# Simplified propulsive model for biomimetic robot fish and its experimental validation<sup>®</sup>

Yu Junzhi (喻俊志 )<sup>2</sup>, Wang Shuo, Tan Min (Institute of Automation, Chinese Academy of Sciences, Beijing 100080, P.R.China)

#### Abstract

As a combination of bio-mechanism and engineering technology, robot fish has become a multidisciplinary research that mainly involves both hydrodynamics-based control and actuation technology. This paper presents a simplified propulsive model for carangiform propulsion, which is a swimming mode suitable for high speed and high efficiency. The carangiform motion is modeled as an N-joint oscillating mechanism that is composed of two basic components: the streamlined fish body represented by a planar spline curve and its lunate caudal tail by an oscillating foil. The speed of fish 's straight swimming is adjusted by modulating the joint 's oscillating frequency, and its orientation is tuned by different joint 's deflection. The results from actual experiment showed that the proposed simplified propulsive model could be a viable candidate for application in aquatic swimming vehicles.

Key words: propulsive model, robot fish, carangiform propulsion, body wave

#### 0 Introduction

Fish in nature propel itself by the coordinate motion of its body, fins and tail, achieving tremendous propulsive efficiency and excellent maneuverability which win the advantage over conventional marine vehicles powered by rotary propellers. Nature selection has ensured that the mechanical systems evolved in fish, although not necessarily, are very efficient and fitted for their living environments. In a sense of engineering, the fish is a distinguished AUV ( Autonomous Underwater Vehicle ) prototype. An overview of fish swimming and the analytical methods that have been applied to some of their propulsive mechanisms can be found in Ref. [1,2]. In recent years, researches in propulsion and maneuvering mechanisms used by fish have demonstrated a variety of prospective utilities in undersea vehicles [23]. In 1994, MIT successfully developed an 8-link, fish-like machine—Robo-Tuna, which may be the first free-swimming robot fish in the world. RoboTuna and subsequent RoboPike projects attempted to create AUVs with increased energy savings and longer mission duration by utilizing a flexible posterior body and a flapping foil (tail fin) that exploits external fluid forces to produce thrust. In the mean time, another motivation is to answer Gray 's paradox , which is that a fish does not seem to have enough power to propel itself at the speed it does. Since then, based on progress in robotics, hydrodynamics of fishlike swimming, new materials, actuators and control technology, much research has been focused on the development of novel fish-like vehicles.

For the convenience of description we define a robot fish as a fish-like aquatic vehicle that is based on the swimming techniques and anatomic structure of a fish: primarily the undulatory/oscillatory body motions, the highly controllable fins and the large aspect ratio lunate tail. As a combination of bio-mechanism and engineering technology, the robot fish is a multidisciplinary field that mainly involves hydrodynamics based control and actuation technology.

In this paper , the objective is to construct a simple propulsive model for carangiform propulsion , which guides the development of a radio-controlled , multi-link and free-swimming biomimetic robot fish . Because the fish 's swimming involves hydrodynamics of the fluid environment and dynamics of the fish body , precise mathematical model is hard to establish by purely analytical approaches . Considering that the fish 's motion can be decomposed into speed control and orientation control , an N-joint oscillating mechanism is employed to fit motion of fish in our model . The speed of fish 's straight swimming is adjusted by modulating joint 's oscillating frequency , and its orientation is tuned by different joint 's deflection . Based on this model , a free-swimming biomimetic robot fish prototype is built to experimentally verify our proposed model .

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 To whom correspondence should be addressed. E-mail: jzyu@mech.pku.edu.cn, yujunzhi@263.sina.com
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#### 1 Previous related work

BCF (body and/or caudal fin) swimming movements are generally categorized into anguilliform, subcarangiform, carangiform and thunniform mode mainly according to the wavelength and the amplitude envelope of the propulsive wave underlying fish 's behavior [1]. To some extent much more interest of investigation focuses on the carangiform locomotion. Some theoretical and experimental studies have explored the possibility of applying the carangiform propulsive mechanism to aquatic vehicles. Early resistive hydrodynamic models were based on a quasi-static approach that uses steady-state flow theory to calculate the fluid forces [4]. Later models dealt with more realistic fish-type motions, Wu originally developed a 2-D waving plate theory, treating fish as an elastic plate [5]. Thereafter elongated-body theory and large-amplitude elongated-body theory that are suited to carangiform swimming were formed <sup>6-8</sup>]. These linear or nonlinear extensions of the waving plate theory allow the analysis of fast starts as well as steady-state swimming.

