Motion Control Algorithms for a Free-swimming Biomimetic Robot Fish[1)]

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Abstract A practical motion control strategy for a radio-controlled, 4-link and free-swimming biomimetic robot fish is presented. Based on control performance of the fish the fish′s motion control task is decomposed into on-line speed control and orientation control. The speed control algorithm is implemented by using piecewise control, and orientation control is realized by fuzzy logic. Combining with step control and fuzzy control, a point-to-point (PTP) control algorithm is proposed and applied to the closed-loop experimental system that uses a vision-based position sensing subsystem to provide feedback. Experiments confirm the reliability and effectiveness of the presented algorithms.

Key words Biomimetic robot fish, motion control, point-to-point (PTP) control

1 Introduction

In recent years, growing studies on robots either have been used to address specific biological questions or have been directly inspired by biological systems. A variety of biomimetic robots ranging from flying to swimming have been constructed, and some reviews concerning biorobotics research have appeared[1]. Most of swimming robots have been motivated by a desire to create AUVs (autonomous underwater vehicles) with the virtue of efficiency, maneuverability and low noise, but they also have been provided with essential insights into the mechanism and control of fish swimming[2]. In 1994, MIT successfully developed an 8-link, fish-like machine RoboTuna, which maybe originated R&D of robot fish[3]. Since then, based on progresses in robotics, hydrodynamics of fishlike swimming, new materials, actuators and control technology, more and more research has focused on the development of novel fish-like vehicles.

Our objective is to develop preliminary motion control strategy for a robot fish that uses a flexible posterior body and an oscillating foil as propulsor. Since robot fish′s swimming involves hydrodynamics of the fluid environment and dynamics of the robot, precise mathematic model is difficult to establish by purely analytical methods. Considering that the speed of fish′s swimming is adjusted by modulating joint′s oscillating frequency, and its orientation is tuned by different joint′s deflections, consequently, the overall motion control is decomposed into on-line speed control and orientation control.

2 Review of prototype of robot fish

Based on an oscillation model of fish′s propulsive mechanism, a radio-controlled, 4-link and free-swimming biomimetic robot fish mimicking carangiform-like locomotion is developed[4]. The mechanical configuration of the robot fish is shown in Fig. 1 and its photos in Fig. 2. The robot fish primarily consists of five parts: control unit (microprocessor + peripherals), communication unit (wireless receiver), support (aluminum exoskeleton + head + forebody), actuation unit (DC servomotors) and accessories (battery, waterproofed skin, tail fin).

For the robot fish, its speed is adjusted by modulating joint′s oscillating frequency f, and its orientation is tuned by different joint′s deflections $\{\phi_1, \phi_2, \phi_3, \phi_4\}$, where ϕ_1, ϕ_2, ϕ_3 and ϕ_4 are joint angles for 4 links respectively. Hence, a parameters set $\{\phi_1, \phi_2, \phi_3, \phi_4, f\}$ can be used to control fish′s motion. Since the mechanical robot fish is composed of four links, all calculations and experiments in this paper are carried out on a four-link model.

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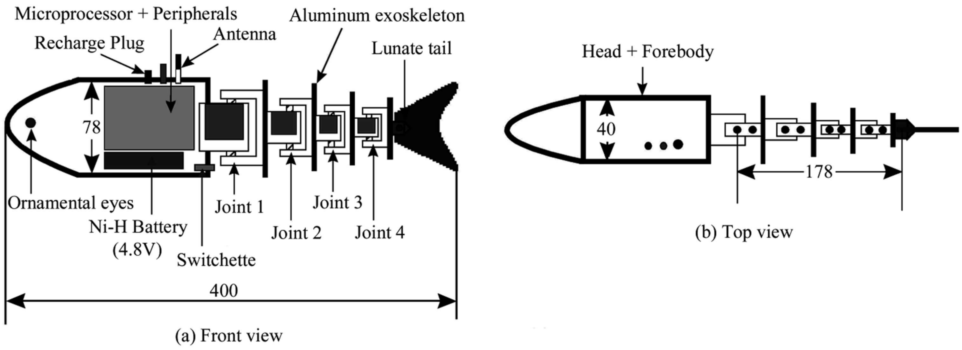

