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Development of 2D Maneuverable Robotic Fish Propelled by Multiple Ionic Polymer-Metal Composite Artificial Fins

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***Abstract*—Due to their high propulsion efficiency, stealthiness, and compact size, bio-inspired robotic fish are promising underwater vehicles that can carry out remote sensing missions in intelligence collection, environmental monitoring, and fishing agriculture. In this paper, a two-dimensional (2D), maneuverable, bio-inspired robotic fish propelled by multiple ionic polymer-metal composite (IPMC) artificial fins is developed. The robot utilizes two pectoral fins for steering and one caudal fin for main propulsion. IPMC artificial muscles are used as actuators in all fins. These IPMC fins are designed and fabricated. An on-board micro-controller with a lithium ion battery and XBee communication device is developed for the robotic fish. Finally, a free-swimming robotic fish is assembled and tested. In its first demonstration of free swimming, the forward-swimming speed reached 0.5 cm/sec, and both the left-turning and right-turning speeds reached up to 1.5 rad/sec. Experimental results have verified the 2D maneuvering capability of robotic fish through multiple-fin propulsion.**

I. Introduction

A mobile underwater sensing network (MUSN) is an emerging technology used for environmental monitoring, fishing agriculture, and marine life studies [1], [2]. A successful MUSN relies heavily on multi-underwater agents that are two dimensional (2D) and have stealth underwater maneuvering capability. In recent years, there have been significant efforts in the development of bio-inspired underwater robots to mimic aquatic animals, such as robotic fish [3], [4], [5], [6], [7], [8], [9], [10], robotic jelly fish [11], [12], [13], and robotic rays [14], [15], [16], [17]. In most of these robots, traditional electric motors have been used to generate rotation motions. However, flapping motions are normally employed by aquatic animals for maneuvering and propulsion. To build such bio-inspired robots using traditional motors, power transmission is needed to translate rotation motion into flapping motion. Electric motors and the power transmission are too bulky for small-scale bio-inspired robots, and energy efficiency will be reduced due to the energy lost in the transmission of power. Rotation also generates unfavorable acoustic noises, which makes the robots detectable and unfriendly to marine life. Moreover, traditional motors cannot generate compliant actuation without force feedback control. Biological fish rely on compliant actuation generated by their biological muscles to obtain highly energy-efficient underwater propulsion [18]. Novel smart materials, which are light, soft, and capable of directly generating a large flapping motion with a simple electrical driving circuit, are highly desirable in the building of such energy efficient, 2D, maneuverable, stealthy, and small-scale underwater bio-robots [19].

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Electroactive polymers (EAPs) are emerging smart materials that can generate large deformations under electrical stimuli [20]. Due to their similarities to biological muscles, EAPs are often called artificial muscles, and they have different configurations, which are basically divided into two categories: dielectric EAPs and ionic EAPs. Dielectric EAPs can generate a large force with a large deformation [21], [22], [23]; however, they require high actuation voltage (typically higher than 1 kV), which limits their applications in bio-inspired robotic fish. Ionic polymer-metal composites (IPMCs) are an important category of ionic EAPs due to their built-in actuation and sensing capabilities. An IPMC consists of an ion exchange membrane coated with two novel metal electrodes [24], such as gold or platinum 1. Application of a small voltage (less than 2 V) to the IPMC leads to ion transportation to the cathode side, which introduces a swelling effect on that side and a shrinking effect on the anode side. Eventually, the IPMC bends to the anode side, thus realizing the actuation effect, as shown in Fig. 1. Since IPMCs are soft, lightweight, low-power consumers, and capable of generating flapping motion, they are ideal artificial muscles for small-scale underwater bio-robots.

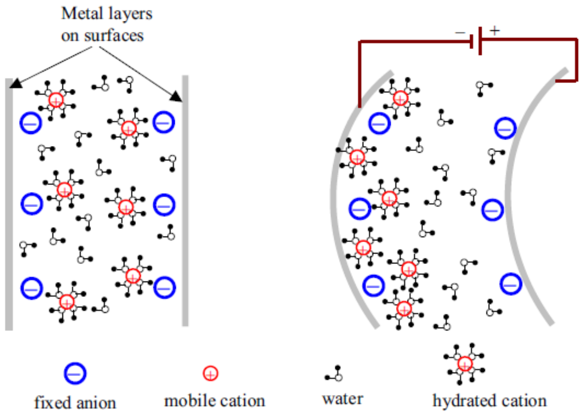

Figure 1. Actuation mechanism of IPMC [25].

