Design and Experiment of Miniaturized and Low-Cost Robotic Fish with Customerized Electromagnetic Actuation

Zhiqing Qian, Hongzhou Liu, and Zhuming Bi

Abstract**—**Motivated by the lack of the study in developing miniaturized and low-cost biomimetic robots, we proposed a novel robotic fish with customized electromagnetic actuations. It has four degrees of freedom (DoF), which is capable of reaching any position in a 3-D space. The system design is introduced in the paper. The design covers its mechanical structure, motion control, and its communication for human-robot-interaction. The exterior shape of the robotic fish was optimized to minimize the power consumption in the operation. In prototyping, the exterior body of the robot was modeled in SolidWorks and materialized using rapid prototyping (RP) technology, and the electromagnetic drivers were customized as swing actuators for the propulsion of the robotic fish. For robotic control, AVR microcontrollers by Atmel were adopted, and the human-robot interaction was through the Bluetooth communication to minimize the needs of using a large number of sensors. In the experiments, the intents of an operator were captured by gesture sensors from hand signals, and the programs were developed to translate the human operator's inputs into the motion commends of the robotic fish. The tests on the prototyped robot have shown the feasibility of (1) customizing electromagnetic actuators for a robotic fish and (2) involving human operator in the control system to reduce the needs of sensors and increase the capability of robot to deal with uncertainties. The robotic fish has been miniaturized greatly. The proposed design concepts have their significance to be extended in developing other biomimetic robots, including medical robots.

Keywords**—**Robotic fish; biomimetic robots; human-computer interaction; electromagnetic drives.

I. INTRODUCTION

Robots are known to people with their efficiency, productivity, and autonomy. Robots are developed to replace human workers in performing dangerous, dirt, or boring tasks in various applications [24-27]. Robots have been widely applied in manufacturing and industry environments since the 1965s [1]. The advancement of robotic technologies depends greatly on that of artificial intelligence. With a rapid development of information technologies (IT), recently developed robots are diversified, miniaturized, and multi-functional; in some cases, the collaborations among robots or with human users are required to synergize the team efforts [14,15]. Various robots have been designed for different applications [1] [2]. One of the emerging research fields is the development of biomimetic underwater robots [1-5]; existing biomimetic technologies are facing challenges in making robots competitive to underwater creatures. It is generally agreed that the main challenges are caused by the fundamental difference of a marine animal and an artificial machine; for example, the skin of a marine animal is soft, wet and flexible, while the exterior of a robot is usually dry and rigid. With the evolution of over thousands of years, a biological system adapts its living environment perfectly; it is desirable to have an artificial machine, which is capable of responding its application environment like a creature [18,21-22]. However, a biological system is so complex, and it is impossible to completely mimic its behaviors and functions with a man-made robot. Taking into consideration of the cost factor and the limitations of available materials, the functional requirements of a biomimetic robot should be more focused and realistic [6].

This paper is focused on the development of a robotic fish. Existing robotic fishes can be classified in different ways. For example, different components in a robot can be actuated for swimming. The actuated components can be body segments, caudal fins, median fins, or a combination of these components, such as body and caudal fin (BCF) or median and paired fins (MPF). The swimming pattern affects the performance of a robotic fish. The swimming pattern with BCF can achieve a greater thrust and acceleration; while the swimming pattern with MPF can obtain a better mobility and higher efficiency of propulsion. It is appropriate in a low-speed movement [7]. The first robotic fish, which was also known as 'RoboTune', was developed by Massachusetts Institute of Technology (MIT) in 1994 [8]. This robot was driven by BCF and it imitated the swimming mode of tuna. Shao et al. [9] introduced a robotic fish with multiple joints

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inside the body. The joints were driven by DC servomotors, and the robot was proposed to be applied in the collaborative transportation. That robot was equipped with a powered tailfin to refine the robot motion. In the robot built by Zhang et al. [11], the power source was placed on the thruster of a long dorsal. This design was inspired by a "gymnarchus niloticus", whose long dorsal fin provides the main propulsion when it hunts or swims in a low speed. It can be classified as MPF.

