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Motion Control for an Underwater Robotic Fish with Two Undulating Long-Fins

Liuji Shang, Shuo Wang, Min Tan, Xiang Dong

Abstract—**Motion control for one kind of underwater robotic fish is presented in this paper. Here our robotic fish prototype has two long-fins installed symmetrically on its both sides. And one long-fin is made up by springiness membrane covered on ten ray-fins. Ten servo-motors are used to control the motions of the ten ray-fins on one side. Due to the special structure of the prototype, swimming motion modes can be broken into four basic motion modes: marching mode, receding mode, rotating mode and side-swaying mode. Aiming at the four motion modes, this paper presents relevant control method separately. Our controller is based on FPGA. Through reading signal data stored in the memory of control chip, servo-motors may oscillate the ray-fins at scheduled way. Therefore, different frequency and different phase difference of adjacent ray-fins may bend the long-fin formed by membrane into relevant waveform. Because the membrane is soft and elastic, hydrodynamic forces produced by expelled water may drive fish body into swimming motions. Using different control methods, hydrodynamic force provide fish body with many motion modes, including the four basic motion modes. In addition, one motion modes switch system is designed based on Mega128. Through producing different voltage level combination, robotic fish may switch its motion mode by the transferred one in swimming. The experiments show our method for motion control is valid.**

I. Introduction

FISH exist everywhere in the ocean. Due to its flexible and small characters, researchers yield keen interest. Unlike other underwater vehicles, robotic fish is very small and has excellent flexibility. It can swim in very narrow and deep mixed ocean [1].

Generally, robotic fish propulsion system can be classified into two categories: median and paired fin (MPF) propulsion and body and caudal fin (BCF) propulsion [2, 3]. BCF propulsion depends on caudal fin to give the thrust forces. At the meantime the propulsive wave traverses the fish body in a direction opposite to the caudal fin. BCF propulsion always has high speed and big energy operating factor. MPF propulsion mostly depends on median fin to give the thrust forces. Paired fins rarely contribute to forward propulsion and mostly supply stabilization and steering purposes. But a special propulsion system with long-fins is paid more attention in recent years, which is classified into MPF. A lot of researchers have done much on long-fins including propulsion and maneuvering, side-sway problem, hydrodynamic analysis, etc. Standen and Lauder [4] gave dorsal and anal fin function during propulsion and maneuvering. Dan Xia, Weishan Chen et al [5] considered the side-sway problem and gave three restraining methods. In addition, many researchers also have carried out many correlative experiments and given some valuable results [6]. However, few researchers look the fish movements as combination of several simple motion modes and most consider fish movements as a whole.

In this paper, our robotic fish employs MPF propulsion. But our robotic fish is propelled by symmetrically installed long-fins which are different to the MPF propulsion mentioned above. By virtue of varied waveforms of the symmetrical long-fins, the robotic fish can yield forces in different direction and make its locomotion more maneuverable. And its special structure makes its gravity centre maintain fixed in the movements. Although its speed does not seem to be impressive, the robotic fish has more excellent flexibility. In order to simplify the analyses of the complex fin undulating, the long-fins movements are concluded into four basic modes: marching mode, receding mode, rotating mode and side-swaying mode. Therefore the complex movements can be obtained be means of the combination of the basic modes. In addition the basic mode can be modeled easily and lay the first stone for future works.

On the basis of the basic modes, a motion modes switch system is designed for the robotic fish. Using convenient interface produced by Mega128, it connects the remote-control unit and our controller. It makes our experiment more convenient and acquires data from other sensors. Another purpose of switch system is saving resources of FPGA and makes our design more independent for every functional module. Obviously, subsequent modeling work may be carried out on the switch system.

The remainder of the paper is organized as follows. Section II introduces the robotic fish prototype. Section III presents four basic motion modes and gives their kinematics analysis. Remote control and motion modes switch system is described in section IV. Section V presents the experiment result and

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The authors are with the Key Laboratory of Complex Systems and Intelligence Science, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China. Phone: +86-10082614439. Fax: +86-10-62650912. Emails: fineshang@163.com; shuo.wang@ia.ac.cn; tan@compsys.ia.ac.cn; dong@compsys.ia.ac.cn. .

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discussion. Finally the conclusion is given in section VI.