To date, some efforts have been devoted toward IPMC-powered underwater robots [3], [4], [5], [6]. For example, Tan *et al.* developed a robotic fish propelled by an IPMC caudal fin [6], and then Chen *et al.* developed a speed model for the robotic fish [26]. An IPMC-powered robotic manta ray and cow-nose ray have also been developed [27],

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[28], [17]. The resulting robotic fish or rays only demonstrated one-dimensional (1D) swimming; 2D or 3-dimensional (3D) maneuvering capabilities were limited because they utilized only one type of IPMC-actuated artificial fin, either pectoral or caudal, which prevents these robotic fish from achieving the high maneuverability exhibited by real fish, e.g., turning, hovering, and breaking. To achieve 2D or 3D maneuvering capability, multiple-fin propulsion and maneuvering need to be considered in the robotic fish design.

In this paper, a 2D maneuverable and wireless controlled robotic fish fully actuated by IPMC artificial muscles is developed. Inspired by biological fish, the robotic fish utilizes two artificial pectoral fins to generate its steering moment and one artificial caudal fin to generate its main propulsion. All fins are actuated by IPMC artificial muscles, which can provide energy-efficient and compliant actuation. Because no gears and motors are involved, the proposed robotic fish can achieve stealth maneuvering capability. Based on the assembly-based fabrication process, two IPMC pectoral fins and one IPMC caudal fin are constructed. Multiple-fin propulsion is realized in a compact size and low-power-consuming robotic fish. An on-board controller with a lightweight and high-energy-density battery and XBee wireless communication device is developed for the robotic fish to enable its free-swimming and wireless controllable capabilities. Experimental data shows that the fish is capable of turning left or right and swimming forward by controlling its pectoral fins and caudal fin, respectively. This study is the first to demonstrate a robotic fish using multiple IPMC artificial fins to achieve 2D maneuvering capability.

The rest of this paper is organized as follows: Design of the robotic fish is described in Section II. Fabrication of the fish is presented in Section III. Experimental results are explained in Section IV. Conclusions and future work are discussed in Section V.

II. Design of 2D Maneuverable Robotic Fish

Mobile underwater sensing networks are calling for 2D or 3D highly maneuverable robotic fish. However, this type of maneuvering technology for robotic fish is still underdeveloped. Biological fish utilize multiple fins to achieve highly maneuvering capabilities. Inspired by nature, the proposed robotic fish in this paper utilizes multiple fins to achieve 2D maneuvering capabilities, such as forward swimming and turning. Fig. 2 illustrates the overall design of a robotic fish that employs one caudal fin for main propulsion and two pectoral fins for steering. This paper is the first to demonstrate the steering capability enabled by a pectoral fin.

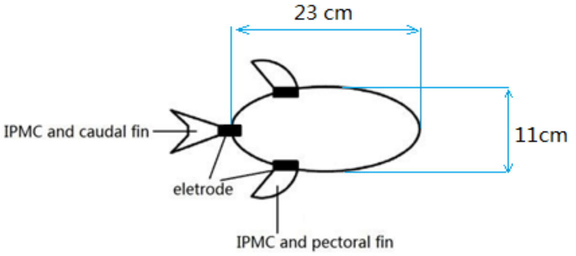


Figure 2. Design of robotic fish propelled by multi-IPMC fins.

