Small Robotic Fish with Two Magnetic Actuators for Autonomous Tracking of a Goldfish

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Abstract—In this study, we describe a palm-sized robotic fish that can automatically track a goldfish. A robotic fish is suitable for ecological surveys because it is difficult to be noticed by aquatic animals. However, so far, there is no palm-sized robotic fish that can automatically track an aquatic animal. Automatic tracking by the robot is carried out by recognizing the goldfish with a camera and changing the swimming direction towards the goldfish. To follow the agile movement of the goldfish, the robot has a high turning ability with multiple joints. Finally, we have confirmed the robot can track a goldfish.

Index Terms—Robotic fish, Autonomous tracking, Magnetic actuators

I. INTRODUCTION

Underwater vehicles [1-4] are often used for the ecological investigation of aquatic animals. However, there are a few aquatic robots used for investigation in narrow spaces such as rivers and ponds. The robots cannot be equipped with screw propellers because algae and aquatic plants may get caught in them. In addition, while investigating aquatic animals such as fishes, a small and quiet robot is desirable because the target animals hardly notice the robot. Hence, a small robotic fish [5-9] is suitable for the ecological investigation of aquatic animals.

We insert a robotic fish into water, and make it search for a target fish. When the target fish is found, the robotic fish tracks and observes the target without being noticed. After a few hours of investigation, we retrieve the robotic fish and transfer its data to a PC. If the robot is successful in collecting data, it will be used as an ecological investigation robot. For this, the robot is required to have the following abilities: (1) ability of swimming to track the target fish without being noticed, (2) ability to judge whether an underwater object is an investigation target, and (3) ability to store the acquired data internally and output to other devices.

For the first ability, in the Techno-Ocean 2010 Pre-Event held at the Suma Ocean Aquarium, it was confirmed that the aquarium fishes are not wary of a robotic fish when they swim together. The caudal fin of a robotic fish is silent and never hurts the fish. However, in the present situation, a caudal fin drive system is inferior to the screw drive system in terms of propulsion and turning ability. In this study, focusing on the fact that a fish bends its body greatly to change its direction, we have manufactured a robot with multiple joints to widen the range of motion of the caudal fin.

For the second ability, there are methods based on color, shape, and movement information for judging whether the object is a fish by image processing. There is a high possibility that methods based on shape and motion can identify a fish. However, they are more difficult than methods based on color information. Therefore, in this study, we have used the latter. We used goldfish as a target because it is small and has a characteristic color.

For the third ability, because radio waves are attenuated in water, high-speed communication using radio waves such as Wi-Fi is not possible. Acoustic communication is also studied for underwater communication. However, because sound waves have a low frequency, they are not suitable for large capacity data transfer such as in images. Therefore, we have studied a method of saving the acquired images inside the robot and projecting the data onto a display after the investigation is finished.

In this study, we manufactured a robotic fish, COMET (compact observation machine equipped with tailfin), for tracking fishes of 50 to 200 mm in size. Finally, we have confirmed that COMET can recognize and track a goldfish.

II. SMALL ROBOTIC FISH “COMET”

A. Turning Ability for Tracking a Goldfish

We used a 74 mm goldfish as a target for the tracking experiment. To clarify how the turning performance and angle of view of the robot work during tracking, we made a model as shown in Fig. 1. The goldfish swims around the robot at an angular velocity \( \omega_g \) maintaining a distance \( L \). The robot rotates at an angular velocity \( \omega_r \) to fit the goldfish within its angle of view \( \theta \). Then, \( \varphi \) shows an angle indicating the position of the goldfish relative to the front of the robot. When \( \varphi \) is larger than \( \theta \), the robot loses sight of the goldfish. We change the angular velocity and angle of view of the robot and calculate the tracking time \( t_T \) taken to keep the goldfish within its field of view using Eq. (1).

\[
t_T = \frac{\theta}{\omega_g - \omega_r}
\]

(1)

For the speed of the goldfish, we use cruising speed, which is the maximum speed that can be maintained for a long time. According to Radcliff’s (1950) research [10], the cruising speed of a goldfish is 3.4 times its
body length per second. Because the goldfish used in this study is 74 mm in length, its cruising speed is set to 252 mm/s. The distance between the goldfish and robot was calculated as 300 mm, and the angular velocity of the goldfish centered on the robot was 0.84 rad/s. The calculated result is shown in Fig. 2.

In Fig. 2, the x-axis shows the angular velocity of the robot and the y-axis shows the tracking time. Each of the lines represents a different angle of view. In this figure, from the relationship between $t_r$ and $\theta$ in Eq. (1), tracking time is proportional to the angle of view $\theta$. In addition, closer the angular velocity of the robot is to the angular velocity of the goldfish, longer will be the tracking time. If the robot can turn at an angular velocity equal to or higher than that of the goldfish, it can always fit the goldfish within its field of view. However, a goldfish has a high exercise performance and it is difficult to make a robot with an equivalent performance. Moreover, the goldfish does not always swim in a certain direction, but it frequently changes the direction of swimming. Therefore, we considered that the robot could track a goldfish if the robot could fit the goldfish within its field of view for several seconds. Consequently, as a design guideline for robots, we increased its field angle, and its angular velocity closely approached the angular velocity of the goldfish.