II. THE ROBOTIC FISH PROTOTYPE

Gymnarchus niloticus [7] is a kind of freshwater fish distributed in the Nile Valley. Its propulsion mode is very special. This fish has only a long dorsal fin without caudal fin and pelvic fin. Swimming is achieved by means of bending the long dorsal into some waveform while its body keeps straight all along. The long dorsal exhibits a lot of ray-fins (up to 183-230). So through different phase combination of the ray-fins, fish body's motion in different direct is achieved. These combinations are very hard to obtain and hydrodynamics is very complicated. So a robotic fish prototype is designed and developed for the long-fin propulsion research. The prototype is shown in Fig.1.

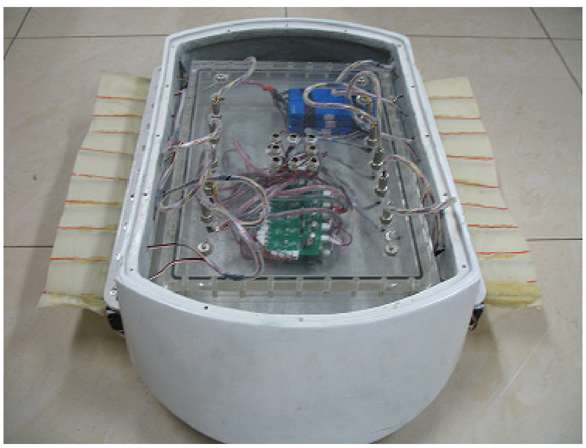

Fig.1. Robotic fish prototype

Fig.1 shows that the robotic fish consists of fish body, two long-fins. Fish body is made of glass fiber reinforced plastic and has installed ten servo-motors symmetrically. Its control system is based on FPGA, shown by Fig.2. First PC sends command by radio modulator. Then robotic fish's controller receives command and read relevant data stored in FPGA chip. Next controller sends these data to servo-motors separately. Finally servo-motors drive the long-fin to complete propulsion. The two long-fins constitute robotic

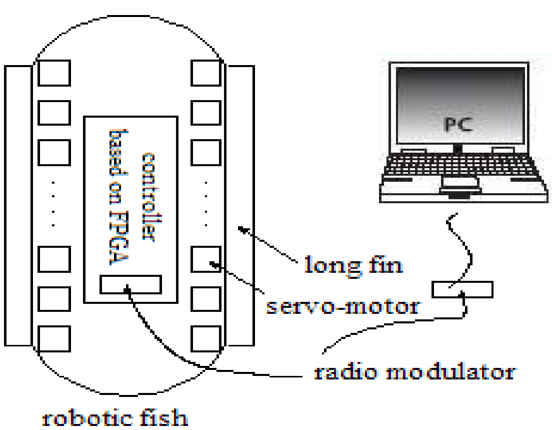

Fig.2. Control system for robotic fish

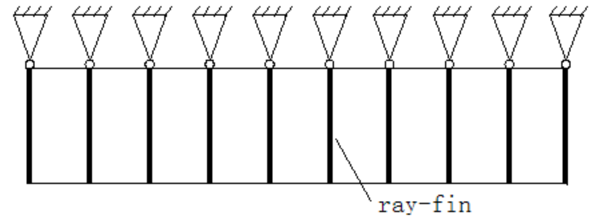

Fig.3. The structure of one long-fin

TABLE I
STRUCTURE PARAMETERS OF ROBOTIC FISH

Name of Structure Division	Value
Length of Robotic Fish	817mm
Width of Robotic Fish	401mm
highness of Robotic Fish	158mm
Length of Membrane	460mm
Width of Membrane	97.4mm
Thickness of Membrane	1mm
Number of Ray-fin	10
Length of Ray-fin	97.4mm
Interval between Ran-fins	51.1mm

fish's propulsion system. As Fig.3 shown, long-fin is a skeleton covered with membrane on ten equally distributed thin rods which are also called ray-fins. Table I shows fish's structure parameters. All the ray-fins are fixed on the fish body. Servo-motors oscillate the ten fin-rays and make the membrane bend at some waveform when it swims in water. Obviously, the oscillating amplitude and frequency of the fin-rays are the keys how the robotic fish works. Therefore coordination control of the two long-fins can generate varied locomotion. In this paper, four basic motion modes are the focal points.