A. 2D Maneuvering Mechanism

Two-dimensional maneuvering capability of a robotic fish can be achieved by controlling the pectoral fins and caudal fin separately. Fig. 3 shows the mechanism of the 2D maneuverable robotic fish, where the center of mass is located at point G. For forward swimming, all fins are activated. The caudal fin generates the main forward thrust, and the two pectoral fins generate complimentary forward thrusts to assist forward swimming. For turning left, the left pectoral fin and the caudal fin are activated. The caudal fin enables forward swimming, and the left pectoral fin enables left steering. Because the center of mass is located at the front of the fish and the pectoral fin is located at the rear of the fish, the force generated by the left pectoral fin creates an anticlockwise steering moment, which makes the fish turn left. For turning right, the caudal fin and right pectoral fin are activated. The caudal fin still generates the forward thrust, and the right pectoral fin generates a clockwise steering moment, which makes the fish turn right.

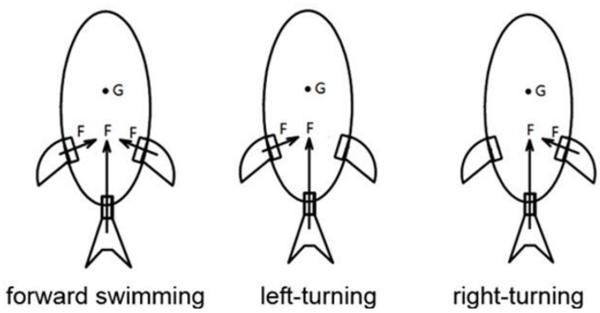
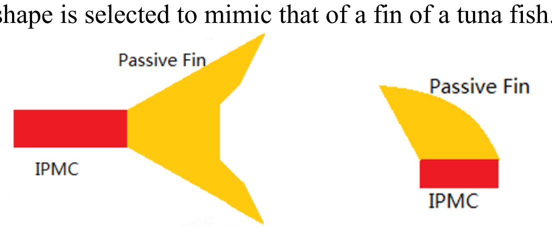


Figure 3. 2D maneuvering capability enabled by multiple fish fins.

B. Caudal Fin and Pectoral Fin Design

Chen *et al.* developed a speed model for robotic fish propelled by an IPMC caudal fin. They found that attaching a passive fin to the IPMC can generate more thrust force [29]. In this paper, we follow the same design to create the caudal fin, as shown in Fig. 4(a). Chen *et al.* also developed an artificial pectoral fin for a robotic manta ray [16]. Since 3D complex deformation on the pectoral fin is needed to generate the main thrust, the pectoral fin consists of multiple IPMCs bonded with a flexible and passive membrane. However, it is difficult to implement an effective on-board control to generate thrust [16]. In this paper, since the pectoral fin is only used to generate the steering moment, the fin does not require 3D kinematic motion. To simplify the design, the pectoral fin consists of only one rectangular IPMC beam attached to a triangle-shaped passive fin, as shown in Fig. 4(b). The shape is selected to mimic that of a fin of a tuna fish.



(a) (b)

Figure 4. (a) Design of caudal fin; (b) design of pectoral fin.

C. Wireless Control System Design

A reliable wireless control system is desirable to control the robotic fish remotely in a mobile sensing network. XBee has been recognized as a low-cost, low-power wireless communication technology and has been used for robotic fish communication [6]. Following the same idea, in this paper, two XBee communication devices were used for receiving command data. One Xbee was connected to a PC to send a command to the robotic fish. Another Xbee was located on the robotic fish to receive the command. The radio frequency (RF) data rate was 250 kbps, the indoor/urban range was 30 m, the frequency band was 2.4 GHz, and the serial data rate was ranging from 1,200 bps to 250 kbps. Since the robotic fish swims on the surface of water, RF signals are receivable if the RF antenna is placed outside of the water surface.

An on-board control system for the robotic fish was developed in order to achieve 2D maneuvering capabilities. All fins need to be controlled well in order to generate the main thrust force and steering moment. The on-board wireless control system design is shown in Fig. 5. A microcontroller was used to generate control signals for the pectoral fins and caudal fin. These three digital signals were driven by three H-Bridges.

