, fish is a distinguished AUV prototype that is suitable for reproduction. Significant work in robot fish was initiated in the 1990s by Triantafyllou [5] and, was further investigated recently by Hirata [6]. Based on rapid progress in robotics, hydrodynamics of fish-like swimming, new materials, actuators and control technologies, more and more research has focused on the design and development of robot fish. As an important research subject in robotics as well as in practical applications, robot fish can be potentially utilized in military detection, undersea operation, oceanic supervision, aquatic life-form observation, pollution search and so on.

To build an autonomous robot fish, many fundamental issues including fishlike motion parameters, sensors, actuators, hydrodynamics, image processing, and intelligent motion control have to be investigated. In [7], we presented a simplified propulsive model for robot fish design where the fish’s motion is produced by a multi-link mechanism, but the length ratio of each link is fixed. Taking into account of ichthyologic theories and problems in the previously developed robot fish prototype, the control parameters of the proposed propulsive model are mathematically optimized in this paper, which can be applied in robot fish design directly.

The rest of the paper is organized as follows. In section II, a simplified propulsive model for carangiform swimming is reviewed and a parameter optimization method for seeking the optimal link-length-ratio is proposed. Experimental setup and corresponding results are given in section III. Finally, the conclusions and future work are contained in section V.

II. PARAMETER OPTIMIZATION

A fast swimmer among fish shares some common characteristics such as a streamlined body, swimming mode of carangiform, and a lunate shaped caudal fin. To enable widespread deployment of effective biomimetic robot fish platform, a comprehensive framework must be established, which should have the following features: (a) the analysis, design, development and control methods are applicable to a broad class of swimming robots, and (b) major elements of the framework can be expanded successively. In order to realize such a framework, one

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strategy is to (a) abstract and simplify the swimming motion of fish “model”, (b) establish a general kinematical model of fish swimming, (c) develop motion control methods for this class of biomimetic mechanism, and (d) develop paradigms for specific systems with different applications or tasks. Within this framework, the first step is to abstract characteristic parameters that combine ichthyologic knowledge with engineering realization.

A. Review of Previous Work

Due to the limitations in sensor, actuator technology, size of onboard central microprocessor, and onboard power capacity, realistic efforts to develop biomimetic fish mostly concentrate on mimicking carangiform swimming. Based on the biological information of carangoid, as shown in Fig. 1, a physical model of the carangiform swimming motion can be divided into two parts: flexible body and oscillatory lunate caudal fin, where the flexible body is represented by a series of oscillatory hinge joints and the caudal fin by an oscillating foil. A swimming model for RoboTuna (typically carangiform) has been presented by Barrett et al. [8], whose undulatory motion is assumed to take the form of a travelling wave (1) originally suggested by Lighthill [9].

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

where \( y_{body} \) represents the transverse displacement of the fish body, \( x \) denotes the displacement along the main 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 (\( \omega = 2\pi f = 2\pi / T \)).

In light of the biological, hydrodynamic, ichthyologic and engineering information collected in the literature [2, 8, 10], characteristic parameters on swimming motion mainly consist of:

1) The length ratio of the fish’s oscillatory part to that of the fish-body (\( R_f \)). Depending on the different value of \( R_f \), fish swimming can be classified as carangiform, anguilliform, thunniform and ostractiform. In a general way, with the decrease of \( R_f \), efficiency and velocity of fish swimming remarkably increase, but maneuverability reduces to a certain extent.

2) The number of simplified joints in oscillatory part (\( N \)). The larger the value of \( N \), in general, the better the mechanism’s maneuverability and redundancy, but the worse the swimming efficiency. Yet \( N \) can’t be too large in view of the construction and size constraints of mechatronic systems as well as large cumulative error in man-made mechanical approximation.