III. MOTION CONTROL FOR FOUR BASIC MOTION MODES

Water is an impressible fluid, so any movements of long-fin will make the fish body in motion [8]. In the past, researchers have studied deeply hydrodynamics about fish and gotten some conclusions. The fish hydrodynamics is so complex that its model is difficult to construct precisely till now. Some difficulties on kinematics modeling also exist in the complex fish motions, especially in the turning or receding. So four basic motion modes are proposed for the robotic fish with two undulating long-fins and the complex motions is achieved by means of combination of the basic modes. In addition, hydrodynamic modeling for these simple motion modes will be easier than that for the complex movement. The four motion modes are marching mode, receding mode, rotating mode and side-swaying mode. The submersion mode is another mode of the robotic fish not included in this paper because the developed robotic fish prototype does not have a submerging device installed. Obviously, most of the movements can be achieved through combinations of the basic motion modes. The four motion modes are discussed in detail as following.

A. Marching Mode

Marching mode is the most common motion mode. And sine wave is used for the long-fin. Let define the waveform function formed by the edge of membrane as ϕ. If define the amplitude as $A_{\max}$ and the frequency as f. The immediate phase is φ. Then ,

$$\phi = A_{\max} \sin(2\pi ft + \varphi) \quad (1)$$

Then traveling of wave in the long-fins is described, as shown in Fig.4. The arrow represents the direction of the wave traveling along the long-fin. The upper diagram is the original waveform of the long-fin and the lower diagram is the subsequent waveform. The figure shows that the

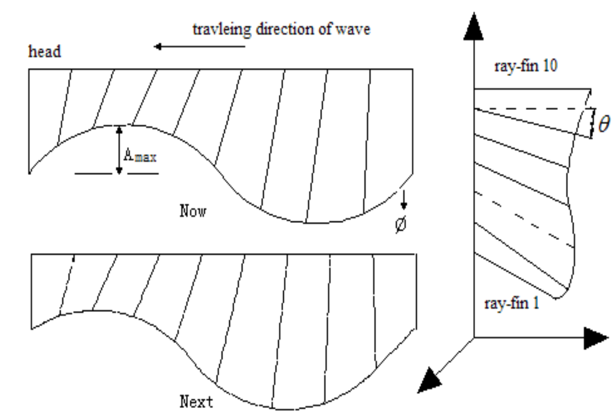

Fig.4. The traveling wave along the long-fin

excursion of long-fin will produce thrust which make fish body marching. Because the ten ray-fins decide the membrane edge waveform, what we need is the output signal of servo-motors for the ray-fins. In Fig.4, each ray-fin oscillating function can be calculated. For example, the first ray-fin oscillation equation may be expressed as:

$$\phi_1 = -A_1 \sin(2\pi ft + 0 * \theta) \quad (2)$$

Where ϕ_1 is the amplitude value for the first ray-fin. A_1 is the amplitude, f is the oscillating frequency and θ is the phase difference between two adjacent ray-fins. Similarly, the

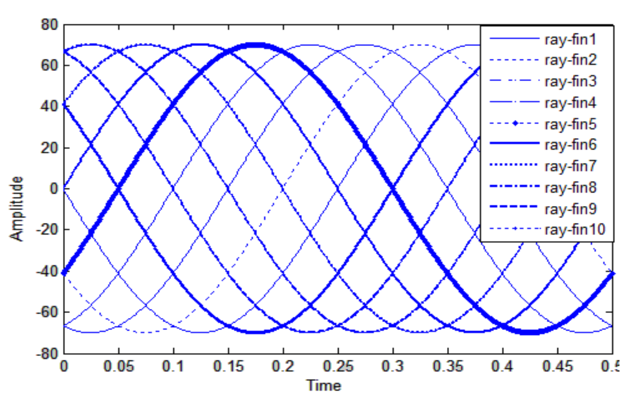

Fig.5. The output signal of motor for the ten ray-fins.

other ray-fin may be expressed as:

$$\phi_i = -A_i \sin(2\pi ft + (i-1) * \theta) \quad i = 1,2,...,10 \quad (3)$$

The robotic fish prototype in this paper has ten ray-fins, so θ is set to $360°/10 = 36°$. Let the symmetrical long-fins produce the same undulating waveform, and then the hydrodynamic forces will be same big and same directional on the two sides of fish body. Therefore, what we need is storing these amplitude values at every time into FPGA chip and export them to servo-motors. Apparently the thrust generated by long-fins makes the robotic fish march forward smoothly. Fig.5 shows the signal output of the ten ray-fins on condition of A_i at 70mm and f at 2HZ.