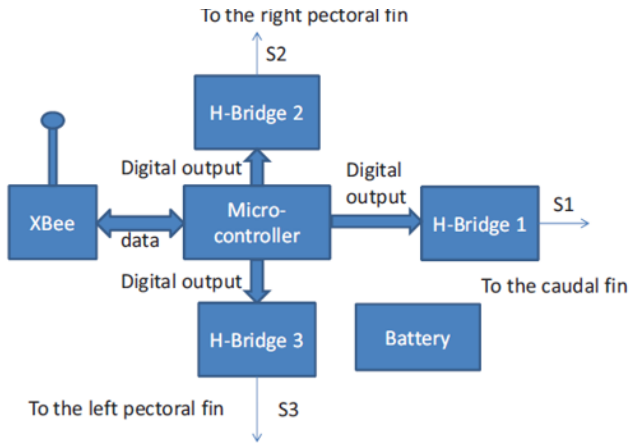


Figure 5. On-board wireless control system design.

III. Fabrication of Robotic Fish

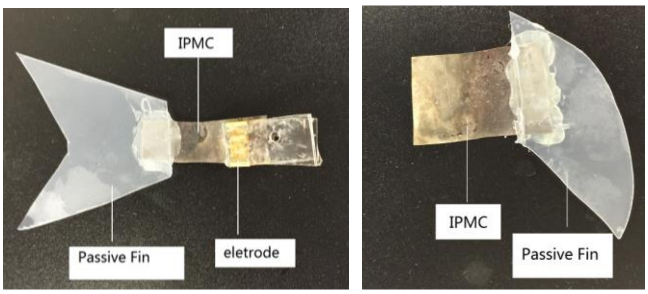
Based on the bio-inspired design described in Section II, a robotic fish was fabricated by following four steps: (1) fabrication of IPMC artificial fins, (2) construction of fish body, (3) realization of on-board circuit, and (4) assembly of robotic fish.

A. Fabrication of IPMC Artificial Fins

To fabricate the artificial fins, the first step was to fabricate an IPMC artificial muscle. This was based on the process developed in [30]. The material supplies used in the process were the following: (1) Nafion ion exchange membranes, Nafion 1110 (240 um thick) (DuPont); (2) tetraammineplatinum chloride 98% (Sigma Aldrich); (3) sodium borohydride (Sigma Aldrich) ($NaBH_4$, reducing agent for reduction); (4) dilute ammonium hydroxide solution (Sigma Aldrich) (NH_4OH 29% solution); and (5) deionized (DI) water. The following fabrication steps were used to fabricate the IPMC:

- Step 1: Clean the nafion film with hydrochloride acid (HCl): Boil the nafion film in 1.0N HCl at 80°C for 30 min. and then rinse with DI water to remove acid residue (this step is used to remove metal particles and other impurities from the film).
- Step 2: Activate ion exchange: In a separate beaker, mix 50 mL DI with 50 mg tetraammineplatinum chloride hydrate. Immerse the membrane in the platinum solution. Add 1 mL ammonium hydroxide 29% to balance the acid. Wait at least one day (at least three hours).
- Step 3: Perform platinum reduction: Fill a large beaker about one-third way with DI, and add the membrane from Step 2. Heat the water to 80°C. Mix 0.5 g sodium borohydride and 25 mL cold DI in a beaker. Add 2 mL (1 full pipet) of the solution into the water bath (avoid deformation of the membrane by pouring a small amount of solution at a time). Observe the reaction of the platinum particles (a black layer of fine platinum particles should deposit on the surface of the membrane).
- Step 4: Carry out further deposition: Repeat Steps 2 and Step 3 to deposit more platinum on the membrane surface.

After the IPMC was fabricated, it was cut into rectangular shapes and bonded with a passive plastic film using epoxy. The fabricated caudal and pectoral fins are shown in Fig. 6.



(a) Caudal fin (b) Pectoral fin

Figure 6. (a) Artificial caudal fin; (b) pectoral fin, both actuated by IPMC.