It is worth to note that the types of actuators are one of the critical factors in the design of a robot. Actuators of conventional robots are mostly servomotors with rotational motions. In recent years, some actuators with new driving materials, such as piezoelectric ceramics and shape memory alloys (SMA), have been applied to drive robotic fishes. For example, Nguyen et al. [4] used a type of lightweight composite piezoelectric ceramic actuators (LIPCAs) to drive a robotic fish. Both of theoretical analysis and experiment showed that the maximized thrust occurred when the fin wiggled at the frequency of 3.7 Hz, and the maximized speed could reach 7.70 cm/s. SMA-actuators have shown their advantages on compact structure, noiseless operation, and low driving voltage. Wang et al. [12] used shape memory alloy wires to drive a micro-robotic fish. SMA wires were embedded in the fish body for propulsion. They argued that SMA-based actuators were very advantageous as the drivers in biomimetic fins; since the mechanisms to store or convert potential energy could be integrated into biomimetic fins to improve the swimming efficiency.

Besides the robotic structures and driving actuators, the dimensional optimization is also important. Analytical models were developed to build the relational models of design parameters and system performances. Vo et al. [3] developed a theoretical model to maximize its forward speed for a robotic fish under the given design restraints. The robotic fish was a carangiform-like fish with three joints, and the design parameters under the consideration were the amplitudes, frequencies and phase differences of actuators. The genetic algorithm (GA) was combined with the hill-climbing algorithm (HCA) to optimize all those design parameters, and the design results were validated through the experiments. Chang et al. [13] developed a hydrodynamic model to analyze the swimming behaviors of a robotic fish; they applied this model to evaluate three shapes of caudal fins including popular crescent-shaped fins, semicircle-shaped fins and fan-shaped fins. Their results showed that a caudal fin with a crescent-shape produced a lower thrust in comparison with the fin with a semi-circle or a fan-shape; however, the corresponding efficiency was the highest among three shapes.

Despite numerous researches on robotic fishes, further developments are demanding to design miniaturized and low-cost robots [23]. Therefore, we are motivated to explore the possibility of using low-cost electromagnetic drivers and involving human operators in the control loop to reduce the robot cost and increase its manipulability in the operation. A new biomimetic fish is designed; it is driven by customized electromagnetic actuators and it can be controlled remotely by users via wireless communication. To our knowledge, it is the first time where electromagnetic actuators are customized as swing actuators in robotic fishes. The rest of paper is organized as follows. In Section 2, the working principle of electromagnetic actuation is introduced; in Section 3, the designs of main components of the robotic fish are discussed, and the controlling and communication system are prototyped. In Section 4, the experiments are provided to illustrate the feasibility of using electromagnetic drivers and wireless control via human and robot interaction. Finally, in Section 5, our works are summarized and the future research in this field is introduced briefly.

II. WORKING PRINCIPLE OF ELECTROMAGNETIC ACTUATION

Actuators in a robotic fish perform the similar functions of muscles in an animal. Three types actuators discussed in Section 1 were fully rotational serve motors, piezoelectric actuators, and SMA-based actuators. The costs for these actuators are relative high. In this section, the feasibility of customizing electromagnetic actuators for swing actuation is investigated to reduce the cost of a robotic fish.

A. Structure of Actuator

The main component in an electromagnetic actuator is the magnetic object. A driving force occurs to the magnetic object when it is exposed to a magnetic field; such a driving force can be used to move the parts, which have the connection with the magnetic object. Fig. 1 has shown the structure of a specific electromagnetic actuator; it has been applied in the proposed robotic fish. The actuator includes three main components, i.e., coils, magnets, and the swing rod. When the power supply is on, it generates the current passing through coils; in turn, the coils for the magnetic field around the magnet object. Therefore, the magnet object is subjected to a driving force within the magnetic field, and the magnitude of the driving force can be controlled by the level of current. In the illustrated configuration, the swing rod is forced to move under the magnetic field by magnet object is aligned with that of coils.