In equation (3), A_i and f are the parameters which influence the swimming speed. The robotic fish will swim faster with increase of the amplitude and frequency of ray-fins. But when the parameters exceed some thresholds, the robotic fish will decrease its speed with the increase of amplitude or frequency instead of increasing its speed.

B. Receding Mode

In this paper, the robotic fish uses the symmetrical long-fins as propulsion system. For the two long-fins are installed at both sides of the body and the fish body's mass distribution is almost equable, it is easy to produce hydrodynamic force to make fish receding. As Fig.4 shown, the direction of hydrodynamic forces is only related with direction of traveling of wave on the long-fin. So like marching mode, only changing the oscillating direction of ray-fin may produce robotic fish's receding mode. Fig.6 shows the wave traveling along the long-fins. And the relevant ray-fins oscillating function is:

$$\phi_i = A_i \sin(2\pi ft + (i-1) * \theta) \quad i = 1,2,...,10 \quad (4)$$

Receding mode is the opposite motion mode against marching mode.

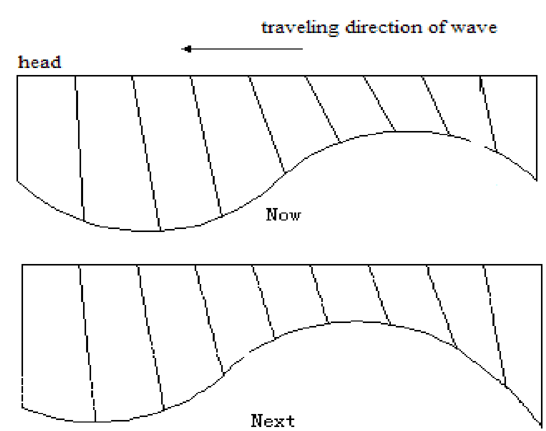

Fig.6. The traveling of wave on long-fin in receding mode

C. Rotating mode

Rotating mode is a special motion mode in fish movement. Strictly speaking, it doesn't belong to fish's motion mode for fish rarely only do rotating. But the rotating mode is an important part in the basic motion modes.

Articulated robotic fish execute rotating movement through changing the angles of body joints and tail joint. But for the robotic fish with two undulating long-fins, rotating is easy and controllable. The direction of thrust is only related to the direction of the wave traveling along the long-fin. So if one long-fin oscillates its ray-fins to form a traveling wave toward one direction, the other long-fin undulates to form an opposite traveling wave. And the hydrodynamic forces produced by the two long-fins may cause a rotary moment for fish body, as Fig.7 shown.

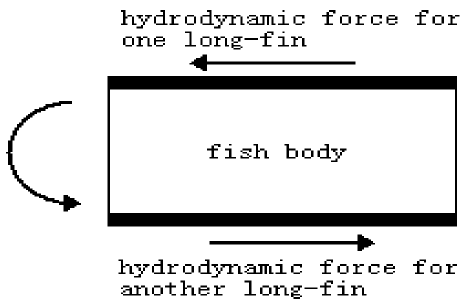

Fig.7. Robotic fish's rotary moment.

Therefore, rotation can be achieved by making the two long-fins generate opposite undulating waveforms. For simplification, we divide rotation motion into two cases.

Case 1: if the amplitude or frequency of ray-fins' oscillation in both sides are equal, the fish body does rotating motion and its center of gravity keeps motionless;

Case 2: if the amplitude and frequency in both sides are not equal, the fish body can not do rotating motion while keeping its center of gravity motionless.