![Fig. 1. Tracking model of goldfish](image)

**B. Structure of the COMET**

Figure 3 shows the side and front views of the COMET, the schematics of its internal structure are shown in Fig. 4, and its specifications are mentioned in Table 1. The robot has a CMOS camera (NIPPON CHEMI-CON, NCM13-K2 Tokyo, Japan) on its head to watch the target. The specifications of the CMOS camera are mentioned in Table 2. Image processing and motion control are carried out using a ZYNQ board (Trenz Electronic, GigaZee, TE0720, Bünde, Germany) containing XC7Z020 (Xilinx Inc., San Jose, CA, USA). The specifications of the ZYNQ board are mentioned in Table 3.

The outer shell of COMET is constructed from acrylic parts. Figure 4 (c) shows a schematic of the tail fin of the COMET, which is constructed from natural rubbers with different hardness and a stick of polyethylene terephthalate for adjusting the hardness of the tail fin. The central part of the tip of the tail fin is made softer than others. [11] The tail fin is connected to the main body by two joints [12-13] and each joint drives independently. COMET can bend the tail fin by up to 90 degree by these two joints. This wide range of swing motion contributes to improved turning performance. Magnetic actuators [14–16] are equipped in each joint. The coil in the front end of the magnetic actuator has 1200 turns of polyurethane wire with a diameter of 0.16 mm, and has a resistance of 53 $\Omega$. A spherical neodymium magnet with a diameter of 15 mm is equipped inside the coil. The coil in the rear end of the magnetic actuator has 1200 turns of polyurethane wire with a diameter of 0.16 mm, and has a resistance of 46 $\Omega$. A spherical neodymium magnet with a diameter of 10 mm is equipped inside the coil. Magnetic force of neodymium magnets used in the magnetic actuators is strong enough to inhibit the other one from driving correctly because of magnetic flux leakage. Therefore, magnetic actuators are surrounded by iron yokes to form closed loop paths of magnetic circuits. Then, the magnetic actuators can be driven well. A lithium polymer battery (3.7 V, 750 mAh) is used as the electric power source. The power is supplied to each magnetic actuator through an H-bridge circuit containing power MOSFETs (SP8M4). The magnetic actuators are controlled by signals from ZYNQ. They are driven by an alternative positive and negative output voltage. When the robot swims straight, the swing period of the caudal fin is 2 Hz, and the second joint is driven with a phase difference delay of 90° of the first joint. However, when the robot turns right or left, the robot fixes the first joint to the side that it wants to turn.

![Fig. 3. Images of COMET](image)
radius of the COMET was read as 101 mm. During the experiment, the angular velocity was 0.67 rad/s.

III. CONTROL AND IMAGE PROCESSING

A. Procedure of Image Processing for Tracking

When a robotic fish investigates the ecology of aquatic animals, the robot has to gather the surrounding information and drive autonomously. There are different means for gathering the surrounding information, such as by using an ultrasonic sensor, an optical sensor, a camera, etc. The use of a camera is suitable for a sensor mounted on a small robotic fish because it can gather a large amount of information at a time and has a small size. Therefore, we mounted a small CMOS camera on the COMET. In addition, the COMET has an FPGA, which is smaller than other devices. Moreover, an FPGA can deal with a large capacity of data at high speed. Hence, we use a DDR3 SDRAM as memory for storing images in the robotic fish. In this section we confirm the following: (1) the COMET can track a red target based on the visual information from its camera; (2) the COMET can store image data in its memory and the data can be displayed after investigation.

Figure 6 indicates the functions and connections of the FPGA. The camera on the head of the robot has a resolution of 640 × 512 pixels, and the image data, in YUV422 format, are sent to the DDR3 SDRAM at 7.6 frames per second. In the FPGA, image processing, storing the images to memory, signal transmission to the outside of the robot, and drive system to control the caudal fin are included as VHDL programs. The COMET can autonomously determine the correct traveling direction to track a red target based on the visual information obtained by the camera. The COMET moves to bring the center of the red target into the center of its own field of view, as shown in Fig. 7.
First, we describe how to recognize the position of the red target. When an image contains pixels identified as red, the summation ($\Sigma X$) is made of the x coordinates of those pixels. The centroid $X_c$ in the x direction of the red region is determined by dividing by the total number of red pixels N. However, because the robotic fish swims by swinging its body to the left and right, it sometimes recognizes a wrong $X_c$ position. Therefore, we solved this problem by taking an average ($\Sigma X$) of $X_c$ for one cycle of the swing of the caudal fin. Then, the area where the COMET can see the object is set as the field of view of the COMET, as shown in Fig. 7.