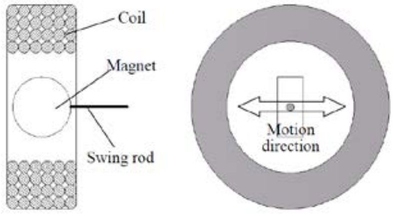

Fig.1. Principle of a specific electromagnetic actuator

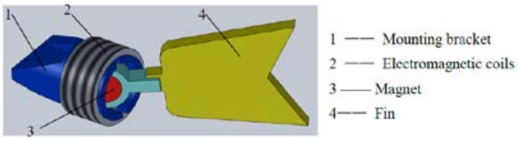

Fig.2. The setup of an actuator on robotic fish

All of joints in the proposed robotic fish are driven by such type of electromagnetic acturator. However, the size and capacity of an actuator can be varied based of the driving requirement. Fig. 2 has shown the setup when the actuator is installed on the robotic fish. The set up for the actuator includes the following parts:

Mounting bracket:	it is used to mount actuator over the body of robotic fish;
Electromagnetic coils:	it generates a magnetic field when there is a current passing through coils;
Magnet objects:	it activates the movement when the driving force becomes available;
Fin:	it serves an interface to convert internal driving force into the pushing force from the residential environment.

B. *Control of Actuator*

It can be seen that changing the current in coils causes the oscillating motion of the swing fin, the direction of motion depends on the direction of current, and the magnitude of driving force is proportional to that of the current. Therefore, controlling such an actuator is all about to control the current in the coils. A direct current is also proportional to the voltage U applied in the circuit. To simplify the actuator, the voltage U is given as a waveform in Fig. 3, and the width of the waveform pulse is controlled by the Pulse-width modulation (PWM).

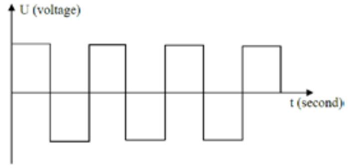

Fig.3. The voltage of electromagnetic actuator

The swing direction of the fin depends eventually on the sign of voltage applied on the coils. As shown in Fig. 4, when the voltage over the coils is positive, the fine swings towards to left; otherwise, it moves to the right when the voltage becomes positive.

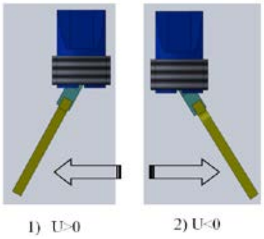

Fig.4. Swing direction depending on the positive or negative voltage

The operation of the proposed actuator is simple; however, its behaviors are very close to those of real fish. The fins on fish only have simple swings, yet, the simple swings are efficient so that fish has elegant and agile movement in water.

III. INTEGRATED DESIGN OF ROBOTIC FISH

In this section, the integrated design of the robotic fish is introduced, and four major tasks are the design of exterior body, the setups of actuators, motion control, and wireless communication for human robot interaction.

A. *Design of exterior body*

The body of the robotic fish serves as the house for all of the electronic components; the manifolds of the exterior body also have a great impact on the power efficiency. The robotic fish should have an internal space enough to accommodate power supply modules, microcontroller, drive modules and the electronic accessories for communication. In addition, the interface should be available on the body to install the electromagnetic actuators outside the body shell. Meanwhile, the size and shape of the body determines the amount of the resistant force when the robotic fish moves in water; therefore, under the given volume of internal space, the body shape of the robotic shape was optimized to achieve an optimized hydrodynamic performance with the minimized resistant force. More specifically, the design criteria of the robotic fish are,

The streamlined manifolds should be adopted to reduce resistant force and achieve better hydrodynamic performance.

The volume of the body should be determined by the sum of those for power supply modules, microcontroller, drive modules, and other accessories. In addition, the body should be sealed easily to the encapsulated space waterproof.

The interface should be designed to connect inside components with the actuators at outside. The interface should also include the brackets to mount driving fins.