3) The length ratio of each link in oscillatory part (\( l_i : l_2 : \ldots : l_N \)). In the part where \( l_i \) (\( i = 1,2,\ldots,N \)) is relatively short, density of joint is high, and flexibility of produced motion is large so that large-amplitude oscillation can be produced. The length ratio of each link in the direction from the nose to the tail of fish, as a general rule, is getting smaller and smaller. However, oscillatory amplitude increases gradually and reaches its maximum at tail peduncle of fish.

4) Characteristics of caudal fin. The aspect ratio (\( AR \)) of the caudal fin plays an important role in propulsive efficiency, which is defined as the fin span \( b \) squared, divided by the projected fin area \( sc \), i.e., \( AR = b^2/sc \). High \( AR \) caudal fin results in improved efficiency in that it induces less drag per unit of lift or thrust produced. At the same time, the shape of the caudal fin makes a great difference to fish’s propulsion. A crescent or forked caudal fin will usually lend itself to high-speed swimming.

Inspired by the propagating propulsive wave underlying the fish body, in [7], a link-based body-wave fitting for robot fish design was proposed, where a discrete body-wave is considered and time variable \( t \) is separated from (1). Rewriting (1), its discrete form can be expressed in (2), in which the travelling body-wave is decomposed into two parts: (a) the time-independent spline curve sequences \( y_{body}(x,i) \) (\( i = 0,1,\ldots,M-1 \)) in an oscillation period, and (b) the time-dependent oscillating frequency \( f \), which is described as the times of recurring oscillations in an unit time interval.

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

where \( i \) denotes the \( i \)-th variable of the spline curve sequence \( y_{body}(x,i) \), \( M \) is defined as body-wave resolution that represents the discrete degree of the overall traveling wave. Consider that the oscillatory part of a fish is composed of many rotating hinge joints, in robot fish’s realization, it can be modelled as a planar serial (\( N \)) chain of links in an interval of 0 to \( R_f \times 2\pi \) along the axial body displacement, where \( R_f \) is the length ratio of wavelength exhibited by the fish’s oscillatory part to that of a whole sinusoid wave. The method for link-based body-wave fitting is to make the end-point of each link fall into the wave curve and the \( x \)-coordinate of the last link’s endpoint just equals \( R_f \times 2\pi \). Without full consideration of the morphological feature and mechanical construction, the cumulative error of the links’ oscillation in an oscillation period is somewhat large and the performance of forward swimming is not very satisfactory. Here, in this paper, a simple optimization method is proposed by seeking the optimal link-length-ratio (\( l_1 : l_2 : \ldots : l_N \)) in the body-wave fitting, which is applied to our robot fish prototype developed in our laboratory and improves the performance of forward swimming.
B. Optimization of Link-length-ratio

As mentioned before, the fish’s oscillatory parts take the form of travelling body-wave shown in (1), whereas the designed robot fish comprises a series of rigid links, which is tough to reproduce the vivid exact motion of the biological fish. That is to say, as shown in Fig. 2, it is essentially impossible that all points in mechanical skeleton fall into the ideal body-wave in a mathematical way. What we can do is to ensure that the key elements of each link satisfy the body-wave, namely, only the end points of each link are assumed to meet the motion equation. Since the oscillatory part of the robot fish involves a planar serial \((N)\) chain of links, in order to reduce the complexity of the mechatronic system, \(N\) is usually limited to a relative small value, e.g., \(10 \leq N \leq 10\). In this case, the motion of the robot fish seems to be somewhat stiff. In particular, it is hard to produce smooth transitions in the conjunction between two links. Consequently an elastic skin is used to envelop the whole skeleton so as to decrease the redundant hydrodynamic drag and increase the flexibility of the fish body, which can generate fishlike motion taking the form of actual fitting curve shown in Fig. 2. Unfortunately, after this elastic transition, there is a relative difference between the actual fitting curve and the ideal body-wave. When this difference becomes large, the hydrodynamic advantages of ideal body-wave will gradually vanish or disappear. Moreover, since the mechatronic system consists of multiple serial links, many limitations in both computation and fabrication have to be simplified or neglected. Therefore there is a great need to optimize the characteristic parameters in the body-wave fitting.

