Proceedings of the ASME 2016 Dynamic Systems and Control Conference
DSCC2016
October 12-14, 2016, Minneapolis, Minnesota, USA

DSCC2016-9915

BIO-INSPIRED ROBOTIC FISH PROPELLED BY MULTIPLE ARTIFICIAL FINS

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ABSTRACT

With advances in actuation and sensing, smart materials has drawn a growing attention from researchers in under water robotic fish. In this paper, a compact, noiseless, and untethered biomimetic robotic fish propelled by Ionic Polymer-Metal Composite (IPMC) actuators is developed. The robot fish employs two pectoral fins to generate steering and one caudal fin to generate main propulsion. A passive plastic fin is attached to the IPMC beam to enhance propulsion. With multiple IPMC fins, the fish is capable of 2D maneuvering. One small size programmable circuit board is designed for the 2D controllable fish. The Experimental results have shown that the forward-swimming speed can reach up to 1cm/sec and the both left-turning and right turning speed can reach up to 2 rad/sec.

INTRODUCTION

In the last few decades, biomimetic systems, such as robotic fish, have been receiving a growing interest towards bio-inspired design, physics-based modeling, maneuvering capability, and high energy-efficient. Since under water robotic fish can do multiply tasks, such as monitoring deep water drilling platform and locating underwater pollution, currently many groups have been developing robot fish, such as robotic fish [1, 2], soft body robotic fish [3]. Most of these robotic fish use traditional electric motors and sever motors to generate rotation and flap movement. However, most electric motors and sever motor generate a lot of noises during operation, which makes those robotic fish difficult to merge into marine life environment. Moreover, traditional electrical motor and sever motor mechanic power transmission are too bulky and heavy for small scale biomimetic robotic fish, which are of more interests in many applications. Last, the traditional electrical-motor driven fish needs a power transmission to translate rotation to flapping, which reduces the energy efficiency during the energy conversion.

Compliant underwater propulsion requires a soft actuator. Electroactive polymers (EAPs) also called artificial muscles are attractive soft actuator for aquatic robots to achieve compliant underwater propulsion. Two typical types of EAP materials are Dielectric EAPs [4] and Ionic EAP. Dielectric EAPs, which is another type of EAPs, can generate a large force with large bending displacement. But the dielectric actuation voltage is much higher than the IPMC actuation voltage requires. It is normal around 1 to 2 KV, which is dangerous for the use as actuator in bio-inspired robotic fish because of the wet condition. Ionic EAPs are driven by ion transportation induced swelling effect, which requires low actuation voltage. Ionic Polymer-Metal Composite (IPMC) is one type of ionic EAP. An IPMC sample typically consists of a thin ion-exchange membrane (eg. Nafion), chemically plated on both sides of the surfaces with rare metal as electrode [5]. When a voltage is applied to the IPMC, transport of hydrated cations and water molecules within the membrane, and associated electrostatic interactions lead to bending motions hence to the actuation effect, as shown in Fig. 1 [11]. Since IPMCs can work under wet conditions, IPMC-based robotic fish have been reported by several groups. 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 [7]. An IPMC-powered robotic manta ray and cow-nose ray have also been developed [8, 9]. The resulting robotic fish or rays only demonstrated one-dimensional (1D) swimming. However, 2D or 3-dimensional (3D) maneuvering capabilities were limited because they utilized only one IPMC artificial fin, either pectoral or caudal, which prevents these robotic fish from achieving maneuvering capabilities exhibited by real fish, such as turning, hovering, and breaking. To achieve 2D or 3D maneuvering capabilities, a multiple-fin propulsion is in great need for the robotic fish to accomplish some real world application, such as environmental monitoring and intelligent collection.

