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AN OBSTACLE AVOIDANCE ALGORITHM FOR AN UNDERWATER ROBOTIC FISH WITH UNDULATING LONG-FINS

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ABSTRACT

Four motion modes of underwater robotic fish by undulating symmetrical long-fins are proposed which include marching mode, receding mode, rotating mode and side-swaying mode. Robotic fish bends the two symmetrical long-fins into different waveform and makes the fin-ray oscillating to produce hydrodynamic forces. Through hydrodynamic force's analysis, force in different direction can be produced for fish body. Different combination of the two long-fins' waveform produces some motion modes for the fish body. The four motion modes are basic and typical. And this paper presents an algorithm for obstacle avoidance based on switching motion modes. By switching the four motion modes, Robotic fish installing infrared sensors can achieve obstacle avoidance. The experiment shows robotic fish swims steady and smoothly. Robotic fish reduce error produced by fish's turning in certain degree. Meanwhile the experiments also show the algorithm for obstacle avoidance is valid.

KEY WORDS

Biomimetic Robotics, obstacle avoidance, Underwater Vehicles, motion control

1. Introduction

Fish is a kind of amazing creature. Because of its flexible and small characters, researchers have done a lot about it for the past few years. Robotic fish is one of hotspots. 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 robotic fish's 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.

MPF propulsion system is employed by our robotic fish in this paper. But it is also different with the MPF propulsion mentioned above because our robotic fish is propelled by symmetrically installed two long-fins. By virtue of varied waveforms formed by 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 by means of the combination of the basic modes. In addition the basic mode can be modeled easily and lay the first stone for future modeling works.

Researches on obstacles avoidance for robotic fish are mostly based on vision control [7]. On the basis of the basic modes, an innovative obstacle avoidance algorithm is presented. Obviously, obstacle avoidance depends on excellent maneuverability of the robotic fish to complete avoiding operation. Some infrared sensors are installed on the robotic fish to detect the obstacles. And a switching strategy of the basic motion modes according to the tasks and sensor feedback is introduced in detail for obstacle avoidance.

The remainder of the paper is organized as follows. Section II introduces the robotic fish prototype. Section III presents four basic motion modes and proves their validity through kinematics analysis. Obstacle avoidance is described in section IV. Section V presents the experiment result and discussion. Finally the conclusion is given in section VI.

2. Our Robotic Fish Prototype

Gymnarchus niloticus [8] is a kind of freshwater fish distributed in the Nile Valley. Its propulsion mode is very special. This kind of 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 electric motors symmetrically. Its control system is based on FPGA. The two long-fins constitute robotic fish's propulsion system. As Fig.2 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. Fish body oscillates the ten fin-rays and makes the membrane bend at some waveform when it swims in water. Obviously, the swaying 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, our obstacles avoidance algorithm is based on these four basic modes.

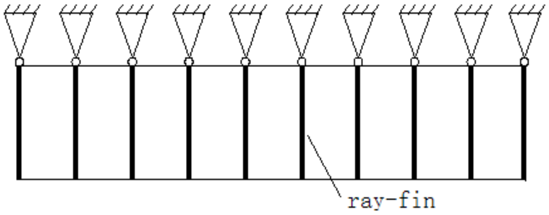

Fig.2. Structure of One Long-fin

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

3. Four Motion Modes of the Robotic Fish

Water is an impressible fluid, so any movements of long-fin will make the fish body in motion. 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.