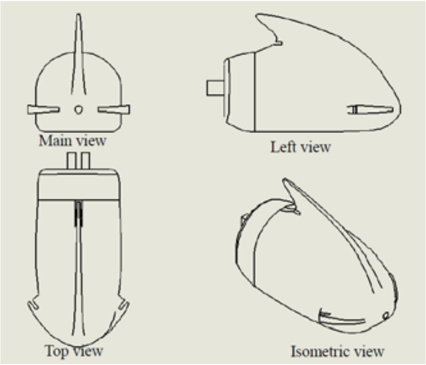

Fig.5. Drawings of the finalized body of the robotic fish

An iterative trial and error procedure was applied to optimize the size and shape of the robotic fish. At each step, all design criteria were considered to create a conceptual model of the robotic body in SolidWorks, and the model was then converted into a stereo lithography (STL) file for rapid prototyping. The prototyped body was verified to see if all of design criteria were satisfied optimally. The drawings of the finalized body were shown in Fig. 5. The exterior shape was streamlined, which was very easily made by three-dimensional printing.

As shown in Fig. 6, the body has the cavity internally to accommodate electronic components. To assembly components together appropriately, the body was cut into two parts, i.e., the front part and the back part. After all of the components were placed in the cavity, two parts were then put back together. Note that the seals must be applied on the interface of two parts to prevent water leak.

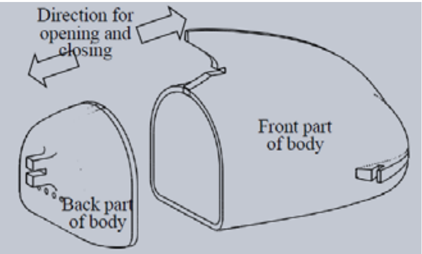

Fig.6. Two parts of the shell

To install swing fins, the body also included some features in local regions for the actuators; Fig. 7 has shown four slots to mount left, right, tail, back swing fins, respectively.

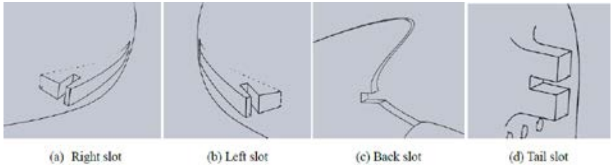
(a) Right slot (b) Left slot (c) Back slot (d) Tail slot

Fig.7. Design details of slots to mount swing fins

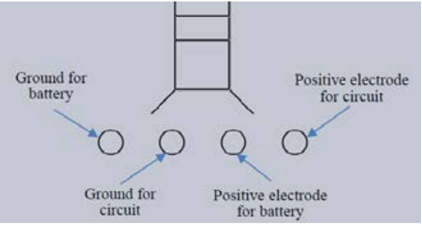

Fig. 8. Interfaces for switches and power supplies

Note that underneath the mounting bracket of the tail fin in Fig. 7(d), the interface for the connections of internal and external components was designed. An interface allows charging batteries when they are used up; it also makes the switches of the circuit accessible from the outside the body. Fig. 8 has shown the locations of pins for the ground of battery, the ground of the circuit board, the positive electrodes of battery and circuit, respectively.

The main properties of the finalized robotic body are included in Table 1. The total mass of the body is 6 (grams), and the total rounded-up volume is less than 5.9×104 (mm3), which has been greatly miniaturized.

Table 1. Properties of finalized robotic body

Item	Value	Unit
Length	57	mm
Width	30	mm
Height	34.5	mm
Mass	6	gram

B. Actuation

The actuators are specially designed so that their behaviors are swing oscillations similar to the moving patterns of fins on fish. The driven fins on the robotic fish swing left and right to get the propulsion from water for the movement. The amount of thrust force depends on the size, shape, and swing frequency of the fin. Cheng et al. [13] compared three different shapes of fins including crescent-shape, semi-circle shape, and fan-shape. Their results showed that the fin with a crescent shape produced less a thrust force than the fins with other shapes. However, the fin with the crescent shape was the most efficient during cruising due to the less loss of the lateral power. Therefore, the selection of the fin shape depends on whether a higher thrust force or higher power efficiency is preferred.