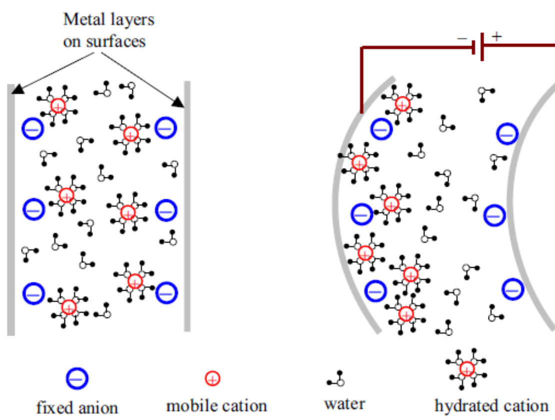


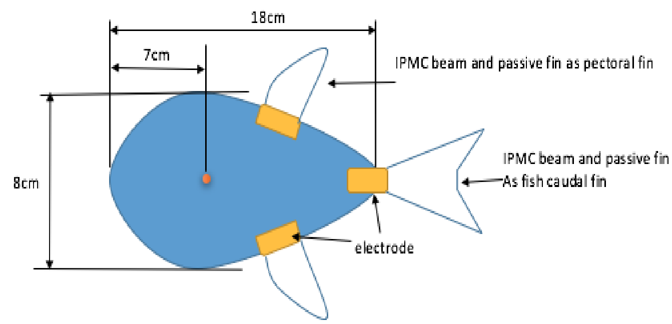
Fig. 1 Actuation mechanism of IPMC [11].

In this paper, a 2D maneuverable, compact and light-weight controlled robotic fish entire actuated by IPMC artificial muscle is developed. A light-weight multiply-fin propulsion is developed for the bio-inspired robotic fish, which consists of two pectoral fins for steering and one caudal for main propulsion. All the fins are actuated by IPMC artificial muscles, which makes the actuation part light and compact. With multiple IPMC fins, the fish is capable of 2D maneuvering. An on-board programmable controller makes the fish free-swimming and controllable. Because there is not gears and electrical motors involved, with noiseless and compliant actuation of IPMC the fish can swim quietly during the system operation, thus the fish can achieve stealth maneuvering capability. The Experimental data shows that the robotic fish is able to turn right, left, and move forward by activating different fins. This work advances our previous work [10] by optimizing the fin design, body shape design, on-board circuit design, which doubles the forward swimming speed and turning speed.

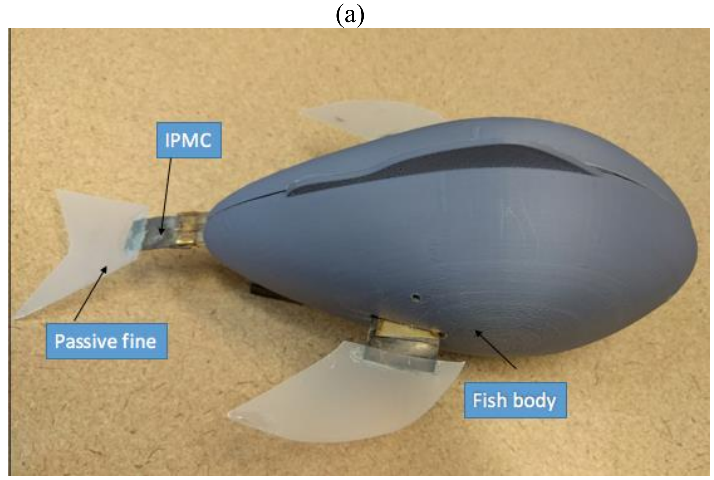
The remainder of the paper is organized as follows. Design of the robotic fish is described in Section II. Fabrication of the robotic fish is presented in Section IV. Experimental data and results are illustrated in Section V. Finally, conclusion and future work are provided in Section VI.