Fig. 1 Mechanical configuration of robot fish

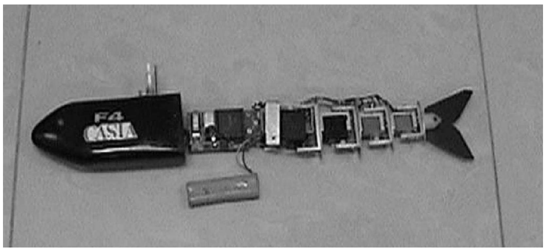

Fig. 2 (a) Outline of non-encapsulated robot fish

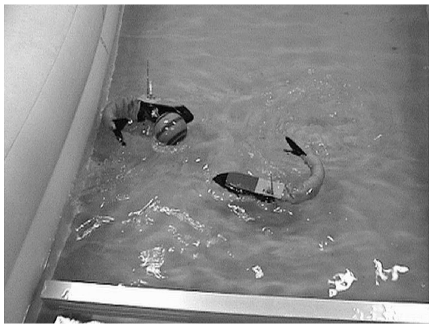

Fig. 2 (b) Robot fishes in playing ball

3 Basic motion control of robot fish

When a robot fish works in water, the regulation of its body speed at the center of mass is realized by solely changing the servomotors′ oscillating frequency. Just for this, there are some unfavorable factors against the robot fish′s speed control. On one hand, the interactions between the fish and surrounding water will result in resonance at a certain resonant frequency, accompanying with the robot′s rolling along its body axis and yawing along the axis perpendicular to the water surface. On the other hand, for the sake of lacking additional stopping mechanism, the fish cannot stop immediately even if the speed of each joint drops to zero. The inertia forces and hydrodynamic forces, in this case, will jointly allow the fish with the stable shape to drift a short distance along the current direction. Without full understanding of hydrodynamic effects on the swimming fish, how to find a tradeoff between swimming speed and hydrodynamic force then becomes a central issue for the fish′s smooth motion.

As exploited in elevator control, an acceptable tradeoff between speed and stress (potential energy) can be achieved by carefully manipulating the moving speed. The fish′s inertia force can be restricted by setting the maximum acceleration to a value of A_m when swimming from a stationary state to the maximum steady speed V_f, at which the rolling and yawing of the fish body are minimum. The steady speed V_f can be determined through a lot of experiments. To ensure the fish motion fast and steady, a fundamental decision is to make it run at $v = V_f$ to the best of its abilities, where v denotes the body speed of a running robot fish. Based upon this choice, holding the acceleration A_m, the fish tries to accelerate to $v = V_f$ as soon as possible, once it started. When the distance between the fish and the goal is less than some threshold, it begins to decelerate with a deceleration $-A_m$ by gradually decreasing oscillating frequency f. And finally, the fish straightens itself and drifts towards the goal with zero-joint-speed by inertial forces, where zero-joint-speed means that all joints stop oscillating and that the corresponding body speed is not necessarily in zero due to hydrodynamic effects. With the assumption that the centers of mass and buoyancy coincide with the origin of the fish coordinate system, the speed profile will be piecewise in terms of the distribution function given by formula (1), and a speed profile like "S" is produced. The overall motion process, as shown in Fig. 3, can be divided into four phases: acceleration phase, constant phase, deceleration phase and drift phase. Different speed strategies are taken at different phases so that the robot fish moves rapidly and steadily. For a given speed, a PID controller is designed for a desired speed, whose sketch is shown in Fig. 4. In particular, when the error e is near zero, PID does not work.

$$V(t) = \begin{cases} 0.5V_f(1-\cos(\pi t/T)), & (0 < t \leqslant T) \\ V_f, & (T < t \leqslant T_d) \\ 0.5V_f(1-\cos(\pi(t-T_d-T)/T)), & (T_d < t \leqslant T_d+T) \\ 0, & (t > T_d+T) \end{cases} \tag{1}$$

where $T = (\pi/2)(V_f/A_m)$, A_m can be determined experimentally in advance.