B. Body Fabrication

The fish body was used to house an on-board circuit, battery, sensors, and camera. The body needs to have a hydrodynamic shape so that drag force can be minimized. The body was designed using Autodesk Inventor. The body consisted of two shells clamped together using screws. Inside the shells were two chambers: one used to house the electronic circuit and battery, and the other used to provide a platform for some specific underwater applications, since this was the goal of the research. The fish body was printed with acrylonitrile butadiene styrene (ABS) material using a 3D printer (Dimension, bst1200es). Since the density of the material is lighter than water, it was easy to make the robotic fish move near the water's surface in order to receive the command from XBee. The fish body consisted of two chambers. The front chamber housed the on-board control circuit, communication device, and battery. The rear chamber was reserved for future sensors or a camera, which could be embedded into the robotic fish for future sensing network applications. Two copper electrodes were placed at the rear aside of the fish to provide actuation voltage signals for the pectoral fins, and one copper electrode was placed at the rear of the fish for applying a voltage signal to the caudal fin. Fig. 7 shows an inside view of the fish body.

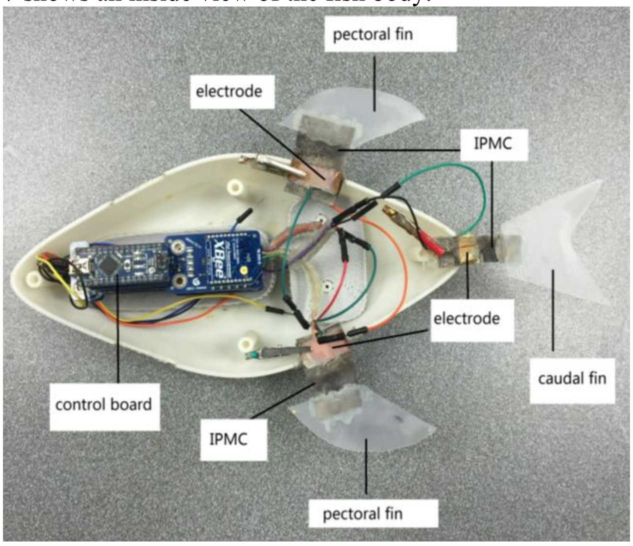


Figure 7. Inside view of fish body.

C. On-Board Circuit

A micro-controller board (Nano, Arduino), which can generate a frequency-varying square signal that is applied to the caudal fin to control the forward swimming speed, was used for the robotic fish. The microcontroller can also generate digital output signals to control the pectoral fins, which generate a turning motion. Three H-Bridges (Gravitech, 2MOTOR-4NANO) were used to amplify the actuation driving current to propel the pectoral and caudal fins. An XBee board (Digi International Inc., XB24-ACI-001) was used for the wireless communication. Since the robot swims on the surface of water, an RF antenna was placed outside the water surface so that the robot could obtain good RF signal reception. A lithium ion polymer battery (Tenergy, 7.4V 6000 mAh) was used to provide electricity to the robotic fish.

D. Assembled Robotic Fish

Fig. 8 shows the assembled robotic fish. The battery and on-board circuit were put into a disposable glove (Ansell, 92-675), and the glove was sealed using tightened stainless steel wires. This water-proof treatment was good enough because the robot only swam on the water's surface. After putting all components into the fish body, the two shells were clamped together with screws. The total weight of the robot was 290 grams. Overall, the fish had slightly positive buoyancy.

Figure 8. Assembled robotic fish.

IV. Experimental Results

A. Power Consumption Measurement

Power consumption is one of the critical issues in an autonomous underwater vehicle. One of the advantages of using IPMC artificial fins in a robotic fish design is to utilize the low power consumption of IPMC. Chen *et al.* characterized the power consumption of the IPMC artificial fin [28]; however, this characterization only included the power consumed by the IPMC, not the power consumed by the driving circuit. It was discovered that the H-Bridge became hot after a few minutes of operation. Since the energy lost in the H-Bridge is not negligible, it should be included in the total power consumption of the IPMC artificial fin. To characterize the total power consumption more accurately, an experiment was set up as follows: A DC power supply (Kepco, BOP 20-10D) was connected to the H-Bridge. The DC voltage was set at 7.32 V, 6.42 V, and 5.73 V. A square wave signal was generated from the micro-controller and sent to the H-Bridge. The frequency of the square wave signal was changed from 0.48 Hz to 3.3 Hz. Both the output voltage and current from the DC power supply were measured. Fig. 9 shows the measured voltage and current output when the actuation frequency was 0.55 Hz. The output voltage was 6.42 V. During one period, there was a peak current up to 2 A when the voltage flipped and then the current dropped down to 500 mA.