DESCRIPTION OF IPMC-PROPELLED ROBOTIC FISH

Fig. 1(a) shows the schematic of the robotic fish, and Fig. 1(b) shows a prototype, which is an upgraded version of the one reported in early prototype [10]. The fish is designed to be a fully autonomous and aquatic sensing platform. It consists of a rigid body, one IPMC actuated caudal fin and two IPMC actuated pectoral fins. Two gold-coated copper electrodes are used for applying voltage to the IPMCs, which reduces the corrosion of the electrodes in water. Corrosion of the electrodes will cause high resistance between IPMC and electrodes, thus downgrades the actuation performance of the IPMC. The IPMC actuator is attached with a plastic passive fin to enhance propulsion [7]. The fish body has a water-drop shape, which is optimized to reduce the water resistance during forwarding and turning movement. Thus the new body design can increase the energy efficiency and achieve faster cruising speed. Also the shell body has enough interior room to locate rechargeable batteries and electronic circuits for the control proposes. All of these components are zipped in a plastic bag to ensure waterproof of those electronic components. Without the hybrid tail. The fish is about 18 cm in length and 8 cm in diameter. Total inside volume around 140 cm^3. The robotic fish is about 150 g.



(a)



(b)

Fig. 2 (a) Schematic of the robotic fish. (b) Prototype of the robotic fish

A. 2D Maneuvering Mechanism

Two-dimensional maneuvering capability of robotic fish can be achieved by activating multiple pins in different combination [10]. Fig 3 shows the mechanism of the 2D maneuverable robotic fish that driving by different fins. The fish G point is defined as the center of mass. For forward swimming, all fins are activated, as shown in Fig. 3(a). The caudal fin generates main forward thrusts to achieve forward swimming. Pectoral fins are locate at both sides of fish symmetrically, thus can generate assisting forward thrusts. For left turning, the fish's left pectoral fin and caudal fin are activated, as shown in Fig. 3(b). The composition of two forces that generated by caudal fin and left pectoral fin pushes the fish body to move to the right but turn the fish to the left, thus achieves left turning. For right turning, the fish's right pectoral fin is activated and caudal fin is activated as well but the left pectoral is deactivated, as shown in Fig. 3(c). The composition of two forces that generated by caudal fin and right pectoral fin pushes the fish body to the left side but turn the fish to the right, thus fish can achieve right turning.

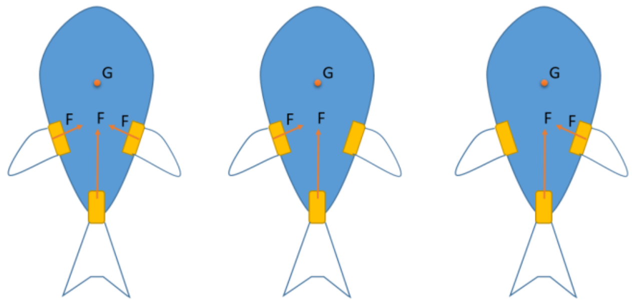


Fig. 3. 2D maneuvering capability achieved by multiple fins. (a) forward swimming; (b) left turning; (c) right turning.

B. Caudal Fin and Pectoral Fin Design

Chen *et al.* developed a speed model for robotic fish [7]. They prototype use one IPMC as caudal fin to generate propulsion force. Chen *et al.* also developed an artificial pectoral fin for a robotic cownose ray [8]. In this paper, we will use the same design about the caudal fin shape, as shown in Fig. 4(a). Since the pectoral fin in only used to generate the steering moment, the fin does not require 3D kinematic motion. To simplify the pectoral fin design, we use a triangle passive fin, which has one side curved, attached with an IPMC. Fig. 4(b) illustrates the design of pectoral fin.