Then, we describe how a controller controls the COMET to track the target. First, the field of view is divided into three areas as shown in Fig. 7. Then, the controller selects the advancing direction of the COMET depending on the area where the target's centroid exists. For example, in Fig. 7, because the centroid exists in the right zone, the COMET turns to its right. Hence, the centroid of the object moves to the center of the COMET's field of view. The COMET can track the target by continuing this control and simultaneously capturing images. However, when the COMET loses sight of the target, the last centroid is used for control calculation.

The images are stored in the DDR3 SDRAM on the ZYNQ board. After the investigation, the images are transferred by a 4-bit parallel communication using pins at the top of the robot. As a receiving device, we use a ZYBO, which is an FPGA evaluation board. A program for the reception is written into ZYBO beforehand and the received images are projected to a display through an analog RGB terminal.

B. Tracking Experiment of a Red Target

Our experiment confirmed the ability of tracking a red target and of the image processing system in FPGA.

Fig. 8. Comparison of images from the CCD and CMOS cameras in the COMET
The same experimental equipment was also used to measure the turning ability of the robot. A man near the pool moved a red ball with 64 mm diameter attached to the tip of a rod with 910 mm length to enable the COMET to track the target. After the experiment, we compared the images taken by the upper CCD camera with those taken by the COMET, as shown in Fig. 8. The left column images of Fig. 8 were taken by the CCD camera, while the right column images were taken by the CMOS camera of the COMET. From these images, we confirm that the robotic fish changes its direction and tracks the moving red ball. We also confirm that the image communication system operated successfully.

IV. AUTONOMOUS TRACKING OF GOLDFISH

We conducted an automatic tracking experiment on a goldfish by the COMET. The same experimental equipment was also used to measure the turning ability. In addition, the threshold used for the image processing of COMET was adjusted according to the body color of the goldfish. The threshold values used in the experiment are shown in Table 4 with the color format as RGB888. Furthermore, an LED was attached on the head of the COMET to check whether it can recognize the goldfish. When the number of pixels in the threshold is more than six, the COMET recognizes the pixels as a goldfish.

We let the goldfish swim in the pool, placed the COMET in front of it, and let the COMET automatically track it. After the COMET completely loses sight of the goldfish, we remove it and retrieve the data from it.

Table 4 Threshold of COMET in RGB888

|     | min | max |
|-----|-----|-----|
| red | 112 | 255 |
| green | 0   | 72  |
| blue | 0   | 192 |

Fig. 9. The behavior of the centroid of goldfish

Fig. 10. Comparison of images captured during tracking goldfish

Figure 9 shows how COMET recognizes the position of the goldfish during tracking. In this figure, the x-axis denotes time calculated based on the frame rate of the camera mounted on the COMET, and y-axis denotes the x coordinate of the pixels of images taken by the
COMET, as shown in Fig. 7. The red points show the x coordinate of the centroid of the goldfish. The green points show that the COMET lost sight of the goldfish. The horizontal lines at 250 and 390 pixels are the boundaries of the three zones shown in Fig. 7. Figure 9 shows that the COMET is controlled such that the centroid of the goldfish lies in the middle zone. When the red point is outside the middle zone, the COMET is controlled to turn.

Figure 10 shows a comparison of images taken by upper CCD camera (left) and the COMET (right) at the same time. The time in Fig. 10 shows the same time as the graph in Fig. 9. At first, from Fig. 10 (a), we can see that the goldfish appears in the left zone of the field of view of the COMET. Then, Fig. 10 (b), COMET turns left and keeps the goldfish in the field of view. Even after that, we can see that COMET tracks the goldfish by changing the direction of swimming depending on the position of the goldfish in the field of view. From this figure, we can see that the COMET recognizes and tracks the goldfish caught in the sight. While tracking, the longest and shortest distance between the COMET and goldfish was 260 and 100 mm, respectively. When the distance is the closest, the goldfish swims at maximum speed. The speed was 171 mm/s, and it shows that the goldfish did not escape using the cruising and burst speeds. In this experiment, we confirmed that COMET can track goldfish in the left-right direction.

V. CONCLUSIONS

In this study, we manufactured a small robotic fish (COMET), which was equipped with a CMOS camera, an FPGA, and two joints. In addition, we programmed a tracking program based on visual data for the COMET, and enabled it to automatically track a goldfish. Finally, we confirmed that COMET can track a live fish. However, some limitations exist in this study. First, we conducted a tracking experiment in the only left-right direction, but not study tracking in the depth direction. Second, we confirmed the COMET can track only a goldfish, but no other species have been considered. Third, since we only experimented with one goldfish, we have not obtained statistical results.

In future work, we will study the methods for autonomous tracking of another species of fish in the depth direction, and then obtain statistical data.

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