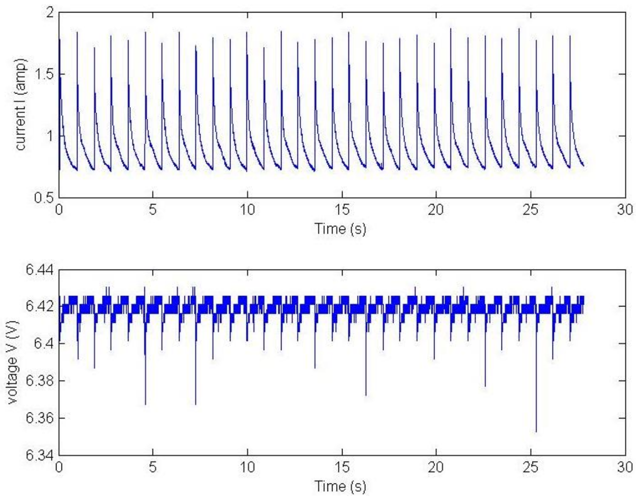


Figure 9. Measured actuation voltage and current.

The power consumption was calculated by

$$P = \frac{1}{T}\int_0^T i(t)u(t)dt. \quad (1)$$

where $i(t)$ is the output current, $u(t)$ is the output voltage, and T is the duration of measurement. During the test, only the caudal fin was actuated. Fig. 10 shows the power consumption versus the operating frequency and input voltage. Overall, the power consumption of the caudal fin was 4.4 W, while the input was 5.73V and the frequency was 0.48 Hz. As shown in Fig. 10, the power consumption increased as the frequency increased. The reason why the overall power consumption was too high is that too much heat was wasted on the H-bridge. To solve this problem, in the future, it will be necessary to find a way to cool down the temperature of the H-bridge in order to improve its conversion efficiency.

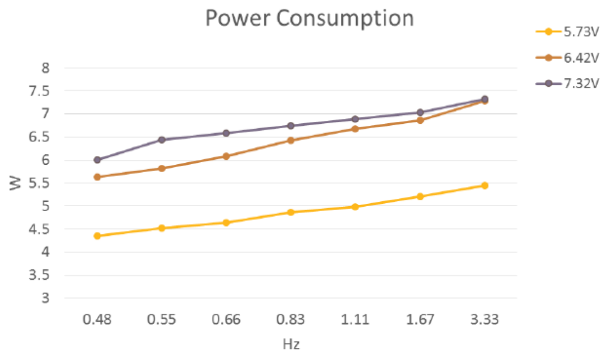


Figure 10. Power consumption versus operating frequency and input voltage.

B. Straight Forward Swimming Test

The robotic fish was tested in a 550-gallon water tank (97 inches long, 38 inches wide, and 37 inches deep). A digital camera in an IPhone 6 smart phone was used to capture a movie of the swimming robotic fish. Fig. 11 shows six snapshots of a forward swimming test. Each snapshot was taken every 5 seconds. The fish's forward swimming speed was controlled by changing the flapping frequency of the caudal fin [26]. A square wave signal with 7.3 V magnitude and 0.55 Hz frequency was applied to the caudal fin. The pectoral fins were also actuated.

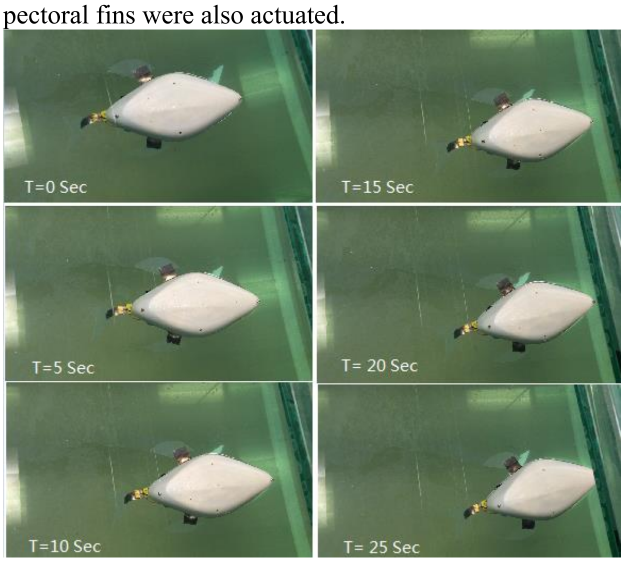


Figure11. Snapshots of forward swimming test.

