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A Miniature Biomimetic Robotic Fish and Its Realtime Path Planning^{*}

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Summary. This paper proposes a novel miniature biomimetic robotic fish based on single link with compact structure, high maneuverability and multiple sensors. The robotic fish mimics the motion of Thunniform mode, and the methods of propelling and turning are given. The information provided by infrared sensors and photosensitive sensors are analyzed and applied to the algorithms of obstacle avoidance, the light source searching and the dynamic light source tracking. Experimental results are given to show the motion ability and the validity of the proposed algorithm.

1 Introduction

There are more and more productive underwater activities and research work, and the Autonomous Underwater Vehicle (AUV) is paid more attentions on. Fish exhibit the advantages of the high efficiency, high maneuverability and low noise, which has the advantages over conventional marine vehicles powered by rotary propellers with the same power consumption. Roboticists explore robotic fish to develop small-size, efficient, maneuverable, and low noise AUV.

Investigation on biomimetic robotic fish systems has provided significant insights into both theory and application of robotics in recent years, whose appealing nature involves higher efficiency, more remarkable maneuverability and quieter actuation[1][2]. These advantages are of great benefit to applications in marine and military fields. Many theories are proposed to explore secrets of fish swimming mechanisms and summarize driving modes of fish motions [3]-[5]. Based on these theories, many prototypes of biomimetic robotic fish have been developed [1] [6]-[9].

Considering that there are some special occasions under the water, such as pipelines, gaps, the development of miniature robotic fish with high maneuverability and adaptability is of great advantages. On the other hand, the

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miniature robotic fish is cheap enough to be mass-produced, which may enhance the quality of the solution by cooperation among them. The miniature robotic fish should be elaborately designed because all the mechanical structures, control units, sensors, communication module and power supply are integrated into a very limited space, which brings new challenge.

There are some miniature robotic fish prototypes. Some of them utilize new materials as the actuators, such as ICPF, which can reduce the volume largely. However, the power dissipation is so much that the power source should be outside [7] [10], which will restrict the robotic fish's motion greatly because of the power line. Some miniature swimming robots are designed for special purposes, and the motion ability is suitable for special environment, for example, for the medical purposes [11], but it may not adapt the general task.

In this paper, the design of a miniature biomimetic robotic fish is given based on single link undulating, which is only 15 centimeters long. The method of propelling and turning are proposed based on the motion law of Thunniform mode. The robotic fish may execute tasks independently and autonomously. The algorithms of obstacle avoidance and light source tracking based on the infrared sensors and photosensitive sensors are introduced.

2 The design of the robotic fish and motion control

2.1 The structure of the robotic fish

According to the wavelength and the amplitude envelope of the propulsive wave underlying fish's behavior, the fish is divided into five different modes: *Anguilliform mode*, *Subcarangiform mode*, *Carangiform mode*, *Thunniform mode*, *Ostraciiform mode* [12].

Thunniform mode is by far the most efficient locomotion mode evolved in the aquatic environment, where thrust is generated with a lift-based method, allowing high cruising speeds to be maintained for long periods. Significant lateral movements occur only at the caudal fin (producing more than 90% of the thrust) and at the area near the narrow peduncle. In addition, the reduction of the length of the undulating part will simplify the structure, and reduce the volume on the whole. A novel Thunniform mode-based miniature robotic fish is designed, as shown in Fig.1. A servo motor is adopted to drive a lunate caudal fin as the propeller of the robotic fish, according to fish outline and its motion characteristics. The servo is agile and controllable in movement without additional driver, and more energy is saved than that of the driving unit adopting some new materials such as SMA.