In the proposed robotic fish, four actuators are applied and mounted on tail, dorsal, and two pelvic positions, respectively. These actuators serve for different purposes as follows,

Actuator on caudal fin: provide main thrust and assistive lateral force when it turns;
Actuators on pelvic fins: provide main lateral force when it turns;
Actuator on dorsal fin: provide the diving or floating force when it changes its depth.

The setup of the actuators is shown in Fig. 9. All of them are placed in the corresponding slots on the shell of the robot body. The driving power for these actuators was from the internal circuit.

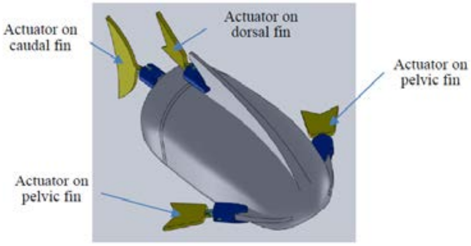

Fig.9. The setup of actuators on the robotic fish

C. Control and Communication

The control system transfers control commends into actual motions of the robotic fish. The control commends are transmitted by the wires which connect external actuators to internal micro-controller and power supplies. The wired connections are essential to the communication, where control signals are transmitted to the actuators from the micro-controller or human operator. Meanwhile, the feedbacks from the actuators or the environment are collected and transferred to the controller for the closed-loop control or decision-making at a high level.

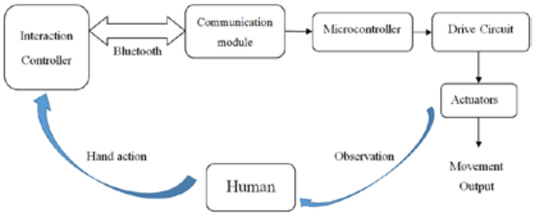

Fig.10. Human operator in the closed-loop control system

For some simple tasks, an open-loop control for an individual robot with the minimized number of sensors can fulfill tasks adequately. However, when the task becomes complicated, it needs the collaborative effort from a group of robots or with the interactive human intervention (Bi et al). Moreover, the human operator might serve as a superior sensor to observe changes in the environment and refine the motion of robot accordingly. In other words, it is advantageous to include the human operator in the closed-loop control system. Fig. 10 has illustrated an interactive control platform where a human operator can control the robotic fish directly by remote-control panel. The main components in the control system are interactive controller, communication module, microcontroller, drivers, actuators, and human operator. Human operator is responsible to monitor the movement of robotic fish, issue the interactive motion commends to the robot. The interactive controller is the receiver and executor of motion commends. The communication module is also responsible to transmit the acquired gesture signals and deliver control signals to actuators through Bluetooth.

The AVR microcontroller Atmega8L by Atmel were selected as the microcontroller for the robotic fish. Its specifications meet the control requirements of the robotic fish satisfactorily. Due to the advanced technologies for the high-density non-volatile memory, an Atmega8L chip has small size and low power consumption. In addition, the programs in its flash memory are rewriteable, and the reprogramming can be executed via an serial program interfaces (SPIs) including SCK, MOSI (input) and MISO (output). Table 2 gives the mapping of pins in SPIs.

Table 2. Mappings of pins in serial program interfaces

Signal	Pin	Description
MOSI	PB3	Data Input
MISO	PB4	Data Output
SCK	PB5	Timer

The input and output (I/O) interfaces in the Atmega8L microcontroller are further illustrated in Fig. 11. Eight outputs are PWM_Turn_0, PWM_Turn_1, PWM_Tail_0, PWM_ Tail _1, PWM_Left_0, PWM_ Left _1, PWM_Right_0, and PWM_ Right _1; they are H-Bridge drive circuits. The interfaces set for downloading are MISO, MOSI, SCK, and ISP_RESET. RXD and TXD for a serial I/O communication. ADC0 ~ ADC5 are the interfaces to connect AD Converters.