The swimming speed was calculated based on how long the robotic fish passed through two fixed lines. The forward swimming speed reached about 0.5 cm/sec. Also, there was a threshold, whereby the frequency was neither too high nor too low for the fish to swim. The forward speed versus the actuation frequency is shown in the Fig. 12. To improve the speed, optimization of the fins and body will be necessary, which will be the focus of a future endeavor.

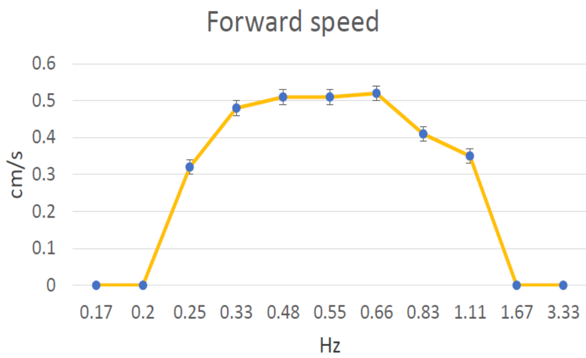


Fig. 12. Forward speed versus actuation frequency.

C. Turning Tests

Turning tests were conducted to verify the steering capability of the pectoral fin. To make a left turn, the left pectoral fin was actuated with the same actuation signal applied to the caudal fin while the right pectoral fin was kept inactive. The caudal fin provided the forward swimming direction, while the force generated by the left pectoral fin made the fish tail turn to the left. To make a right turn, the right pectoral fin was actuated with the same actuation signal applied to the caudal fin while the left pectoral fin was kept inactive. Actuation of the right pectoral fin made the fish turn to the right. The left turning speed reached about 1.5 rad/second. The right turning speed was achieved at 1.5 rad/second. Similar to the forward swimming test, there were two thresholds for the actuation frequency. When the frequency was neither too high nor too low, the fish did not turn, as shown in the Fig.13.

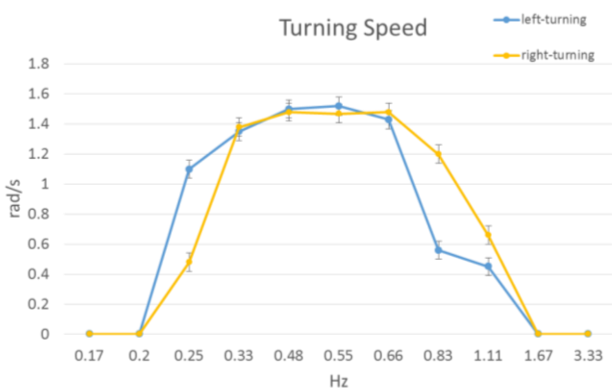


Figure 13. Turning speed versus actuation frequency.

V. Conclusion

This paper explains the development of a 2D maneuverable robotic fish propelled by multiple IPMC artificial fins. The robot design was inspired by a biological fish, which uses a caudal fin for its main propulsion and two pectoral fins for steering. By controlling the pectoral fins with XBee, the robotic fish was able to make left and right turns as well as swimming forward. The free-swimming tests showed that the fish can reach a forward speed of up to 0.5 cm/sec. The left turning speed and right turning speed can reach up to 1.5 rad/sec. With the multiple-fin propulsion, the robot demonstrated its 2D maneuvering capability, which shows its potential in underwater sensing network applications.

Future research will be conducted in the following four directions: (1) hydrodynamic modeling of fins, (2) optimization of fish fins and fish body, (3) modeling and control of the robotic fish, and (4) applications in a mobile underwater sensing network.

Acknowledgment

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