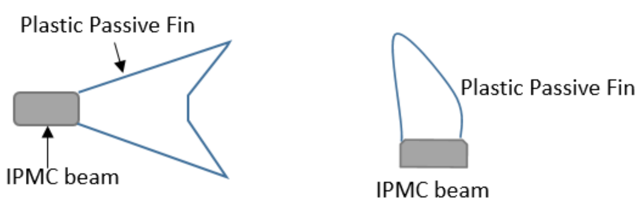
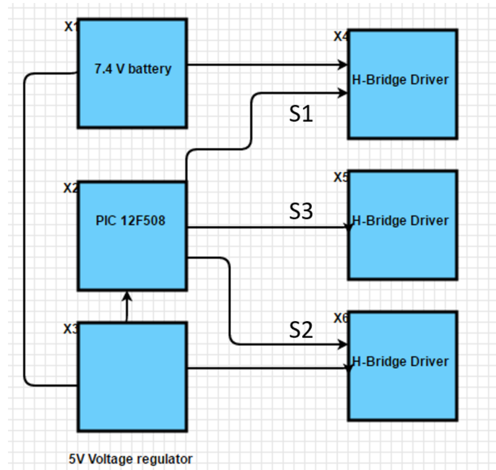


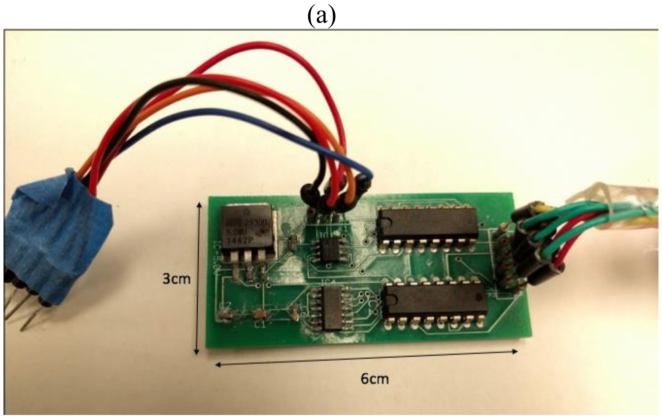
Fig. 4. Design of caual fin and pectoral fin.

C. On-boad Circuit

A light-weight on-board circuit was designed for the robotic fish to provide actuation voltages to the IPMCs, as shown in Fig. 5. A rechargeable 7.4 voltage 400 mAh AA portal Power Corp Lithium Ion Polymer batttery was used as the power source. A PIC12F508 microcontroller was used to generate three square wace control signals. The singal S1 and singal S2 were generated to drive the pectoral fins, respectively. The signal S3 was generated to drive the caudal fin. Because the microcontriller draws only 25 mA and the output current go thourgh the IPMC up to 500 mA, three H-bridge drivers were use to provide up to 2A peak current output to the IPMCs. The total weight of on-boarch circuit and one battery weight is around 20 grams.



(a)



(b)

Fig. 5 (a) Circuit Schematics. (b). Picture of the PCB

D. Fabrication of IPMC Artificial Fines

To fabricate the IPMC artificial fins, the fist step is to fabricate the IPMC. All the fabrication processes were modified from the processes reported in the article [12]. The required materials in the fabrication include:

(1) Nafion 1110. 240um thick. Nafion ion exchange membranes.
(2) Tetraammineplatinum Chloride 98%.
(3) Sodium borohydride (NaBH4, reducing agent for reduction)
(4) Dilute ammonium hydroxide solution (NH4OH 29% solution)
(5) De-ionized water