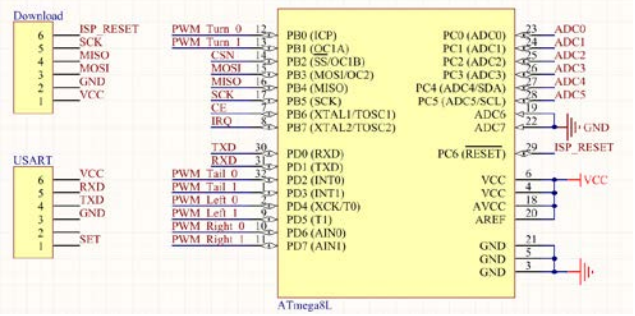

Fig.11. I/O configurations in the microcontroller

The application of a robotic fish can be restrained by the communication mode. A variety of wireless communications are available; each communication mode has its advantages and disadvantages [16,19]. In our prototyping, the bluetooth communication was selected mainly because it involves a low cost and it has been widely used in many industrial applications. For examples, the majority of personal digital assistants (PDA), such as smart phones and ipad, support the bluetooth communication. Therefore, it becomes feasible for a human operator to interact with the robotic fish via a smart phone or ipad. Fig. 12 has shown the communication system of the robotic fish.

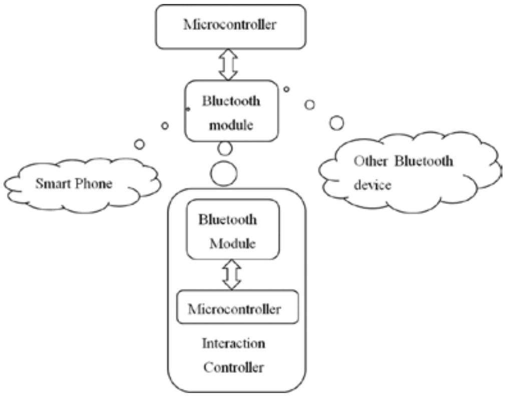

Fig.12. The communication system of the robotic fish

In the prototyping system, the selected buletooth module was BLK-MD-BC04-B, which was developed based BlueCore4-Ext by the CSR Company in U.K. The module is compatible to universal asynchronous receiver/transmitter (UART) and SPI interfaces. Furthermore, it has the advantages of a low cost, low consumption, small size, and high sensitivity of transmission. This module was adopted to communicate the micro-controller with a few of external devices.

D. Human robot interaction

A robot is a typical mechatronic device with an integration of mechanical system, electronic and electrical system, sensing system, computing and control system [17, 20]. In particular, the level of intelligence of a robot relies greatly on the information visibility in the environment. To acquire information from the environment, various sensors, such as encoders, cameras, sonars, and range finders, can be applied to obtain different types of information. The feedbacks from sensors are essential to implement closed-loop controls.

With the objective of the low cost, it is impractical to include a large number of sensors for the robotic fish. However, involving the human operator in the control system alleviates this problem greatly. Human operator can monitor the movement of the robotic fish and the environment directly. Through the remote controller, the commends to the robotic fish can be refined readily to adapt the changes of environment directly. Therefore, the interactive remote controller by the human operator serves for two purposes: (1) collect gesture signals from the attitude sensors from the operator, and (2) send and receive data as a signal transceiver. Accordingly, the human operator is responsible to (1) Observe the robotic fish and its application environment, and (2) make the decisions for the motion of robot, and issue control signals to the microcontroller via the control panel.

The most important components of the control system is the Atmega8L chip, and it is connected to other components in the system including power modules, the communication module and the module for ADXL335 sensors. Fig. 13 shows the configuration of the interactive controller. The microcontroller is required to capture gesture signals from ADXL335 sensors, and it also sends control signals to actuators via the bluetooth communication.

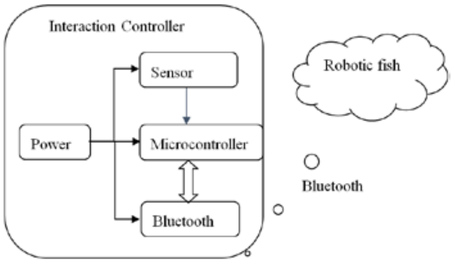

Fig.13. Configuration of interactive controller

ADXL335 is a three-axis accelerometer, which is capable of measuring the accelerations along three directions. One can calculate the posture of the robot based on the accelerations. If an acceleration is high, the inclination angle of the posture is large. The output of ADXL335 is the voltage signal so it can be transferred easily by an AD Converter. The specifications of ADXL335 are shown in Table 3.