3.1 Marching Mode

Obviously, the most common and important motion mode is marching mode. According to swimming mode of *Gymnarchus niloticus*, 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 defined as φ. Then,

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

Then traveling of wave in the long-fins is described, as shown in Fig.3. 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

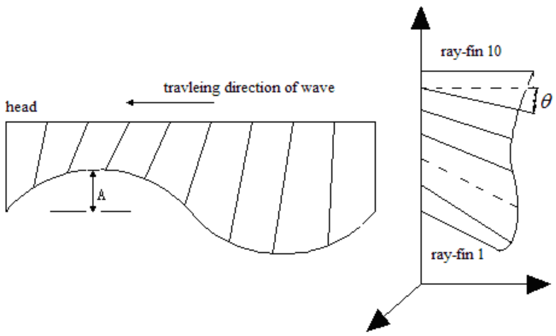

Fig.3. Traveling Wave along the Long-fin

that the 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 motors for the ray-fins. In Fig.3, each ray-fin oscillating function can be calculated. For example, the first ray-fin oscillation equation may be expressed as:

$$\phi_1 = -A_1 \sin(2\pi f t + 0 * \theta) \qquad (2)$$

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 other ray-fin may be expressed as:

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

The robotic fish prototype in this paper has ten ray-fins, so θ is set to $360° / 10 = 36°$. Fig.4 shows the signal output of the ten ray-fins on condition of A_i at 70mm and f at 2HZ. 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. Apparently the thrust makes the robotic fish march forward smoothly.

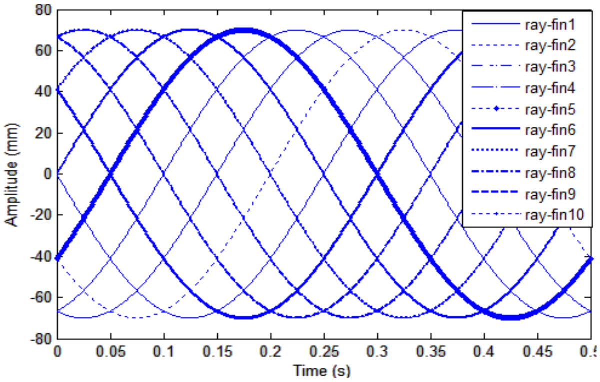

Fig.4. Output Signal of Motors for the Ten Ray-fins.

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.

3.2 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.3 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. So the relevant ray-fins oscillating function is:

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

Receding mode is the opposite motion mode against marching mode.

3.3 Rotating Mode

Rotating mode is another 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 undulates 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.5 shown.

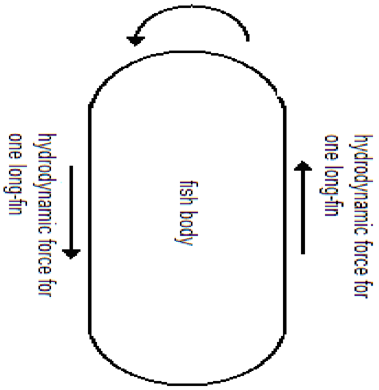

Fig.5. Robotic Fish's Rotary Moment Generating

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 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.6 shows the signal output of the twenty ray-fins 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.

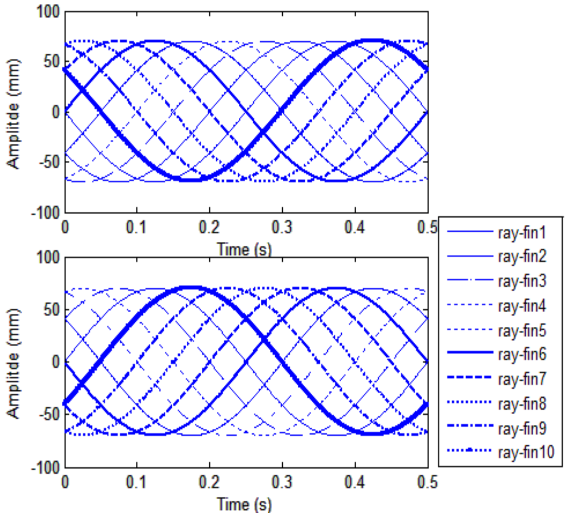

Fig.6. Output Signals for Ten Ray-fins' Motor Control

3.4 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:

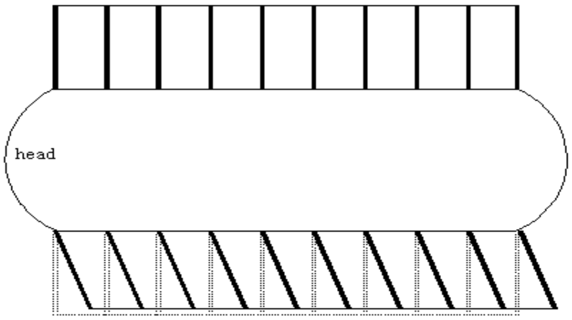

Fig.7. Robotic Fish's Right Side-swaying Motion Mode

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

Fig.7 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.

4. Obstacle Avoidance

In practical applications, obstacle avoidance is a very important part for robots. So detecting obstacles and recognition is indispensable in robotic fish's movement. In common, rocks, walls, plants and other underwater machines are the obstacles to avoid. The walls are the obstacles considered in this paper.

To avoid obstacles, how to find them is the first task. Here, infrared sensors are installed on the robotic fish body and used to detect obstacles, as shown in Fig.1. Infrared sensors are very sensitive with colored obstacles and different color has different effect on them. The emission frequency of the installed sensors is about 38 KHz and the detection distance range is within 1m. The sensor sends infrared signal and get a return signal when there are some obstacles in effective distance. And the robotic fish may give different control commands based on the return signals and execute. But something must be paid attention to. Although the robotic fish has relatively slow velocity, the detected distance between the robot and the obstacle should be long enough for the robotic fish to have enough time to execute its control commands and overcome its inertia.

As mentioned above, four basic motion modes of the robotic fish is analyzed and given. So the obstacle avoidance can be designed based on the basic motion modes. Different returned sensor signals make the robotic fish carry out different basic motion modes.

When the robotic fish finds obstacles on its left side it will stop marching and start right side-swaying until the return signals show no obstacles. In a similar way, it also can avoid obstacles on right side.

Second, when the robotic fish finds obstacles ahead it will stop marching too and begin rotating slowly. There are two rotating mode: left rotating and right rotating. How to choose the two modes is decided by sensor input. Rotating must be very slow because of inertia. Rotating will stop when there are no obstacles ahead.

Finally, if robotic fish enters into a narrow area and obstacles exist in its both sides. It will begin receding until withdrawing the area. Then it begins rotating and chooses right direction.

As shown by Fig.1, our robotic fish have six infrared sensors. Define the front infrared sensor as F, the left front sensor as LF, the right front sensor as RF. In a similar way, define the sensor on the back as B, the sensor on left back as LB, the sensor on right back as RB. And $\overline{X}$ (sensor) means X finds obstacle and X means it don't find obstacles. Aiming at four motion modes, following rule may be gotten.

RULE 1:

if $\overline{B}+\overline{B}\wedge\overline{LB}+\overline{B}\wedge\overline{RB}+F\wedge LF\wedge RF\wedge B\wedge RB\wedge LB$, then marching mode is chosen. Here"$\wedge$" means "AND", "+" means "OR", same below.

RULE 2:

if $\overline{F}+\overline{F}\wedge\overline{RF}$, then left rotating mode is chosen.

RULE 3:

if $\overline{F}\wedge\overline{LF}$, then right rotating mode is chosen.

RULE 4:

if $\overline{LF}\wedge\overline{LB}+\overline{B}\wedge\overline{LF}\wedge\overline{LB}+\overline{F}\wedge\overline{LF}\wedge\overline{LB}$, then left side-swaying mode is chosen.

RULE 5:

if $\overline{RF}\wedge\overline{RB}+\overline{B}\wedge\overline{RF}\wedge\overline{RB}+\overline{F}\wedge\overline{RF}\wedge\overline{RB}$, then right side-swaying mode is chosen.

Here shows the base method for obstacles avoidance. More detailed tactics should be made according to applications and circumstance.

5. Experiments

In a pool with four blue walls around, the experiments are 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) testing the validity of obstacle avoidance algorithm.