Because of the volume restriction, all assembly units are highly cost-effective ones. The forebody is fish-shape thin hard plastic and a servo is fixed on it. The controller integrates the functions of information acquisition and processing, communication, control and motion decision to improve the

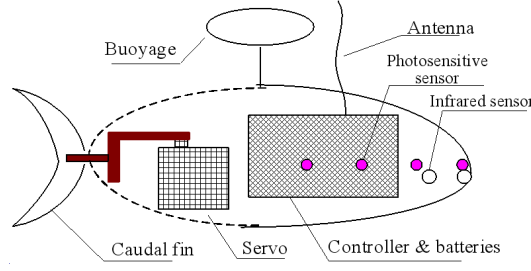


Fig. 1. The schematic structure of the robotic fish

integration level and reduce the volume and power dissipation. The tail is covered by thin flexible rubber film as waterproof, which has little effect on the undulating. The wireless signal is sent by an antenna out of the water. The Li-Polymer Batteries are chosen for the high energy density. In the system of sensors, the infrared switch sensors are selected instead of the sonar sensors because of the volume. The average density of the robotic fish except the buoyage is made a little higher than water by fixed weight on bottom, and the robotic fish will float on water with the buoyage so that all the body is under water, which is favourable to the propelling and stability.

2.2 The structure of the robotic fish

Thunniform mode motion involves the undulation of the entire body, whose large amplitude undulation is mainly confined to the last 1/3 part of the body. A Thunniform propulsive model is given to describe the motion in the frame of polar coordinate for caudal motion as shown in Fig.2.

$$A_{body}(t) = Amp \cdot \sin(\omega t) \quad (1)$$

where the A_{body} is the realtime angle of the tail, Amp is the undulation amplitude, ω is the frequency of the wave ($\omega = 2\pi f = 2\pi/T$).

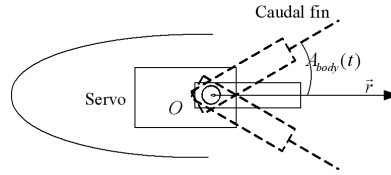


Fig. 2. The polar coordinate for caudal motion

(1) provides a method to design the robotic fish: choose the parameters including Amp , ω , to determine the proper body wave and then develop a

mechanical structure to fit the curve so that the fish's locomotion may be emulated. Discrete (1), then we have:

$$A_{body}(i) = Amp \cdot \sin(\frac{2\pi}{M}i) \quad (2)$$

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.

The interval of time and the movement distance between every two points is restricted by the maximum angle velocity and amplitude of the servo, which is described as follows.

$$\begin{cases} \max\{|A_{body}(i) - A_{body}(i-1)|\} \cdot f \cdot M < \Omega_{\max} \\ A_{body}(i) \leq Amp_{\max} \end{cases} \quad 1 \leq i \leq M \quad (3)$$

where $\Omega_{\max}, Amp_{\max}$ are the maximum angular velocity and amplitude respectively. $\max\{A_{body}(i)\} \leq Amp$, so Amp is proportional to $\max\{|A_{body}(i) - A_{body}(i-1)|\}$ with M being constant. Let:

$$Amp = c \cdot \max\{|A_{body}(i) - A_{body}(i-1)|\} \quad (4)$$

Then the constraint equations between the Amp and f are obtained:

$$\begin{cases} Amp \leq Amp_{\max} \\ f \leq c\omega_{\max} / (M \cdot Amp) \end{cases} \quad (5)$$

The turn of the fish, according to the observation, is implemented by changing the axis of the body undulation. Based on it, the direction of the robotic fish may be controlled. A certain angle is superposed on the caudal fin. It is necessary to insure that the undulating rule marches (2) when turning, Rewriting (2), we have:

$$A_{body}(i) = Amp \cdot \sin(\frac{2\pi}{M}i) + A_{turn} \quad (6)$$

where A_{turn} is the deflection angle of the caudal fin. This turning method is used in continuing, stable turning in the movement. The motion of servo should also fit the constraint of (3)

3 The realtime path planning based on sensors information

The path planning is necessary for the robotic fish to complete the task. Considering that the limitation of the volume, infrared sensors are chosen to detect the obstacle, and the photosensitive sensors to detect the light source. Firstly, the inertial frame of reference for the motion is defined as shown in Fig.3. O is the center of inertia of the robotic fish, and is the direction of the rigid forebody.