At present, some artifical systems are developed to investigate fish-like locomotion mechanism. In particular, oscillating foil has been proposed as an alternative propulsor to the conventional screw propeller [3,9,10]. The development of 8-link, foil-flapping robotic mechanism (Robotuna) acquired detailed measurements of the forces on an actively controlled body [3,11]. Harper et al. proposed the design of optimal spring constant to actuate the oscillating foil 12]. Kelly et al. proposed a model for planar carangiform swimming based on reduced Euler-Lagrange equations for the interaction of a rigid body and an incompressible fluid 13]. Mason et al. built a three-link robot system to study carangiform-like swimming 14]. They experimentally verified a quasi-steady fluid flow model for predicting the thrust generated by flapping tail. However, these exploratory developments in propulsive model are not applicable or general for real aquatic applications.

#### 2 A simplified propulsive model for carangiform swimming

This paper concentrates on the lateral motion of fish body, which is in the form of a traveling wave smoothly increasing from the front to the tail end. The method employs a discretized numerical fitting combining simulation with experiment. It is suggested by ichthyologist that the passage of a wave underlies the fish 's propulsive structure [1]. The propulsive wave behaves as lateral curvature in spine and musculature, which begins posterior of head and increases with amplitude as it moves posteriorly. It

traverses at a speed greater than the forward speed. A typical carangiform swimming mode for RoboTuna has been presented by Barrett et al. [15], which is composed of two basic components: the fish body represented by a planar spline curve and its lunate caudal tail by an oscillating foil. The spline curve starts from the fish 's center of inertia to the caudal joint, which is assumed to take the form of a traveling wave (1) originally suggested by Lighthill [6].

 $y_{body}(x,t) = [(c_1x + c_2x^2)] \sin(kx + \omega t)]$  where  $y_{body}$  is the transverse displacement of body, x is the displacement along main 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,  $\omega$  is the body wave frequency  $(\omega = 2\pi f = 2\pi/T)$ .

For simplicity, a discrete planar spline curve is considered, i. e. time t is separated from the body-wave function  $y_{body}(x,t)$ . In other words, the traveling body-wave is decomposed into two parts: the time-independent spline curve sequence  $y_{body}(x,t)$  ( $t=0,1,\ldots,M-1$ ) in an oscillation period, which is described by (2) and the time-dependent oscillation frequency f.

$$y_{body}(x, i) = [(c_1x + c_2x^2)] \sin(kx - \frac{2\pi}{M}i)]$$
(2

where i is the variable of spline curve sequence, M is the body-wave resolution that represents the discrete degree of the overall traveling wave, which is restricted by the maximum oscillation frequency of servomotors (here, we assume that joints are actuated by servomotors).

Before fitting the spline curve , we define the relative wavelength R (  $0 < R \leqslant l$  ) as the length ratio of the fish 's oscillating part to a whole sine wave. When R approaches zero , to some extent , the fish 's oscillating part may be viewed as a rigid rod which hardly produces thrust ; with a proper R , the fish oscillates harmoniously and moves efficiently. In reality , the appropriate R keeps to be about 0.5 , which is to say , half a sinusoidal wave recurs in the oscillating part during an efficient locomotion .

As mentioned above, since the wavelength of a whole propulsive wave is viewed as  $2\pi$  at k=1, the wavelength of the oscillatory part at R is then  $R\times 2\pi$ . On the assumption that the fish-like mechanical system is to be made up of N joints and body-wave resolution is M, the body wave at an interval of 0 to  $R\times 2\pi$  along the axial body displacement can be fitted with an N-link mechanism. It is also assumed that the full control of a fish relies on the internal shape (the joint angle  $\phi_i$ ) for maneuverability and on the oscillation frequency f for speed. Once the amplitude coefficients ( $c_1$ ,  $c_2$ ) are de-

termined , the shape of the sine wave at some time is ensured. Mathematically , the joint angle  $\phi_i($  i=1 ,2 ,... , N ) at different time in a cycle can therefore be calculated by fitting each planar spline curve at an interval of 0 to  $R\times 2\pi$  along the axial body displacement. As a result , a 2-D  $M\times N$  rectangular array OscData [ M ] ( 3 ) is obtained , which will be used as the primitive oscillating data of the robot fish . Based on this oscillatory array , the fish body 's shape can geometrically be changed by adding different deflections  $\Delta\phi_i$  to the first N' ( 0< N' < N)

joints , the corresponding oscillatory array OscData '[ 
$$M$$
 ] [  $N$  ] is shown in ( 4 ). The motion orientation of the fish varies with the unstable shape in a limited cycle due to a complex hydrodynamic interaction , so called added mass effect .