The following fabrication steps were used to fabricate the IPMC

1. Ion Exchange
    i) On a separate beaker, mix 50ml DI with 50mg Tetraammineplatium Chloride hydrate
    ii) Immerse the membrane in the platinum solution
    iii) Add 1ml Ammonium hydroxide 29% to balance the acid
    iv) Wait for a least 1 day (least 3 hours)
2. Reduction (Day2)
    i) Fill a large beaker about 1/3 way with DI and add the membrane from Step 3
    ii) Heat the water to 65 ºC
    iii) Mix 0.5 g Sodium Borohydride and 25 mL cold DI in a beaker
    iv) Add 2mL (1 full pipet) of the solution into the water bath (avoid deformation of the membrane by pouring little bit of solution at a time)
    v) Observe the reaction occurring with platinum particles (Bubbles should form)
    vi) A black layer of fine Pt particles should deposit on the surface of the membrane
    vii) Turn over the membrane every 5 minutes to balance the reaction on both sides of the membrane
    viii) Repeat procedure #4 multiple times until all the solution is used
    ix) When finished (no more bubbles appearing on the surface of the membrane), wash the sample with DI
3. Further Deposition
    i) Repeat Step 1
    ii) Pl solution can be reused by adding 50mg Tetraammineplatinum Chloride hydrate
    iii) Add more DI as necessary to completely immerse the membrane in the solution
    iv) Repeat Step 2 (Day 3)

EXPERIMENTAL RESULTS

A. Power consumption Measurement

For autonomous underwater robotic fish, power consumption is one of big challenges. Experiments need to be done to characterize the power consumption of the robotic fish. In the power consumption tests, we set up the power supply to the microcontroller with a constant 7.3 voltage. This voltage was also supplied to the H-bride chips and the voltage regulator in parallel. A dSpace was used to collect the experimental data, including the voltage and current from the power supply. The power calculation was based on the equation:

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

where $i(t)$ and $u(t)$ are the measured current and voltage, respectively. T is the period of the applied voltage signal to the IPMC. All experiment data were measured within 30 seconds. The power measurement tests were done with the IPMC flapping frequency ranging from 0.4 Hz to 1 Hz. The measured voltage and current with 0.83 Hz flapping frequency are shown in Fig. 5.

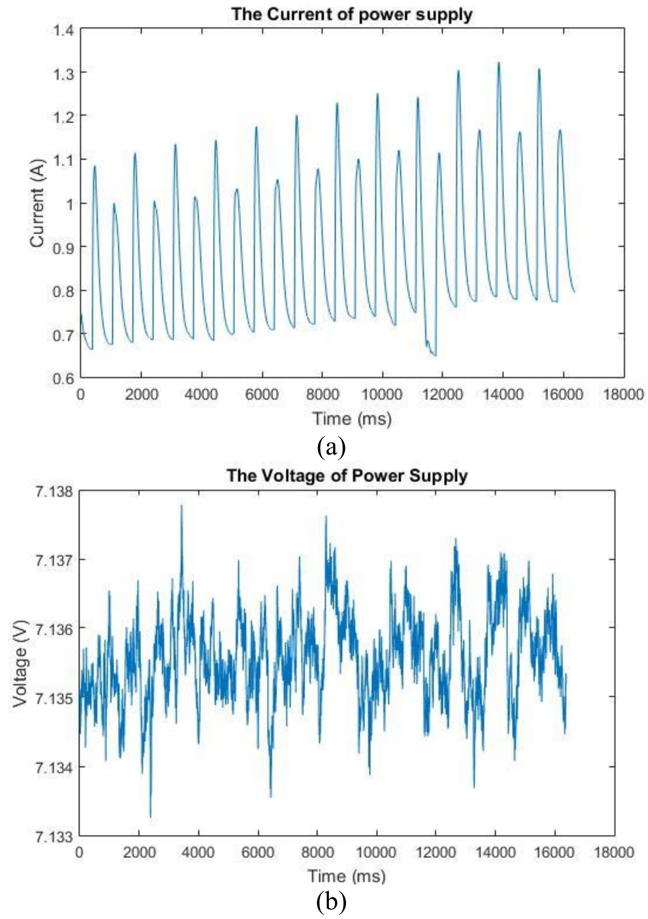


Fig. 6. (a) Measured actuation current, and (b) measured actuation voltage.

Power consumptions for the controller under different flapping frequency are illustrated in Fig. 7. We can clearly see that as the IPMC flapping frequency increased the total power consumption also increases.