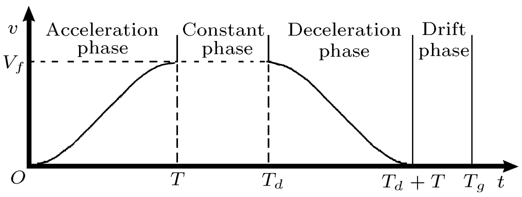

Fig. 3 Speed profile of robot fish

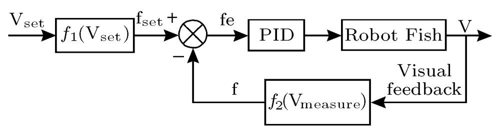

Fig. 4 The structure of PID controller for a desired speed

With regard to the orientation control, a fuzzy logic method is utilized in the implementation. As discussed above, the robot fish can be navigated to the desired position with a certain speed by choosing four proper joint angles $\{\phi_{i1}, \phi_{i2}, \phi_{i3}, \phi_{i4}\}$. The deflections of the joint angles, in the method, are added to the first two joint angles $\{\phi_{il}, \phi_{i2}\}$ so that the fish can turn with different turning radius. The key issue then becomes how to choose suitable deflections in response to environmental changes, which is clearly a hard nut to crack owing to un-modelled uncertainty in fish′s motion. According to the three basic modes for a fish propelled only with oscillating tail fin, which is initially discussed by Hirata *et al*[5], they are redefined as follows. 1) turning during advancing, where the robot fish intentionally deflects its body only to one side by exerting on geometric bias during advance, 2) snap turning, where the fish suddenly bends its body to a "C" sharp and keeps the posture during motion, and 3) turning from rest, where the fish deflects its body only to one side swiftly from a stationary state. Combined with these turning modes, perhaps, path planning can be implemented if having a high quality control system for motion of servomotors. The fuzzy logic algorithm[6] will be used for robot fish′s orientation control. The objective is to make a fuzzy logic controller (FLC) that generates the deflections of the first two joint angles when the fish moves from any initial position to its final position. Essentially, different joint deflections lead to different turning radiuses, and different turning radiuses lead to different angular speed. With proper angular speed, the desired heading of the fish can be achieved. In some sense, the FLC for orientation control is reckoned as a quantitative use of turning mode A.

Fig. 5 shows the structure of FLC for orientation control, which takes two inputs and produces two outputs. Suppose that in a certain instant k, the values for error and change of error are e and ec respectively, which serve as the inputs described by $e_k = r_k - y_k$ and $ec_k = e_k - e_{k-1}$, where r indicates the desired input, namely the desired angle θ_d that the fish should face every instance to approach the destination, y denotes the measured angle by visual subsystem, *i.e.*, the fish′s current angle θ_f. The outputs of the controller are the deflections of the first two joints: u_1 and u_2, which will be used for various orientation adjusting.

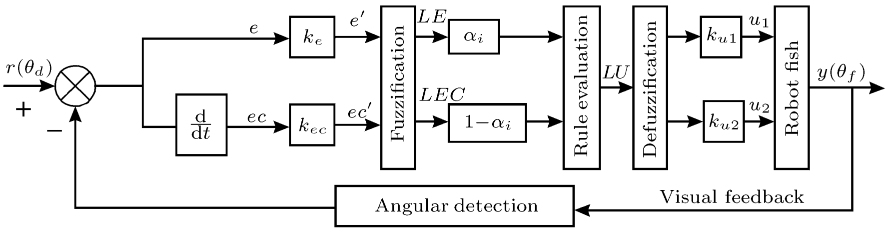

Fig. 5 Structure of FLC for orientation control

4 Point-to-point control algorithm

After discussing some algorithms for the speed and orientation control of our robot fish prototype, we will explore the implementation of steering the fish from an arbitrary initial position to a destination point in 2-D Euclidean space. Notice that the idea of the orientation control is achieved by continuously reducing the angular error in an average sense at the assumption that a possible path connecting the initial point and destination point is a straight line. Also, the fish can only averagely be driven in a straight line by changing the oscillating frequency. Combined the speed control and orientation control, a straight-line-based motion is consequently achieved.

In order to realize the PTP control of the robot fish, the strategy we choose is to get rid of the error of the orientation between the fish body and the line from the initial point (Fx, Fy) to the destination point (Px, Py) while advancing along the specified line. An ideal PTP unit position vector ($\boldsymbol{V}_{PTP}$) is given by

$$\boldsymbol{V}_{PTP} = \frac{1}{\sqrt{(\mathrm{Px}-\mathrm{Fx})^2+(\mathrm{Py}-\mathrm{Fy})^2}}\begin{bmatrix}\mathrm{Px}-\mathrm{Fx}\\ \mathrm{Py}-\mathrm{Fy}\end{bmatrix} \tag{2}$$

where the coordinate pair (Px, Py) specifies the position of the destination of the fish, the coordinate pair (Fx, Fy) is the current fish position. These positional variables and orientation are defined by the vision subsystem.

On the basis of piecewise control, as shown in Fig. 6, different strategies are chosen according to different distance (l) between the fish body and the destination point. The measure being taken is from crude to fine. If $l > L_d$, the fish speeds up to approach the destination; if $L_s < l < L_d$, when the fish is in motion, accurate control is employed, that is, it slows down and approaches within a certain orientation error; otherwise, it approaches with a nonzero low speed V_s; if $l < L_s$, when the fish is in motion, it stops oscillation and straightens itself, then drifts onwards with zero-joint-speed; otherwise, it approaches at $v = V_s$. Once overshot, special measures will have to be taken. Finally, a steering function *MoveToGoal* is designed and applied to the following experiments.

