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A Marsupial Robotic Fish System

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Abstract: A marsupial robotic fish system including a mother robotic fish and a daughter robotic fish is proposed. The mother robotic fish, with strong ability of movement, can transport the daughter robotic fish in its cabin. The structures of these two robotic fish are presented and fish-like motions are introduced. A dynamic light source tracking method of the daughter robotic fish is given to follow the mother, and a heterogeneous communication-based finite state machine is presented for the cooperative task modeling. Experiments are carried out to verify the system.

1. INTRODUCTION

Robotic fish has received much attention, under the category of biology-inspired swimming robots, whose appealing nature involves higher efficiency, more remarkable maneuverability, and quieter actuation than conventional underwater vehicles equipped with thrusters (M J. Lighthill, 1971; M. Sfakiotakis, et al. 1999; M. S. Triantafyllou and G. S. Triantafyllou, 1995). These advantages are of great benefit to applications in marine and military fields such as underwater operation, military reconnaissance, leakage detection, and so forth. Biomimetic robotic fish is generally defined as a fish-like aquatic vehicle based on the swimming skills and anatomic structure of a fish: the undulatory/oscillatory body motions, the highly controllable fins and the large aspect ratio lunate tail.

The robotic fish are expected to work in the unreachable place for human being, such as the gap of underwater rock, the inside of oil pipeline and the interior of sunken ship. The development of miniature robotic fish with high maneuverability and adaptability is of great advantages. On the other hand, the miniature robotic fish is cheap enough to be mass-produced, which may enhance the quality of the solution by cooperation among them. Although miniaturization of the robotic fish is useful in some special situation, the strict volume limit makes the development difficulty. The simplification of the structure reduces the ability of movement, the reduction of the battery capacity cuts down the endurance time, and the lack of sensors makes the robotic fish be short of means to detect surroundings.

Inspired by marsupial animals, e.g. kangaroo and the former relative works of marsupial and shape-shifting robots for urban search and rescue (R. Murphy, 2000; B. Minten, R. Murphy, et al. 2001), a heterogeneous marsupial robotic fish system is proposed in this paper for the purpose of resolving contradictions of applications. This system is composed of a mother robotic fish (MRF) with a cabin for a miniature robotic fish, as a daughter robotic fish (DRF). MRF can load with DRF and move together to the designated workplace, release it, and assist it with the task. In this heterogeneous system, MRF can swim with long endurance, strong ability of movement and may mounted more sensors, which compensate shortages of the miniaturization of DRF.

MRF is a *Carangiform-mode* robotic fish with a cabin and multiple-link tail. DRF is a *Thunniform-mode* miniature robotic fish based on single link and it is mounted several infrared sensors and light intensity sensors to detect the underwater surroundings. Based on the undulation propelling, a sensor-based dynamic light source tracking method is proposed, which is used for the cooperation in the process of deployment. A heterogeneous communication-based finite state machine (HCFSM) is given to model the task, such as deployment and follow, of the heterogeneous robotic fish cooperation.

The rest of the paper is organized as follows. The structure of the marsupial robotic fish system is introduced in Section II. Section III describes the cooperation method of MRF and DRF. Experimental results are given in Section IV and Section V concludes the paper.

2. THE MARSUPIAL ROBOTIC FISH

As shown in Fig. 1, it is the simplified diagram of the marsupial robotic fish structure. DRF is involved in the cabin. The cabin is openable and the daughter robotic fish can swim out of MRF by itself. MRF may be the information relay between DRF and the upper console to exchange the information. MRF and DRF may cooperate with each other to accomplish the assigned task.

The communication between the upper console and MRF, MRF and DRF is through the wireless on the water. The light source on MRF provides the relative location for DRF. DRF gets the information of the obstacle and the position of the light source from the infrared sensors and the light density sensors, respectively.