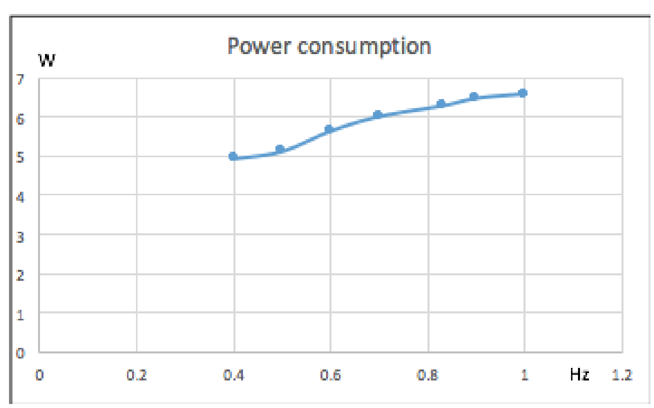


Fig. 7. Measured power versus frequency.

B. Straight Forward Swimming Test

The robotic was tested in a 550-gallon water tank. (250 cm long 98 cm wide, and 90 cm deep) A digital camera, web-camera logitechC920, was used to capture robotic fish moving motion. Fig. 8 shows six snapshots of a swimming robotic fish. Each snapshot was taken every 5 seconds. The fish's swimming forward was controlled by caudal fin. A square wave signal with 7.3 V and 0.5 Hz was applied to all the fins.

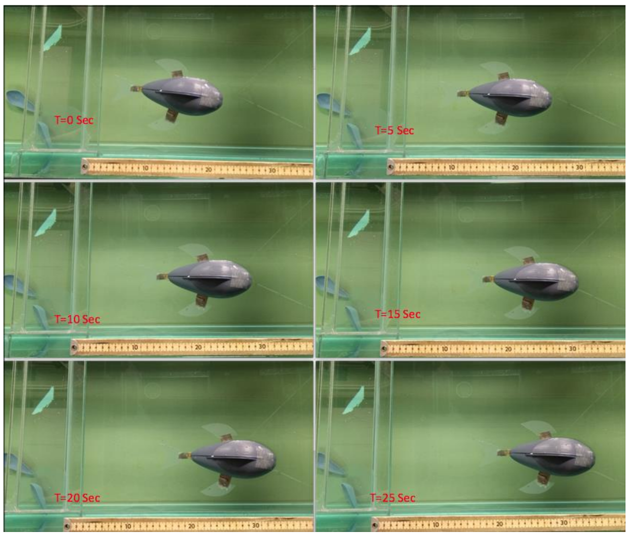


Fig. 8. Snapshots of forward swimming test under fix frequncey.

The fish swimming forward speed was calculated based on dividing the displacement between the beginning line and the ending line by the total swimming time. The forward speed versus the actuation frequency is in the Fig. 7. The fastest forward speed reached up to 9.35 mm per second, which is doubled compared to the speed reported in our previous study [10]. We can see that the speed becomes much higher after the fish body was optimized and the total weight was reduced.

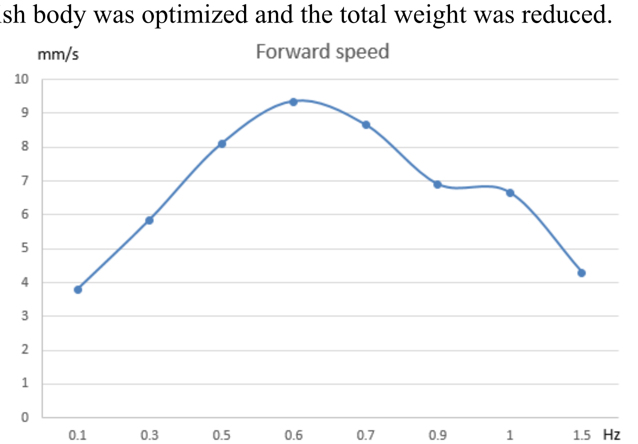


Fig. 9. Forward speed versus frequency.