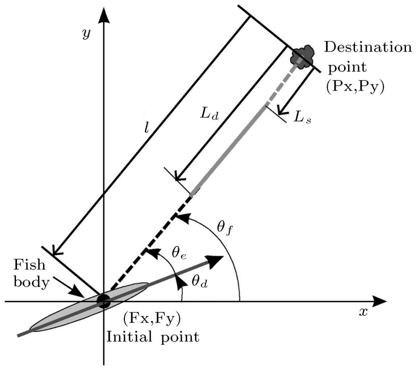

Fig. 6 Decomposition of PTP control

5 Experimental system and relating results

To verify the feasibility and reliability of algorithms, an experimental robot fish system has designed and developed. The system is composed of four subsystems: robot fish subsystem, vision subsystem, decisions-making subsystem and communication subsystem. All aquatic experiments presented in this paper are carried out in a 2000mm×1150mm pond with still water. The information of fishes and their surrounding captured by an overhead CCD camera, is effectively processed and sent to the decision-making module as input, then output of decision-making subsystem is transmitted to the single robot fish through the communication subsystem, thus robot fishes work effectively. In our vision subsystem, robot fishes, ball, and obstacles are in specified colors. To locate robot fish and other objects quickly and accurately, a parallel visual tracking algorithm based on color information has developed, mainly by adaptive segmentation and a closure operation[7]. In particular, the visual tracking is performed in real-time, and provides a feedback signal to robot fish control.

Using the vision-based tracking system to provide real-time feedback, we perform an experiment of playing-ball designed to evaluate our control strategies. In the pond with still water, a floating ball (radius 45mm) is regarded as a target, and the robot fish swims to the ball from an arbitrary initial position and orientation. The fish (Fx, Fy, θ_f) and the ball (Px, Py) are located by the vision subsystem. By calling the steering function *MoveToGoal* continuously, the fish swims toward the ball, and sometime pushs it. Because ball is too light to remain still, the fish looses it and pushs it again just like playing a game. This can be considered that the fish tracks the floating ball continuously. Fig. 2 (b) shows a photo of the experimental scenario during the game, Fig. 7 (a) shows a moving trajectory of the fish swimming towards the ball, where the positions of fish and ball are denoted in image plane coordinates in which the whole view field is a plane with 320×l240 pixels, Fig. 7 (b) shows the corresponding orientation difference θ_e, where the characteristic points are sampled at a interval of 0.3 seconds.

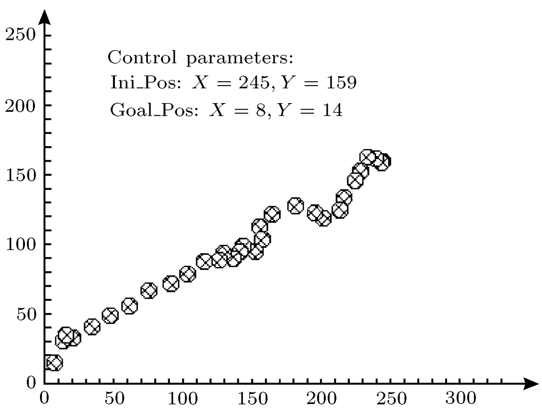

Fig. 7 (a) Moving trajectory

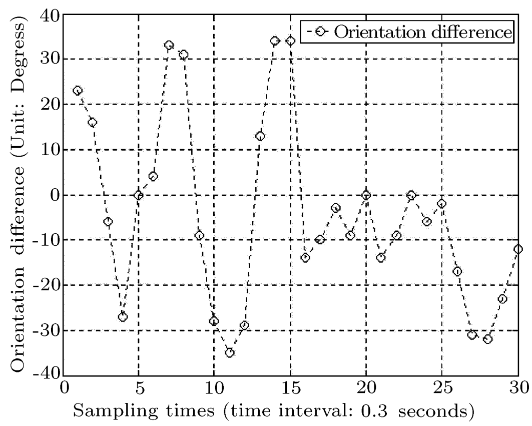

Fig. 7 (b) Orientation difference

6 Conclusion

We have developed an experimental system for closed-loop control of a 4-link and free-swimming biomimetic robot fish. The speed of the fish is adjusted by modulating the joint′s oscillating frequency, and its orientation is tuned by different joint′s deflections. Therefore, the fish′s motion control task, based on control performance of the fish, is decomposed into on-line speed control and orientation control. We have proposed an algorithm for speed control, and designed a fuzzy logic controller for orientation control. On the basis of speed and orientation control, a point-to-point control algorithm is realized. Experiments with this system have demonstrated the good performance of the robot fish using vision-based position sensing feedback.

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