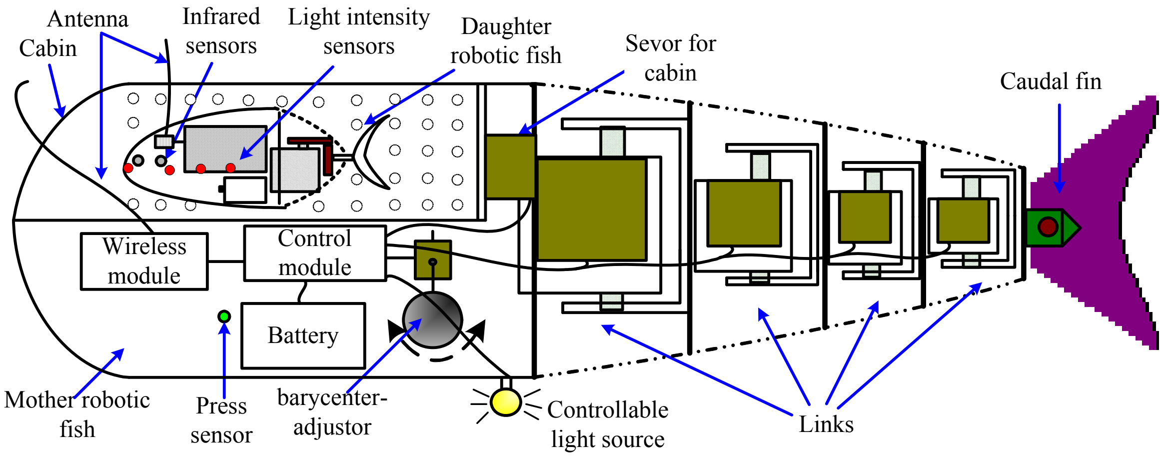

Fig. 1. The structure of the marsupial robotic fish

The mother robotic fish is proposed to transport DRF to cover its shortage of motion ability. The *Carangiform mode* (C. M. Breder, 1926) is chosen as the natural prototype, as shown in Fig. 1. Four links swing with the caudal fin to propel the robotic fish forward like the spine and tail of fish. The control module, the communication module, the battery and other devices are installed in the head.

The method of *changing the barycenter* (C. Zhou, Z. Cao, et al. 2006) is selected to implement three-dimensional locomotion. The fish robot can adjust the body's pitching angle at rest, or ascend/descend with suitable swimming speed by moving the inside weight. A pressure sensor is installed on the side to measure the water pressure as a feedback to the control module for depth control with some control method (C. Zhou, S. Wang, et al. 2006). A cabin on MRF is designed for loaded DRF in it, which is composed by two hatch cover controlled by a servo.

The control laws of the propulsive system have been made an extensive study (J. Yu, et al. 2004; C. Zhou, S. Wang, et al. 2006). The body-tail undulation is assumed to be a traveling wave, which travels from the head to the tail, gradually increasing amplitude. Lighthill (1971) suggested the undulatory motion take the form of (1).

$$y_{body}(x,t) = [(c_1 x + c_2 x^2)][\sin(kx + \omega t)] \quad (1)$$

where y_{body} is the transverse displacement of body; x is the displacement along main axis. k, λ, c_1, c_2 and ω are the body wave number, the body wave length, the linear wave amplitude envelope, the quadratic wave amplitude envelope and the body wave frequency .Once parameters (c_1, c_2, k, ω) are chosen, Equation (1) is discretized. Then the swimming gaits for the multi-link mechanism are calculated (J. Yu, et al. 2004). The propulsive system is controlled based on the swimming gaits to generate propulsion. And the fish robot speed can be adjusted by the frequency and amplitude of the body-tail undulation, or the length of the body-tail undulatory part. The real fish change their swimming orientation by body bending, pectoral fins, or the coordination of the tail and pectoral fins. With respect to the multi-link structure, its yawing control is realized by body bending that the fish robot adds different deflection for each link to curve its body.

DRF is a Thunniform-mode-based miniature robotic fish, as shown in Fig. 1. *Thunniform mode* is one of the most efficient, where thrust is generated with a lift-based method, allowing high cruising speed to be maintained for long periods. Significant lateral movements occur only at the caudal fin. In addition, the reduction of the length of the undulating part will simplify the structure, and reduce the volume on the whole.

A servo motor is adopted to drive a lunate caudal fin as the thruster of the robotic fish, according to fish outline and its motion characteristics (C. Zhou, Z. Cao, et al. 2007). All assembly units are highly cost-effective ones because of the volume restriction. The controller integrates the functions of information acquisition and processing, communication, motion decision and control. In addition infrared sensors were selected, instead of the sonar sensors to minimize volume. Light density sensors are mounted on the robot for the detecting the light source.