Fig.8 is the robotic fish swimming in the pool. There are blue walls around. First, four motion modes experiments were done respectively.

Fig.8. Swimming Robotic Fish in Water

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.

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.

Thirdly, the side-swaying mode experiments are done. The frequency and amplitude parameters are almost same as marching mode. But the observations show that the 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

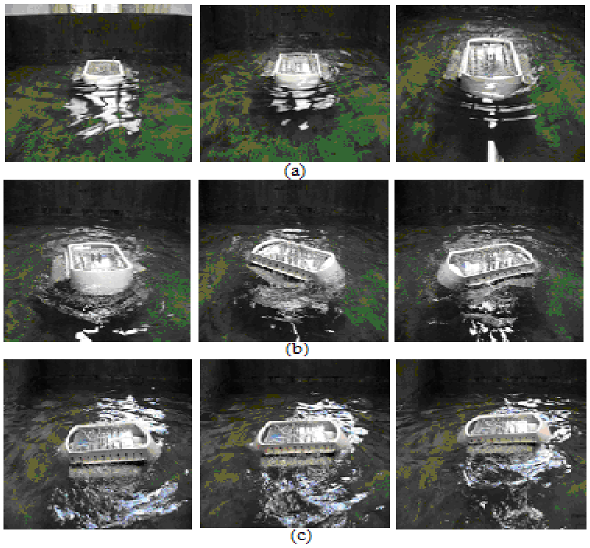

Fig.9. Three motion Modes of Robotic Fish

mode is about 146mm/s and maximum speed is about 214mm/s when the frequency is 1.5Hz and the amplitude is 48.7mm.

Fig.9 shows the experiments of three motion modes respectively. And experiments also show our robotic fish have more flexibility to achieve obstacles avoidance.

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

Table II
Experiment Results

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

Finally, the obstacles avoidance experiment based on switching motion modes is carried out. The sensor's detection distance is set to 250mm and emission frequency is 38 KHz. The experiments show the robotic fish can detect the obstacles and avoid them based on the given obstacle avoidance algorithm. And the experiments also show the robotic fish with two undulating long-fins has high maneuverability and flexibility.

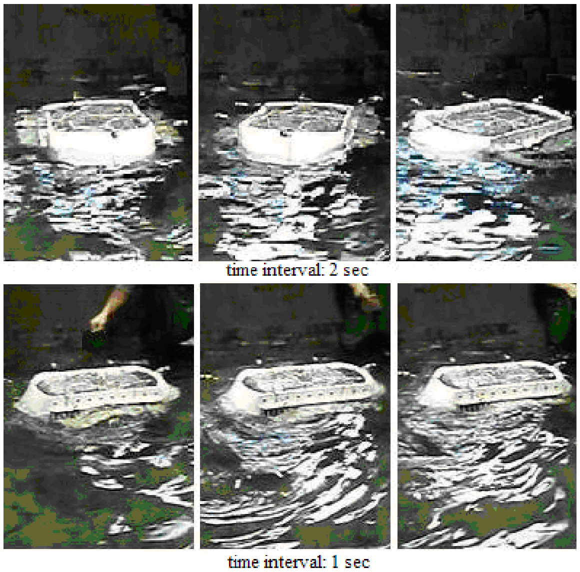

Fig.10 Obstacles Avoidance of Robotic Fish

Fig. 10 shows the experiments of obstacles avoidance. The upper picture group shows that robotic fish changes the marching mode into rotating mode when it encounters obstacles ahead. The lower picture group shows that robotic fish changes the rotating mode into right side-swaying mode when it encounters obstacles on left sides.

6. 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. Based on these basic modes, an algorithm for obstacle avoidance is presented. Based on the sensor inputs, the robotic fish can switch to suitable motion mode to avoid the detected obstacles. The experiments show the performance of the four motion modes of the robotic fish. And the experiments also show the obstacle avoidance algorithm is valid.

Acknowledgments

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