Table 3. The specifications of ADXL335

Item	Parameter
Voltage	3~5 V
Current	400 uA
Output	Voltage
Temp.	-40 ~ 85°

IV. PROTOTYPING AND EXPERIMENTS

The aforementioned components were assembled as a robotic fish. The overall volume and weight were measured. As shown in Table 4, it was found that the overall dimensions of the robotic fish are 77.84 mm in length, 48.80 mm in width, and 35.84 mm in height with a tolerance of ±0.02 mm, respectively; its total weight is 25.61 g with a tolerance of ±0.01 g. The robotic fish was greatly miniaturized in comparison with other existing robotic fishes reported in the literature.

Table 4. Physical properties of the robotic fish

Parameters	Values
Length	77.84 ±0.02 mm
Width	48.70 ±0.02 mm
Height	35.84 ±0.02 mm
Mass	25.61 ±0.01 g

The moving speed is an important measure for the robotic fish. Therefore, the robot was tested for two types of motion, i.e. the maximized forward speed and the maximized turning speed.

When the robotic fish swings its caudal fin, the thrust force is generated, and it moves forward. If the robotic fish swings one of its pelvic fins, it turns left or right depending on which pelvic fin takes action. For example, if the robotic fish swings its right pelvic fin and keep the caudal fin on the left, it turns left eventually. Otherwise, if it swings its left pelvic fin keep the caudal fin on the right, it turns right instead. The recorded sequence of the forward motion is shown in Fig. 14. The measured forward speed was 25.95 mm/s.

Fig.14. The recorded sequence of the forward motion

The recorded sequence of the turning motion is shown in Fig. 15. The measured maximized turning speed was 40 °/s.

Fig.15. The recorded sequence of the turning motion

V. SUMMARY AND FUTURE WORKS

Distributed intelligence seems the most effective strategies to deal with the complexity of emerging engineering problems [16,19-22]. Instead of developing an integrated system with a higher level of complexity for advanced functionalities, a distributed system consists of a large number of modular systems; each module is autonomous, but they can collaborate with each other to achieve high-level goals at the system level. Due to the number of modules, the cost effectiveness of the distributed intelligence depends on how well to miniaturize sizes and weights, and to reduce the costs of modules. It is our understanding that little work has been done on the structural optimization of robotic fishes for the reduction of size, weight, and eventually the cost. We are motivated to design a compact robotic fish by (1) simplifying the configurations of the propulsion systems, (2) customizing low-cost electronic-magenitic actuators, (3) minimizing the body of robotic fish with the consideration of hydrodynamic performance, and (4) involving human operator in the control system to reduce the needs of sensors and increase the flexibility and robustness of the robotic fish. The design concept has been implemented and the prototyped robotic fish was tested. It was found feasible to use the customized electronic magnetic actuators to drive a robotic fish. In addition, the integrated interface allows a human operator interact with the robotic fish directly. The prototyped fish was miniaturized into a volume within 78×49×36 mm3 and the total weight of 25.6 grams. The maximized forward and turning speeds from the measurements were 25.95 mm/s and 40 °/s, respectively. It should note that the ideas of using customized electromagnetic actuators and involving human operator in control system are applicable to other robotic designs when the size, weight, and cost are critical factors to the applications.

The main purpose of the presented work was to explore the feasibility of using customized electromagnetic actuators in biometric robots and involving human operator in the control system to miniaturize robots. The prototyped robotic fish is preliminary, and we have identified the following areas to extend our research in the field: (1) to optimize the configurations of driving systems for higher speed and agility; for example, include multiple actuators on a fin; (2) to develop comprehensive kinematic and dynamic model for advanced control of the robotic fish; (3) to investigate the scalability of the system, so that the developed methods can be applied to any scale of robot in terms of sizes, weight, and working capacity; (4) to study the coordination and collaboration of robotic team for distributed intelligence; (5) extend the developed methods for other types of biomimetic.

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