A Thunniform propulsive model is given to describe the motion in the frame of polar coordinate for caudal motion as shown in Fig.2.

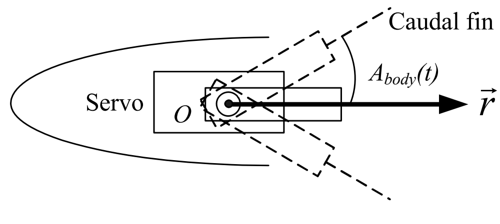

Fig. 2. The polar coordinate for caudal motion

$$A_{body}(t) = Amp \cdot \sin(2\pi f t) \quad (2)$$

where the A_{body} is the real-time angle of the tail, *Amp* is the undulation amplitude, and *f* is the frequency of the wave.

Equation (2) provides a method to design the robotic fish: choose the parameters *Amp* and *f* to determine the proper body wave and then make the mechanical structure to fit the curve, so that the fish's locomotion may be emulated. The turn of the fish is also implemented by changing the axis of the body undulation. Rewriting (2), we have:

$$A_{body}(i) = Amp \cdot \sin(2\pi ft) + A_{turn} \tag{3}$$

where A_{turn} is the deflection angle of the caudal fin.

3. THE COOPERATION OF MRF & DRF

In order to cooperate MRF with DRF effectively, an elaborate design should be required. In this paper, we address specific issues related to the problem of Daughter-Mother following, which requires that DRF firstly swims out the cabin of MRF, finds and tracks the dynamic light source on MRF, and finally follows the motion of MRF. Before modelling the Daughter-Mother following, a multiple objectives optimization based dynamic light source tracking method of the daughter robotic fish is given firstly.

The dynamic light source tracking method for DRF is given by the former works (C. Zhou, et al. 2007).

In the following, a heterogeneous communication-based finite state machine is proposed to model the Daughter-Mother following task. The basic idea is to decompose the task into several states and transit the states according to the information from sensors and communication, which is shown in Fig. 3. The detailed description is as follows.

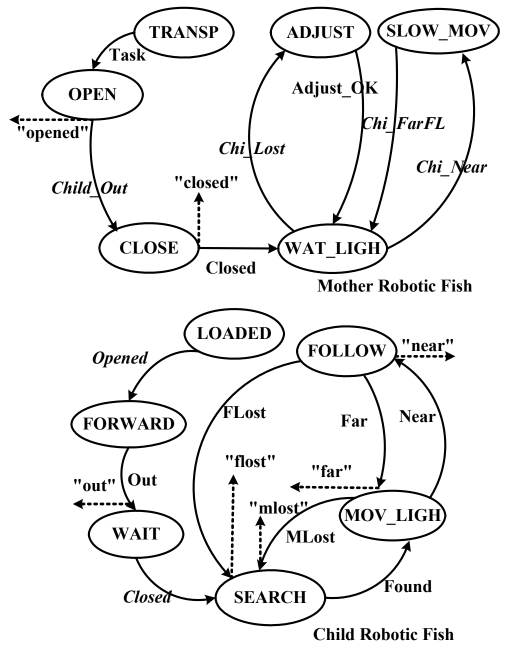

Fig. 3. The heterogeneous communication-based finite state machine. The solid line is the transition of states, and the dotted line is sending the message.

The states of MRF:

TRANSP: MRF moves with DRF in its cabin.
OPEN: MRF stops and opens the cabin.
CLOSE: MRF closes the cabin.
WAT_LIGH: MRF turns on the light.
ADJUST: MRF propels and turns with a slight motion to adjust the position of MRF a little.
SLOW_MOV: MRF advances slowly (equal to the max velocity of DRF approximately) after it confirms to establish the connection with DRF.

Trigger conditions of MRF's state:

Task: The task starts.
Chi_Out: DRF has been out of the cabin, which means MRF has received "out" from DRF.
Chi_Lost: DRF has not found the light source (MRF), it is "mlost" or "flost".
Adjust_OK: MRF has finished the adjustion.
Chi_FarFL: MRF has received "far" or "flost", which shows DRF is far away or lost when following.
Chi_Near: DRF is near the MRF, which is "near" from DRF.