OscData[ 
$$M$$
  $I$   $N$  ] = 
$$\begin{bmatrix} \phi_{01} & \phi_{02} & \dots & \phi_{0N} \\ \phi_{11} & \phi_{12} & \dots & \phi_{1N} \\ \dots & \dots & \dots & \dots \\ \phi_{M-1,1} & \phi_{M-1,2} & \dots & \phi_{M-1,N} \end{bmatrix}$$
(3.3)

OscData[ 
$$M$$
  $I$   $N$  ] = 
$$\begin{bmatrix} \phi_{01} + \Delta\phi_1 & \phi_{02} + \Delta\phi_2 & \dots & \phi_{0,N'-1} + \Delta\phi_{N'-1} & \phi_{0N'} & \dots & \phi_{0N} \\ \phi_{11} + \Delta\phi_1 & \phi_{12} + \Delta\phi_2 & \dots & \phi_{1,N'-1} + \Delta\phi_{N'-1} & \phi_{1N'} & \dots & \phi_{1N} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \phi_{M-1,1} + \Delta\phi_1 & \phi_{M-1,2} + \Delta\phi_2 & \dots & \phi_{M-1,N'-1} + \Delta\phi_{N'-1} & \phi_{M-1,N'} & \dots & \phi_{M-1,N} \end{bmatrix} (4)$$

Since the mechanical robot fish is composed of four links , all calculations and experiments in this paper are performed on a four-link model. A schema of the link-based body-wave fitting is shown in Fig.1. Because the tail fin is attached to the last link , the angle  $\alpha$  derived from the slope of the last link is just the fin 's attack angle. The parameters for the body-wave fitting are as follows:  $c_1=0.1$  ,  $c_2=0.05$  , k=1 , M=18 , R=0.5 , N=4. Here , the eventual results for the propulsive mode are a 2-D 18  $\times$  4 rectangular array of joint angles and the oscillation frequency , which are independent of fish 's dimension and shape. In other words , only a parameters set  $\{\phi_1$  ,  $\phi_2$  ,  $\phi_3$  ,  $\phi_4$  , f } is chosen to control the fish 's motion .

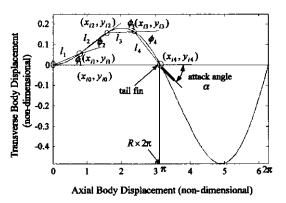


Fig.1 Link based body-wave fitting

## 3 Biomimetic robot fish prototype and experimental validation

#### 3.1 Development of robot fish prototype

Based on the above simplified propulsive model , a radio-controlled , multi-link and free-swimming biomimet-

ic robot fish mimicking carangiform-like locomotion has been designed. The mechanical configuration of an updown motioned robot fish is shown in Fig.2. Fig.3 shows that it swims downwards in a swimming tank. It can swim forwardly and turn realistically like a fish in the water.

The developed robot fish primarily consists of  $\sin$  parts:

- Control unit (microprocessor + peripherals)
- Communication unit ( wireless receiver )
- Sensor unit (infrared, visual, ultrasonic, etc.)
- Support unit ( aluminum exoskeleton + head + forebody )
  - Actuator unit ( DC servomotors )
- Accessories ( battery , waterproof skin , tail fin , etc. )

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 that act 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 biological fish " model ". In the meantime, some steel balance weights are located in the forebody and lower side of the exoskeleton to adjust the equilibrium between gravitational forces and buoyant forces.

In the fish 's control unit, the servomotors are controlled by an onboard microprocessor and a Pulse-Width

Modulation ( PWM ) signal generator. The speed of fish 's straight motion is adjusted by modulating the joint 's oscillating frequency , and its orientation is tuned by different joint 's deflection. Adding various deflections , plus or minus , to the front joint angles ( e.g. ,  $\phi_{i1}$  and  $\phi_{i2}$  ) in each oscillation period , different motion direction is achieved. By the manual mode ( remote controller ) or the automatic control mode , the robot fish can swim forward , accelerate , decelerate , turn right or left , or even submerge or ascend like a real fish .