In this paper, case 1 is chosen for the robotic fish rotating mode design because it is easier to implement than case 2. In addition, the rotating motion in case 1 can not cause marching

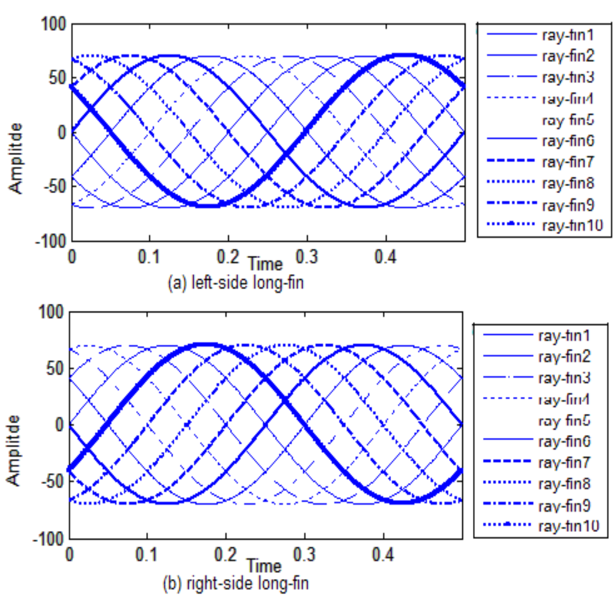

Fig.8. The output signals for ten ray-fins' motor control.

or receding. The left rotating is similar to the right rotating, so the left rotating is introduce as an example. In the two motion modes mentioned above, the same oscillating function applies to the symmetrical long-fins. But in the rotating mode, the oscillating functions of the right long-fin and the left long-fin are different and shown as following:

$$\phi_i = -A_i \sin(2\pi f t + (i-1)*\theta) \quad i = 1,2,...,10 \quad (5)$$

$$\phi_j = A_j \sin(2\pi f t + (i-1)*\theta) \quad j = 1,2,...,10 \quad (6)$$

So the oscillating functions can be used to generate control signals for the ray-fins' driven motors to make the robotic fish rotate. Fig.8 shows the signal output of the twenty servo-motors on condition of A_i and A_j at 70mm and f at 2HZ. The upper picture shows the signal of right long-fin and the lower one shows the signal of left long-fin.

D. Side-swaying Mode

Side-swaying mode is a special motion mode based on two long-fins. In nature, fish rarely swim at side-swaying mode because its propulsion system can not produce hydrodynamic forces which make the fish body side-sway. In fact this mode is very useful in underwater robot applications. In unknown circumstance, it may help the robot adjust its body position and pose.

The thrust is only related to the long-fins' motion. If only one long-fin oscillates or undulates and the other long-fin does not, the produced thrust is only on the side of the moving long-fin. Because the whole body of the robotic fish prototype has same mass distribution, different kinds of ray-fins' oscillation can determine the different thrust directions. And if the amplitude, frequency and immediate phase are all the same, the robotic fish may do side-swaying motion. The side-swaying toward left is similar to side-swaying toward right, so side-swaying to right is described as an example. The right long-fin will keep still and the left long-fin oscillates. The oscillating function of ray-fins can be described as:

$$\phi_i = -A_i \sin(2\pi f t) \quad i = 1,2,...,10 \quad (7)$$

Control for this motion mode is making the ten servo-motors on one side produce same signal. That is, controller read same data from FPGA chip for the ten servo-motors. Fig.9 shows how the robotic fish moves. The real line shows the state of the left long-fin at a time and the dot long-fin shows the state at the subsequent time.

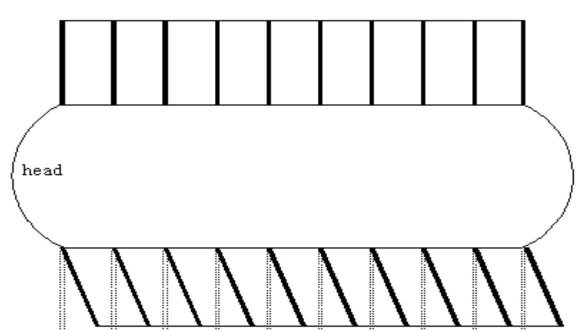

Fig.9. Robotic fish's right side-swaying motion mode

IV. REMOTE CONTROL AND MOTION MODES SWITCH SYSTEM

A. Remote Control

The remote controller is a radio modulator connected with PC. First PC sends commands by the radio modulator. Then another radio modulator installed on robotic fish receives the modulated signal and demodulates it for the controller chip. Finally the controller decodes the signal and translates it into some commands predefined by us. Our commands include all of the motion modes mentioned above. According the commands, controller can drive the servo-motors and execute relevant operations.