The message sent out by MRF:

"opened": The cabin has been opened.
"closed": The cabin has been closed.

The states of DRF:

LOADED: DRF is in the cabin and stops.
FORWARD: Swimming forward.
WAIT: Stop and wait.
SEARCH: Search light source at random.
MOV_LIGH: Move to the light source with $M_1=1$ and $M_2=0$ (C. Zhou, et al. 2007).
FOLLOW: Follow the light source

Trigger conditions of DRF's state:

Opened: The cabin has been opened, which means that DRF has received "opened" from MRF.
Closed: The cabin has been closed which is "closed" from MRF.
Out: DRF has been out of the cabin.
Found: DRF has found MRF
Far: DRF is far away from the light source.
Near: DRF is near to from the light source.
MLost: DRF can not find the light source when moving to the light source.
FLost: DRF can not find the light source when following the light source.

Messages sent out by DRF:

"out": DRF has been out of the cabin.
"far": DRF is far away from the light source.
"near": DRF is near to from the light source
"flost": DRF can not find the light source when moving to the light source.
"mlost": DRF can not find the light source when following the light source.

4. EXPERIMENTS

The developed robotic fish MRF prototype is shown in Fig.4, DRF in Fig. 5, and Fig. 6 shows the opened cabin with DRF in.

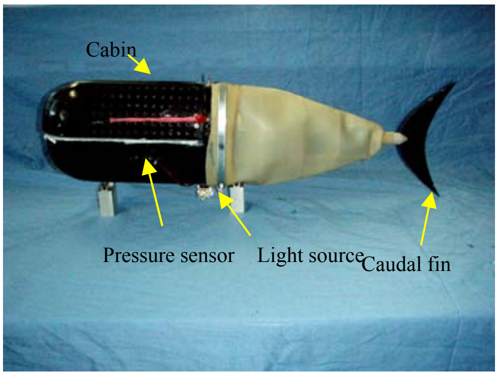

Fig. 4. The prototype of the robotic fish MRF

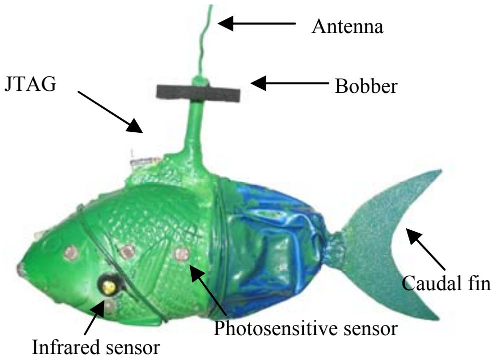

Fig. 5. The prototype of the robotic fish DRF

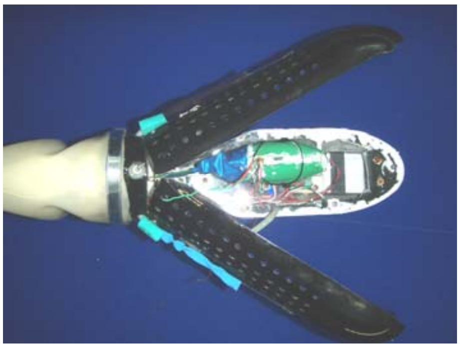

Fig. 6. The opened cabin with DRF

Based on the proposed HCFSM, the Daughter-Mother following task is performed. Fig. 7 shows a motion sequence of the marsupial robotic fish swimming in the experiment pool, and DRF is pointed by the arrow. Fig. 8 shows motion trajectories of it, which shows the effectiveness of the system.