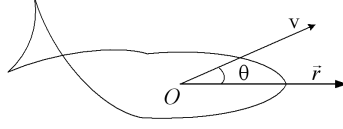


Fig. 3. The inertial frame of reference

The motion state of the robotic fish $S_{jatt=j}$ includes the velocity and direction, which is shown in (7).

$$S_j = [v_j, \theta_j]^T \quad (7)$$

We denote with F the motion function and we have:

$$S_j = F(S_{j-1}, \dots, S_{j-n}, Act_j) \quad (8)$$

where Act_j is the action of the robotic fish $att = j$,

$$Act_j = [Amp, f, A_{turn}]_j^T \quad (9)$$

It means that the action of robotic fish includes the frequency, amplitude, and deflection angle. The C-turn is not involved because it is not suitable for the path planning. In the implementation, all the three parameters are discrete and numbered, and the sets of them are $\{Amp^n\}$, $\{f^m\}$, $\{A_{turn}^l\}$, so the Act is numbered, therefore, all the action of the robotic fish is:

$$\Phi_{act} = \{Act \mid Amp \in \{Amp^n\}, f \in \{f^m\}, A_{turn} \in \{A_{turn}^l\}\} \quad (10)$$

3.1 The algorithm of obstacle avoidance

Three infrared sensors are installed on the robotic fish, the output of them are Boolean variables and labeled as Ir_l (left), Ir_m (middle), Ir_r (right). '1' means there is obstacle. The distribution of the sensors is shown in Fig.4. θ is the angle between the velocity v and r . α_r , α_m and α_l are the detecting directions of three sensors, respectively.

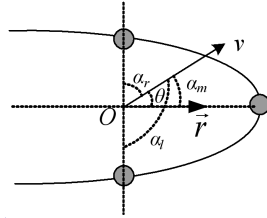


Fig. 4. The distribution of infrared sensors

The purpose of avoiding obstacle algorithm is to select the safest direction for robotic fish. The risk factor function $att = j$ is defined as follows:

$$\begin{aligned} Risk_j &= -(Ir_{l,j} \cdot \alpha_{l,j} + Ir_{m,j} \cdot \alpha_{m,j} + Ir_{r,j} \cdot \alpha_{r,j}) \\ &= -[Ir_{l,j} \cdot (90^\circ + \theta_j) + Ir_{m,j} \cdot |\theta_j| + Ir_{r,j} \cdot (90^\circ - \theta_j)] \end{aligned} \quad (11)$$

The smaller $Risk_j$ is, the smaller the collision probability of robotic fish is. So the algorithm is to calculate the robotic fish action $att = j + 1$, $Act_{j+1}^* = [Amp^*, f^*, d_{turn}^*]^T$, which satisfy:

$$\begin{aligned} &\min_{Act_{j+1} \in \Phi_{act}} \{Risk_{j+1}\} \\ &= \min_{Act_{j+1} \in \Phi_{act}} \{-[Ir_{l,j+1} \cdot (90^\circ + \theta_{j+1}) + Ir_{m,j+1} \cdot |\theta_{j+1}| + Ir_{r,j+1} \cdot (90^\circ - \theta_{j+1})]\} \end{aligned} \quad (12)$$

The information of sensors, $Ir_{l,j+1}$, $Ir_{m,j+1}$ and $Ir_{r,j+1}$ are unknown $att = j$, so the values $att = j$, $Ir_{l,j}$, $Ir_{m,j}$ and $Ir_{r,j}$ are accepted for estimation. Thus,

$$Act_{j+1}^* = \arg \min_{Act_{j+1} \in \Phi_{act}} \{-[Ir_{l,j} \cdot (90^\circ + \theta_{j+1}) + Ir_{m,j} \cdot |\theta_{j+1}| + Ir_{r,j} \cdot (90^\circ - \theta_{j+1})]\} \quad (13)$$