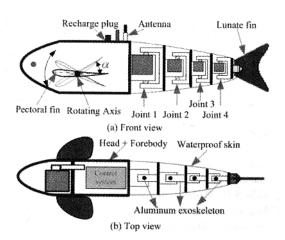


Fig. 2 Mechanical configuration of an up-down-motioned robot fish

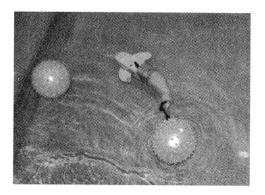


Fig.3 Swimming downwards in a swim tank

#### 3.2 Experimental setup and results

To verify the feasibility and reliability of the proposed propulsive model and the corresponding control method , 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 decision making subsystem and the communication subsystem. All aquatic experiments in this paper were conducted in a static swim tank 3050 mm  $\times$  1830 mm  $\times$  560 mm ( length  $\times$  width  $\times$  depth ) at room temperature. The global information of the fishes and their surroundings captured by overhead CCD camera is effective.

tively 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 .

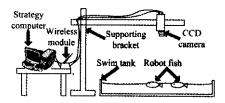


Fig. 4 Configuration of the experimental robot fish platform

With the vision-based tracking system to provide real-time position feedback of the robot fishes [16], we test the speed performance of the developed robot fish prototypes. Based upon the experimental data, the relationship between the oscillating frequency and the straight swimming speed is shown in Table 1. It is observed that the maximum swimming speed near is 0.32m/s, i.e., about 0.8 times the body length per second, at the frequency of 2 Hz with a lunate tail fin. In contrast to a real fish, such a swimming efficiency is not high due to large friction resistance between the oscillatory part and water. However, a general tendency is that the swimming speed increases with the oscillating frequency. For a practical reason, the speed cannot be infinitely expanded since the servomotors can hardly follow sufficiently high speeds in high oscillating frequency areas.

Furthermore, as an essential element of maneuverability, the turning performance of the fish is measured. Table 2 shows the experimental results of angular speed at f = 2Hz. The fish is required to round a  $2\pi$  circle with different turning radiuses in the experiments, and corresponding angular speeds are obtained. During the measurements, 8 directional levels are sampled at intervals of 7.5°. The corresponding deflection in degrees is added to the first two joint angles ( $\phi_{i1}$ ,  $\phi_{i2}$ ) in each oscillation period, accordingly the fish body deflects to one side. It is also attempted to add deflections to the last two joints ( $\phi_{i3}$ ,  $\phi_{i4}$ ), but some differences to turning radius are found. In this paper, only deflections added to the first two joints are discussed. As seen from Table 2, the angular speed increases with augment of deflections, and the values of the angular speed are not quite symmetric with bias. This problem seems to indicate that the current system is lack of mechanical symmetry due to joint binding, motor installation and so on.

	Table 1	ble 1 Oscillation frequency (Hz) versus speed (m/s) of straight swimming							
Frequency	0.5	0.57	0.67	0.8	1.0	1.34	2.0		
Speed	0.12	0.16	0.18	0.20	0.23	0.26	0.32		

Table 2	Angular speed ( α	, rad/s) versus	deflections ( $\Delta\Phi$	, degree ) at $f = 2$ Hz
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		<i>o</i>					, <i>j</i>		
$\Delta\Phi$	- 30	- 22.5	- 15	-7.5	0	7.5	15	22.5	30
ω	-1.2	-0.92	-0.8	-0.5	-0.1~0.1	.4	.75	.95	1.1

#### 4 Conclusions and future work

A simplified propulsive model for carangiform propulsion has been presented, whose eventual results are a 2-D rectangular array of joint angles and the oscillation frequency. Based on this model, a radio-controlled, multi-link and free-swimming biomimetic robot fish has been developed. The speed of fish 's swimming is adjusted by modulating the joint 's oscillating frequency, and its orientation is tuned by different joint 's deflection. Experimental measurements partially verified the feasibility of the model in the application of robot fish.

Future research should be focused on self-contained robot fish design and optimization method taking account of both kinematics and hydrodynamics. In the meantime, human-machine interaction-based autonomous robot fish using advanced sensor and intelligent control techniques should also be developed.

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Yu Junzhi , born in 1975. He received the B. E. degree in safety engineering in 1998 and the M.E. degree in precision instruments and mechanology in 2001 from North China Institute of Technology , Taiyuan , China. In Dec. 2003 , he received the Ph.D. degree in control theory and control engineering from the Institute of Automation , Chinese Academy of Sciences. He is currently a postdoctoral researcher at the Center for Systems and Control , Peking University. His research interests include autonomous robots , embedded system and intelligent information processing.

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作者: Yu Junzhi, Wang Shuo, Tan Min

作者单位: Institute of Automation, Chinese Academy of Sciences, Beijing 100080, P.R.China

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