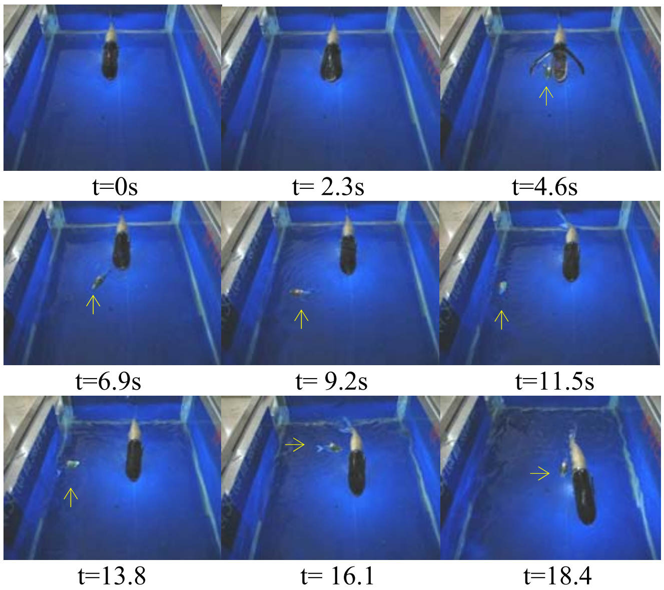

Fig. 7. The serial of the motions

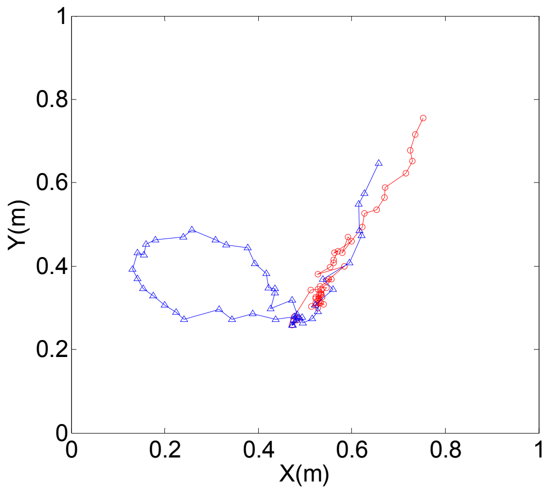

Fig. 8. The trajectories of the motions. The red is the track of MRF, and the blue is the tack of DRF.

5. CONCLUSION

In this paper, a marsupial robotic fish system constituted by a mother robotic fish with a cabin and a daughter robotic fish is designed based on fish-like motion. The information of sensors is used to plan path of the daughter robot for the dynamic light source tracking. A typical cooperative Daughter-Mother following task is modelled based on a heterogeneous communication-based finite state machine. Experiments verify the design and method of the system.

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REFERENCES

B. Minten, R. Murphy, J. Hyams and M. Micire (2001). Low Order Complexity Vision-Based Docking. In: *IEEE Transactions on Robotics and Automation*. Vol. 17, No. 6, pp. 922-930

C. M. Breder (1926). The locomotion of fishes. In: *Zoologica,* Vol. 4, pp. 159-256.

C. Zhou, S. Wang, Z. Cao and M. Tan (2006). A Control Paradigm for 3-D Locomotion and Depth Maintaining of Fish Robot TPF. Submitted to: *Robotics and autonomous systems*.

C. Zhou, Z. Cao, S. Wang and M. Tan (2006). The Posture Control and 3-D Locomotion Implementation of Biomimetic Robot Fish. In: *IEEE IROS*, pp. 5406-5411

C. Zhou, Z. Cao, S. Wang, X. Dong and M. Tan (2007). A Miniature Biomimetic Robotic Fish and Its Realtime Path Planning. In: *FSR*. pp. 22-31

J. Yu, M. Tan, S. Wang, E. Chen (2004). Development of a biomimetic robotic fish and its control algorithm. *IEEE Transactions on SMC*, 34 (4): 1798-1810

M. J. Lighthill (1971). Large-amplitude elongated-body theory of fish locomotion. In: *Proc. R. Soc. Lond, Ser. B.* vol.179, 125-138

M. Sfakiotakis, D. M. Lane, and J. B. C. Davies (1999). Review of fish swimming modes for aquatic locomotion. In: *IEEE J. Oceanic Eng.*, Vol. 24, no. 2, pp. 237–252.

M. S. Triantafyllou and G. S. Triantafyllou (1995). An efficient swimming machine. In: *Sci. Amer.*, Vol. 272, no. 3, pp. 64–70.

R. R. Murphy (2000). Marsupial Robots for Urban Search and Rescue. In: *IEEE Intelligent Systems*. Vol. 15, No. 2, pp. 14-19.