3.2 The algorithm of light source searching

There are seven mini photosensitive sensors installed on the rigid forebody, and the distribution of the sensors is shown in Fig.5

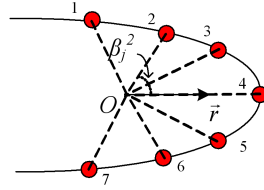


Fig. 5. The distribution of the photosensitive sensors

Label β_j^k as the detecting directions of the k^{th} sensor at $t = j$, as β_j^2 shown in Fig.5. The light intensity detected by the k^{th} sensor is labeled as I_k and the direction of the light source is calculated as follows:

Firstly, obtain maximum value of I_k :

$$I_{\max} = \max_{1 \leq k \leq 7} \{I_k\} \quad (14)$$

If $I_{\max} < I_{env}$, it means that there are no light sources, where I_{env} is the light intensity of environment.

else

$$K = \arg \max_{1 \leq k \leq 7} \{I_k\} \quad (15)$$

Secondly, determine the direction of the light source at $t = j$:

$$\beta_j^* = \frac{\sum_{k=K-1}^{k=K+1} (I_k - I_{env}) \cdot \beta_j^k}{\sum_{k=K-1}^{k=K+1} (I_k - I_{env})} \quad (16)$$

From (16), it is seen that only K^{th} , $(K-1)^{th}$, $(K+1)^{th}$ sensors are considered because the robotic fish body rocks about when it swims, and the detecting for the light intensity is disturbed. Define the photokinesis function:

$$Light_j = |\theta_j - \beta_j^*| \quad (17)$$

Thus, the photokinesis action for the robotic fish at $t = j + 1$ is:

$$\begin{aligned} Act_{j+1}^* &= \arg \min_{\forall Act_{j+1} \in \Phi_{act}} \{Light_{j+1}\} \\ &= \arg \min_{\forall Act_{j+1} \in \Phi_{act}} \{|\theta_{j+1} - \beta_{j+1}^*|\} \end{aligned} \quad (18)$$

As well, β_{j+1}^* are not known at $t = j$, and β_j^* is introduced as the estimation. We have:

$$Act_{j+1}^* = \arg \min_{\forall Act_{j+1} \in \Phi_{act}} \{|\theta_{j+1} - \beta_j^*|\} \quad (19)$$

3.3 The algorithm of dynamic light source tracking

In actual task, the goal (light source) is usually dynamic, which means the robotic fish has to track light source while avoiding obstacles. When the robotic fish is close to the light source, which is both the goal and obstacle, the corresponding conflict should be considered. Because of the limited information, the robotic fish can not distinguish the obstacle and moving light source. Therefore, a multiple objectives optimization approach with self adaptive weight is proposed to solve this problem. The action of the robotic fish is decided by both the infrared sensors and photosensitive sensors:

$$\begin{aligned} Act_{j+1}^* &= \arg \min_{\forall Act_{j+1} \in \Phi_{act}} \{M_1 \cdot Light_{j+1} + M_2 \cdot Risk_{j+1}\} \\ &= \arg \min_{\forall Act_{j+1} \in \Phi_{act}} \{M_1 \cdot |\theta_{j+1} - \beta_{j+1}^*| \\ &\quad - M_1 \cdot [Ir_{l,j+1} \cdot (90^\circ + \theta_{j+1}) + Ir_{m,j+1} \cdot |\theta_{j+1}| + Ir_{r,j+1} \cdot (90^\circ - \theta_{j+1})]\} \end{aligned} \quad (20)$$

where M_1 and M_2 are the weights of the photosensitive sensors and infrared sensors, respectively. As well, β_{j+1}^* and $Ir_{l,j+1}$ are replaced by the estimated values, and we have:

$$Act_{j+1}^* = \arg \min_{\forall Act_{j+1} \in \Phi_{act}} \{M_1 \cdot |\theta_{j+1} - \beta_j^*| - M_1 \cdot [Ir_{l,j} \cdot (90^\circ + \theta_{j+1}) + Ir_{m,j} \cdot |\theta_{j+1}| + Ir_{r,j} \cdot (90^\circ - \theta_{j+1})]\} \quad (21)$$