B. Motion Modes Switch System

As mentioned above, our motion modes switch system employs Mega128 as controller. After receiving command for switch motion modes, Mage128 decode the command and transfer it to controller based on FPGA. Fig.10 shows the working process.

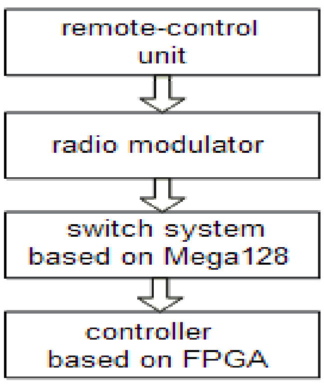

Fig.10. Motion modes switch system

Mega128 has good ability to receive signals from radio modulator and transfer data to FPGA. This method may save resources of FPGA effectively. And it also can make our controller more effective and easier. Through programming Mega128, command signal can be achieved, then transfer it by a high-speed level translator unit. Next controller analyzes the voltage level combination and compare with program for FPGA. Last one motion mode is chosen.

This method has better flexibility. It is convenient for us to acquire data and lay the first stone for future works.

V. EXPERIMENTS

In a 3.41m×2.61m×0.80m pool, the experiment is done with the robotic fish prototype shown in Fig.1. Through wireless communication, the robotic fish may receive the commands sent from PC. And the experiments for the four basic motion modes are carried out. The purposes are: (1) testing the robotic fish's maneuverability and propulsive performance; (2) measuring the robotic fish' basic motion parameters, including average speed and rotary speed with different undulating frequency and amplitude.

Fig.11 is the robotic fish swimming in the pool. There is a high-speed camera using to measure speed above the pool.

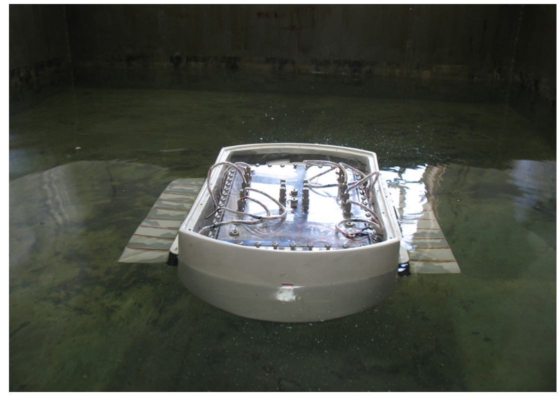

Fig.11. The swimming robotic fish in water

Four motion modes experiments were done respectively.

Firstly, the frequency parameter is set from 1Hz to 2.5Hz and the amplitude parameter is set as 48.7mm, 68.9mm and 84.4mm respectively in marching mode and receding mode. Experiments show that robotic fish swims fast when amplitude is 48.7mm. Through observation, analyses show there are two main points which have effect on the results. One is that the membrane covered on ray-fins limits ray-fin's oscillating. The other is there is a maximum value of hydrodynamic forces with undulating long-fins at certain amplitude. Experiments also show that robotic fish swims fast when frequency is 2Hz. We have done frequency tests at 1, 1.5, 2, 2.2, 2.5Hz. When the frequency is 1 or 1.5Hz, the robotic fish may get small thrust; when the frequency is 2.2 or 2.5Hz, the produced bigger water wave makes the robotic fish un-steady. Maximum speed can be achieved at 2Hz. Through three same experiments the average speed is about 232mm/s and the maximum speed is about 370mm/s. The robotic fish swims smoothly. Fig.12 shows the experiments of marching and receding motion mode.