C. Turning Test

Turning test was done to verify the robotic fish steering capability using two fish pectoral fins. To make the fish turn righ and left, the two pectoral fins need to be activated differently. When the fish was controlled to turn right side, the left side IPMC actuator and caudal fin were actived. The experiment test of fish turing as the same condition of forward swimming enviroment also in the same water tank. The controler frequency was set at 0.5 Hz. In the turnning test, the fish was controlled to turn left, which means that the right pectoral fin and caudal fin were activated. Six snapshots were taken every 5 seconds, which are shown in Fig 10.

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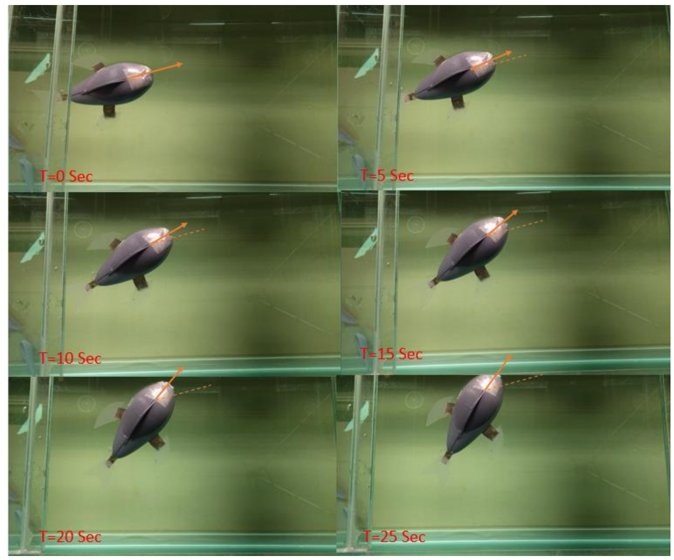

Fig. 10. Snapshot of swimming turning test.

The swimming direction was measured as an angle shown in Fig. 10. A average of turning speed was calcuated based on the angle difference divided by the time difference between two snap shots. Fig 11. inlustrates the turning speed versus the operational frequency. We found the fastest turning speed reached about 2 degree per second under the flapping frequency of 0.6 Hz..

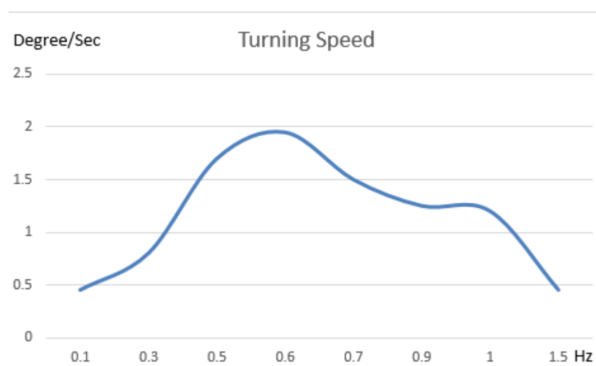

Fig. 11. Turning speed versus actuation frequncy.

CONCLUSION

This paper describes a development of 2D maneuverable robotic fish propelled by multiple fins actuated by IPMC artificial muscle. The robotic fish body were optimized with more hydrodynamic shape to reduce the water resistance force.

A light-weight electronic circuit was designed to control the fish forward swimming and turning. Experimental results show that the forward speed can up to 1 cm/sec and the turning speed can reach up to 2 rad/sec.

Future research will go through the following four directions: (1) Hydrodynamic modeling of fins and fish body. (2) Modeling the control of the robotic fish; (3) establishing a wireless communication through WIFI network to control the fish remotely; (4) Establishing a visual tracking system to localize the robotic fish for swarming control of the fish.

ACKNOWLEDGEMENT

This research was supported by the National Science Foundation under the Grant CNS#1446557.

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