To aid in the description of the numerical optimization of the fitted body-wave, some specific terms are illustrated in Fig. 3. Suppose that a straight line \(g(x)\) intersects a curve \(f(x)\), the two points of intersection are \(P_{\text{Start}}\) and \(P_{\text{End}}\) respectively. The enveloped area \(S\) between \(g(x)\) and \(f(x)\) can then be described as:

\[
S = \int_{\text{Start}}^{\text{End}} [f(x) - g(x)]dx
\]

where \(\text{Start}_{x}\) and \(\text{End}_{x}\) are the horizontal coordinates of \(P_{\text{Start}}\) and \(P_{\text{End}}\) respectively. Extending this to the body-wave fitting, when \(g_i(x)\) corresponds to the straight line of the \(j\)-th link at arbitrary \(i\)-th time, \(f_i(x)\) to the body-wave curve intersected with \(g_i(x)\), and \(S_i(x)\) to the sum of enveloped area of each link at arbitrary \(i\)-th time, \(S_i(x)\) will equal

\[
S_i(x) = \sum_{j=1}^{N} S_j = \sum_{j=1}^{N} \int_{\text{Start}_{x_{ji}}}^{\text{End}_{x_{ji}}} [f_{ij}(x) - g_{ij}(x)]dx
\]

where \(\text{Start}_{x_{ji}}\) and \(\text{End}_{x_{ji}}\) are the horizontal coordinates of the two end-points of the \(j\)-th link at arbitrary \(i\)-th time respectively. Hence, from (4), the total enveloped area in an oscillation period \(S_{\text{sum}}(x)\) can be expressed by

\[
S_{\text{sum}}(x) = \sum_{i=0}^{M} \sum_{j=1}^{N} \int_{\text{Start}_{x_{ji}}}^{\text{End}_{x_{ji}}} [f_{ij}(x) - g_{ij}(x)]dx
\]

It is assumed in this paper that the ideal body-wave owns the best hydrodynamic and kinematic performance. Meanwhile, the length ratio of each link in the oscillatory part \((l_1:l_2:...:l_N)\) tends to be smaller and smaller in the direction from nose to tail of the fish. Obviously, a relationship can easily be obtained:

\[
l_1 \geq l_2 \geq ... \geq l_N
\]

In an attempt to utilize the hydrodynamic predominance of the ideal body-wave, and to minimize the distance error between the actual fitting curve and the ideal body-wave, the total enveloped area \(S_{\text{sum}}(x)\) is minimize by searching appropriate \(l_1:l_2:...:l_N\) (i.e., \(L = [l_1 \ l_2 \ ... \ l_N]^T\)). Hence, we consider the following optimization problem:

\[
\min \sum_{i=0}^{M} \sum_{j=1}^{N} \int_{\text{Start}_{x_{ji}}}^{\text{End}_{x_{ji}}} [f_{ij}(x) - g_{ij}(x)]dx, \quad \text{subject to}
\]

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\[(End - x_y - Start - x_y)^2 + (End - y_y - Start - y_y)^2 = f_j^2\]
\[f_j(x) = (c_1 x_y + c_2 x_y^2 )\sin(\omega x_y - \frac{2\pi}{M})\i \]
\[g_j(x) = k_j x + b_j\]
\[k_j = \frac{End - y_y - Start - y_y}{End - x_y - Start - x_y}\]
\[b_j = Start - y_y - k_j Start - x_y\]
\[l_i \geq l_2 \geq .. l_N > 0\]
\[Start - x_y = Start - y_y = 0 \quad (j = 1)\]
\[Start - x_y = End - x_{i,j-1} \quad (j = 2, 3, .., N)\]

where the subscript \(i\) indicates the \(i\)-th time of the oscillating sequence (\(0 \leq i \leq M - 1\)), and \(j\) denotes the \(j\)-th link (\(1 \leq j \leq N\)).