M_1 and M_2 are decided based on actual application. In the light tracking, it can be self adapted according to light intensity. When the light is weak, the robotic fish is far from the light source. If obstacle is detected, the algorithm of obstacle avoidance should be validated and $M_1 > M_2$ in this case. When the light intensity is high, the obstacle detected may be the light source, thus $M_1 < M_2$. When the light is very high, it means that the robot is very close to the goal, and the obstacle avoiding should be validated to avoid the collision with light source, therefore we have $M_1 > M_2$. In the experiment, we choose a piecewise function:

$$M_1 = \begin{cases} 2 & I_{\max} < I_a \\ 0.5 & I_a < I_{\max} < I_b \\ 2 & I_{\max} > I_b \end{cases} \quad (22)$$

$$M_2 = 1$$

where I_a and I_b are the thresholds of light intensity, which are decided by the light source.

4 Experiments

The developed robotic fish prototype is shown in Fig.6.

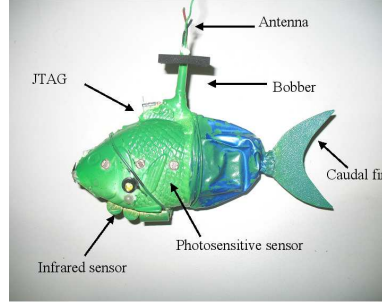


Fig. 6. The prototype of the robotic fish

The experiments are conducted in an experiment pool of 1.80m*1m to testify the miniature biomimetic robotic fish. An overhead camera is introduced

to capture the video of the robotic fish motion and the video information is sent to the computer to recognize and record the realtime position of the robotic fish by the help of a platform for the motion control of robotic fish, MRFS (Multiple Robot fishes coordinate System). The top right part shows the result of the recognition. The position data is filtered, and the movement track is got by Least-squares spline approximation. The relative parameters are then calculated.

Experiment 1: Testing the velocity

According to the law in (2) and the constraint of (5), the velocity at different frequencies and amplitudes are measured in detail. The results are shown in Fig.7. The maximal velocity is $v=7.63\text{cm/s}$.

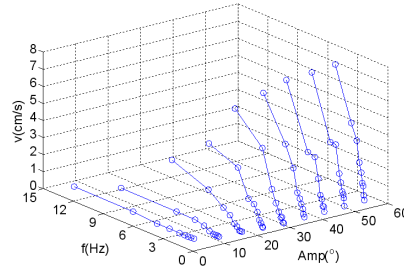


Fig. 7. The velocity at different frequencies and amplitudes

Experiment 2: Dynamic light source tracking

Firstly, the motion function $F(*)$ is built as a look-up table. The results of (21) are calculated offline and stored in the MCU. A light source moves randomly in the pool, and the robotic fish is put away from the light source. The trajectories are shown in the following:

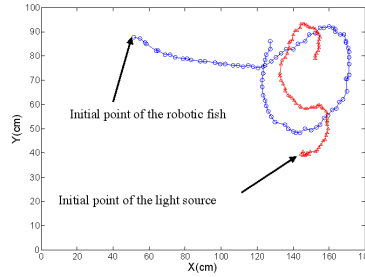


Fig. 8. The series of dynamic light source tracking

where ' Δ ' is the trace of the light source, and 'O' is the trace of robotic fish. X and Y in the figure are the edges of the pool which is regarded as obstacles in this experiment. From the figure, the robotic fish traces the light source without collision with the light source or pool edges.

5 Conclusion

In this paper, a miniature biomimetic robotic fish is given, which reduces the volume of the robotic fish largely. The method of propelling, turning, and C-turning for the robotic fish is proposed based on the motion law of Thunniform mode. The realtime path planning is given based on the sensors information. Experiments validate the design and algorithms.

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