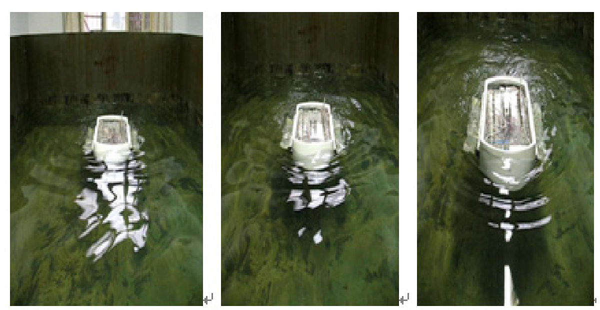

Fig.12. Marching and Receding Mode of Robotic Fish

Secondly, the rotating mode experiments are performed. As mentioned above, rotating mode is one of the basic motion modes. Its main function is to adjust the direction of the robotic fish. The experiments were carried out when the oscillating frequency is 1.5Hz and amplitude is 48.7mm. The average rotational speed is about 120°/s. And the robotic fish's rotational speed increases with the oscillating frequency in the range of 1-2.2Hz. Fig.13 shows the experiments of rotating motion modes.

Thirdly, the side-swaying mode experiments are done. The frequency and amplitude parameters are almost same as

Fig.13. Rotating mode of robotic fish

marching mode. But the observations show that the robotic fish body will be very unsteady when the ray-fins' oscillating frequency is bigger than 2Hz. The reason is that such oscillation will produce a bigger rotary moment and the rotary moment will make the robotic fish body rolling. This kind of rotary moment increases with the oscillating frequency and decreases the propulsion efficiency. The experiments show the average speed in side-swaying mode is about 146mm/s

Fig.14. Side-swaying mode of robotic fish

TABLE II
EXPERIMENT RESULTS

Swimming Mode	Maximum Speed	Average Speed
Marching	370mm/s	232mm/s
Receding	370mm/s	232mm/s
Rotating	——	120°/s
Side-swaying	214mm/s	146mm/s

and maximum speed is about 214mm/s when the frequency is 1.5Hz and the amplitude is 48.7mm. Fig.14 shows the experiments of side-swaying motion mode.

Table II gives the experiment results of the four motion modes.

Finally, motion modes switching experiment based on Mega128 is carried out. First three color control patches are put on the robotic fish for detect by camera. Then one path based on four basic modes is designed for robotic fish. Next, through switching motion mode, robotic fish can finish the prepared work. And the experiments also show the robotic fish with two undulating long-fins has high maneuverability and flexibility.

VI. CONCLUSION

In this paper, a new kind of robotic fish with two undulating long-fins is introduced. The undulating long-fins can generate thrust to propel the robotic fish. Four basic motion modes of the robotic fish are proposed and described. The basic modes include marching mode, receding mode, rotating mode and side-swaying mode. Aiming at these basic modes, control methods to servo-motors are presented separately. Using remote control with the radio modulators, we did the experiments of four motion modes. The experiments show the performance of these motion modes of the robotic fish.

REFERENCES

[1] P. W. Webb, Form and function in fish swimming [J]. *Sci. Amer.*, 1984, pp.72-82.

[2] M. Sfakiotakis, D. M. Lane, and J. B. C. Davies, "Review of fish swimming modes for aquatic locomotion," *IEEE J. Oceanic Engineering*, vol. 24, no. 2, April 1999, pp.237-252.

[3] G. Drucker and G. V. Lauder, Locomotor function of the dorsal fin in rainbow trout: kinematics patterns and hydrodynamic forces. *The Journal of experimental Biology*, 2005, pp. 4479-4494.

[4] E. M. Standen and G.V. Lauder, Dorsal and anal fin function in bluegill sunfish *Lepomis macrochirus*: three-dimensional kinematics during propulsion and maneuvering. *The Journal of experimental Biology*, 2005, pp. 2753-2763.

[5] Dan Xia, Weishan Chen et al, "Simulation study on the body side-sway characteristic for rigid robot fish," *Robotics, Automation and Mechatronics*, Sept 2008, pp.1179-1184.

[6] A. Malcolm, E. Fontaine, and W. Burdick, "Designing future underwater vehicles: principles and mechanisms of the weakly electric fish," *IEEE J. Oceanic Engineering*, vol. 29, no. 3, July 2004, pp.651-659.

[7] Guangming Wang, Lincheng Shen, and Tianjiang Hu, "Kinematic modeling and dynamic analysis of the long-based undulation fin," *Control, Automation, Robotics and Vision*, Dec 2006, pp.1-6.

[8] R. Cortez, L. Fauci., N. Cowen, and R. Dillon, "Simulation of swimming organisms: coupling internal mechanics with external fluid dynamics," *Computing in Science & Engineering*. May 2004, pp.38-45.