Although it is very difficult to obtain analytical solutions to problem (7), numerical solutions are able to be efficiently obtained by the existing constrained optimization techniques [11]. An improved cyclic variable method (Method of Coordination Rotation), is employed to solve this problem, which has good calculation precision and stability by introducing a set of new search directions [12]. We can then obtain the optimal link-length-ratios ranging from 3 links to 8, which are shown in Table I.

<table>
<thead>
<tr>
<th>(N)</th>
<th>The optimal link-length-ratio</th>
<th>(S_{sum})</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.0.72 0.65</td>
<td>5.641085</td>
</tr>
<tr>
<td>4</td>
<td>1.0.73 0.63 0.61</td>
<td>3.127202</td>
</tr>
<tr>
<td>5</td>
<td>1.0.7 0.65 0.6 0.6</td>
<td>2.000007</td>
</tr>
<tr>
<td>6</td>
<td>1.0.69 0.65 0.59 0.57 0.57</td>
<td>1.384241</td>
</tr>
<tr>
<td>7</td>
<td>1.0.68 0.66 0.6 0.57 0.56 0.56</td>
<td>1.017727</td>
</tr>
<tr>
<td>8</td>
<td>1.0.66 0.63 0.59 0.55 0.53 0.53</td>
<td>0.782454</td>
</tr>
</tbody>
</table>

As can be seen from Table I, a general tendency is that the total enveloped area (\(S_{sum}\)) decreases as the number of the links (\(N\)) increases, and that there is a drastic decrease between the first link and the second one. This partly matches the construction of a biological fish. However, for practical reasons, the number of links cannot be infinitely large for the sake of engineering realization, and the precise link-length-ratio is difficult to implement due to the limitations of the size of actuators and the mechanical construction.

Substituting the optimized link-length-ratio for the fixed-length ratio, the end-point coordinate pair \((x_{i,j}, y_{i,j})\) can then be calculated according to the calculation method in [7]. Finally, a two-dimensional rectangular array \(\text{OscData}\{M\}[N]\) (8) for the joint angle \(\phi_j\) is obtained, which will be directly used for joint control in the robot fish. The speed of the swimming fish can be adjusted by changing oscillating frequency, oscillating amplitude and the length of oscillatory part, respectively, and its orientation is tuned by different joint’s deflections.

\[\text{OscData}\{M\}[N] = \begin{bmatrix} \phi_0 & \phi_1 & \cdots & \phi_N \\ \phi_1 & \phi_1 & \cdots & \phi_N \\ \vdots & \vdots & \ddots & \vdots \\ \phi_{M-1,1} & \phi_{M-1,2} & \cdots & \phi_{M-1,N} \end{bmatrix}\]

III. EXPERIMENTAL SETUP AND RESULTS

To verify the feasibility and reliability of the proposed design and corresponding algorithm, an experimental robot fish platform has been constructed. The system, as depicted in Fig. 4, comprises four subsystems: the robot fish subsystem, the vision subsystem, the decisions making subsystem and the communication subsystem. All aquatic experiments in the paper were conducted in a static swim tank 3050 mm×1830 mm×56 mm (length×width×depth) with the room temperature. The global information of the fishes and their surroundings captured by overhead CCD camera is effectively processed and sent to the decision-making module as an input, and then the output of the decision-making subsystem is transmitted to the single robot fish through the communication subsystem. Hence, the robot fishes can work effectively and cooperatively. These four subsystems, from the control viewpoint, ensure a closed loop.

Based on the improved simplified kinematic model of propulsive mechanism after optimization presented in the previous part, a series of radio-controlled, multi-link and free-swimming biomimetic robot fishes mimicking carangiform-like locomotion, have been designed in our laboratory. Fig. 5 exhibits six types of robot fish prototypes developed in our laboratory. In the robot fish’s construction, based on a hydrodynamic analysis, hollow, streamlined, rigid head and forebody are molded using fiberglass, which allows for larger space to house electrical and communication components. In order to swim in a small experimental water pond, the built fish has to be as compact as possible. The onboard microprocessor, sensors, additional peripherals, wireless receiver and power supply are hence put in the cell of the fish’s forebody. DC servomotors acted as the actuator of joints are linked with aluminum exoskeleton. A lunate foil is attached to the last link, which serves as the tail fin. The installation position of the joints and the size of the tail are designed with consideration of the shape of a specific

Fig. 4 Configuration of experimental robot fish platform.
(Note: 1. strategy computer, 2. wireless communication module, 3. supporting bracket, 4. CCD camera, 5. swim tank, 6. robot fish.)
biological fish “model”. In the meantime, some steel balance weights are located in the forebody and lower side of the exoskeleton to adjust the balance of gravitational forces and buoyant forces.

![Fig. 5 Prototypes of different robot fishes.](image)

(a) Up-down motioned, 3-link robot fish, 380mm long.
(b) 4-link robot fish with infrared sensors, 450mm long.
(c) 4-link, 2-D motioned robot fish, 400mm long.
(d) 3-link, 2-D motioned robot fish, 380mm long.
(e) 2-link robot fish with infrared sensors, 280mm long.
(f) 3-link robot fish with miniature wireless camera, 400mm long.

![Fig. 6 Robot fish prototype with different link-length-ratio.](image)

(a) Robot fish prototype with fixed link-length-ratio.
(b) Robot fish prototype with the optimized link-length-ratio.

Fig. 6 Robot fish prototype with different link-length-ratio.

With the vision-based tracking system to provide realtime position feedback of the robot fishes [13], we tested the speed performance of the developed prototype with different length ratios. Fig. 6 (a) shows a prototype with an identical link-length-ratio of \( l_1 : l_2 : l_3 : l_4 = 1:1:1:1 \), and Fig. 6 (b) with an optimized link-length-ratio of \( l_1 : l_2 : l_3 : l_4 = 1:0.73 : 0.63 : 0.61 \). A comparative result on forward speed in steady swimming versus oscillatory frequency is given in Fig. 7. According to the experimental data, the robot fish with optimized link-length-ratio has better hydrodynamic performance in swimming speed, which partly demonstrates the expected objective. However, for the optimized fish, its maximum swimming speed is only about 0.9 \( BL/s \) (\( BL \), body length), which shows that there is a long way to go to achieve the distinguished speed as high as several \( BL/s \) in biological fish.

Moreover, in Fig. 7, it can be observed that, forward swimming speed \( (U) \) increases directly with the oscillating frequency \( f \). The regression equations describing the relationship are: \( U=0.108+0.134f \) \( (r^2 = 0.93, N=21) \) for the fish with identical link-length-ratio and \( U=0.091+0.154f \) \( (r^2 = 0.94, N=21) \) for the fish with optimized link-length-ratio respectively. Comparison of the slopes also showed significant difference in speed performance for the two lines. It is noted that the speed cannot be infinitely expanded with increasing frequency since the servomotors can hardly provide enough torque to push water in high frequency areas to some extent. The mean forward speed would drop about 15 percent as \( f=2.5 \) Hz for our robot fish prototype in test. So an optimal or sub-optimal oscillating frequency maybe exists, which can be found from published data in propulsion using oscillating hydrofoil: \( f=1 \) Hz for VCUUV [14] and \( f \approx 3 \) Hz for a 3-joint prototype fish robot [15] respectively. The preferable working frequency for our prototypes lies about 2 Hz.
IV. CONCLUSIONS AND FUTURE WORK

In this paper, the characteristic parameters in the simplified propulsive model of biomimetic robot fish were optimized taking into account of both hydrodynamic properties and feasibility of physical realization. The optimal link-length-ratio was numerically calculated by an improved constrained cyclic variable method, and applied to the construction of the 4-linked robot fish in our laboratory. The comparative results illustrated the effectiveness of the optimization.

Future research should be concentrated on multiple control parameters optimization combining with kinematics and hydrodynamics to achieve higher propulsive speed. In the meantime, the autonomous navigation for robot fish based on multiple sensors fusion and intelligent control techniques will also be investigated.

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