A Biologically Inspired Ray-like Underwater Robot with Electroactive Polymer Pectoral Fins

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Abstract **– This paper describes an electroactive polymer robot with ray-like pectoral fins. Electroactive polymers are materials that change their geometry in response to electric field and can be used to replace electromechanical devices. The aim of this study is to show that these materials can be used to build more complicated devices and the behaviour of these devices can be coordinated to some extent. Both of the pectoral fins are built of eight electroactive polymer muscles. The experiments show that the fins are able to generate undulating motion and propel the body forward. The speed of the device is considerably slower than that of ray-like fishes but the device also has a smaller muscle mass and total mass ratio compared to aquatic animals.**

I. INTRODUCTION

Electroactive polymers (EAP) are materials that change their shape in response to electric field. Their working principle resembles closely the behaviour of biological muscles and therefore these materials are considered as a new emerging technology for robot actuators (see [1] for an overview).

The advantages of EAP compared to traditional electromechanical devices are their low energy consumption, noiseless motion and continuous flexibility. Since the devices built on EAP actuators have low metal concentration, it is difficult to detect them by metal detectors or radars. Therefore they are promising candidates for reconnaissance, intelligence gathering and surveillance. EAP materials are lightweight and permit building small devices.

Since EAP actuators are still in their early phase of development, they face difficulties characteristic to any emerging technology. Researchers still lack thorough understanding of the electrochemical processes taking place in these materials and their mathematical models are still an intensive research issue [2]. As a consequence EAP actuators lack efficient control methods. The applications reported so far (including the study at hand) drive the actuators in an open-loop manner. The manufacturing technology of EAPs is also in a developing phase. The properties of EAPs vary considerably and change in time (the muscles “get tired”). The devices reported so far use and off-board power supply because the lightweight materials are not able to carry the weight of the batteries.

In our earlier work [3] we have described a device with four muscles (two pectoral fins of an underwater vehicle, both consisting of two muscles). The experiments with this preliminary prototype showed that since the properties of EAP muscles are not uniform and change over time their behaviour is rather difficult to coordinate. The purpose of this study was to elongate the fins to replicate undulating motion and thereby prove that we are able to coordinate the behaviour of a more complicated device. The long-term goal of this research is to build and experimental platform that can be used for future studies of EAP actuator control methods. We also aim at using this platform to investigate biomimetic underwater locomotion inspired by fish swimming [4].

Applications of EAP reported so far include a dust wiper of a planetary rover [5], an application in an entertainment industry [6] and a hexapod robot [7]. Biomimetic EAP devices are inspired by a starfish [8], tadpole [9] or mimic a caudal fin [10] [11] and an annelid animal [12].

Our device consists of 16 EAP muscles (8 muscles on both pectoral fins). The test results show that we are able to coordinate the behaviour of the muscles. The muscles generate undulating motion and propel the body forward. Considering the number of muscles used, this is to our knowledge the most complicated device built on electroactive polymers.

This paper is organized as follows. In the rest of the introductory part we give an overview of electroactive polymers and a brief description of the biological background of ray-like swimming. In section II we describe the pectoral fin design, the robot and the experimental setup. Section III represents experimental results and compares them to biological evidence. The last section draws some conclusions about the experiment and describes the future work directions.

A. Electroactive Polymers

Electroactive polymer actuators change their geometry in response to electric field or current. Elasticity, damage tolerance and large actuation strains make them functionally similar to biological muscles.

There are several kinds of electroactive polymers and the shape change mechanism is somewhat different in case of different types. Electronic polymers (polypyrrole, etc.) contract when an electric potential is applied. The conformational geometry of molecules will change when the electronic structure is excited. These polymers require high voltage (several kV) on very low current for operation. They are remarkably strong, but their contraction is only some percentage of they total length.

In our application, we use another type of electroactive polymers, so called ionic polymer metallic composites (IPMC), which belong to the class of ionic conducting polymers. They bend in respond to electric current and their working principle is based on ion conduction.

The IPMC material is highly porous liquid filled ion fluorinated polymer, like Nafion®, Flemion®, Teflon® and their modifications. During material fabrication the free radical groups are replaced with metal ionic cations (Na, Li), so there is an excess of free cations in the material (see Fig. 1.). The polymer film is covered with a metal coating, usually platinum.

While applying electric current, the cations move to one side of the material causing expansion of the material from one side and contraction from the other side. Cations also capture some of the water molecules (Fig. 2.).

The bent conformation is an imbalanced situation. Water starts to diffuse in an opposite direction and the polymer sheet relaxes after some time (Fig. 3.). These materials do not keep their position under direct current. However their action length is remarkable and they operate at low voltage (1.2 – 7V). At the same time they are not so strong and require from dozens up to several hundreds of mA of current.

Fig. 4 represents a test with an EAP sheet manufactured by Musclesheet™.

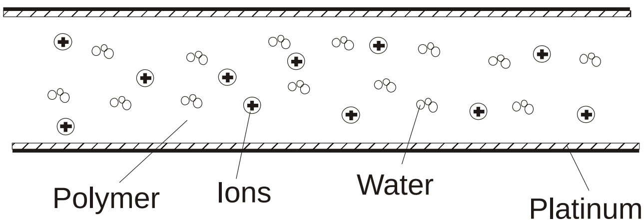

Fig. 1. EAP in an initial configuration

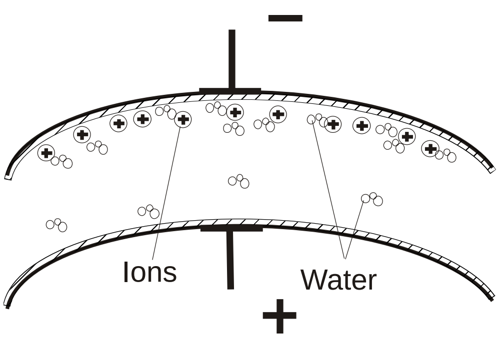

Fig. 2. EAP in a bent configuration**.**

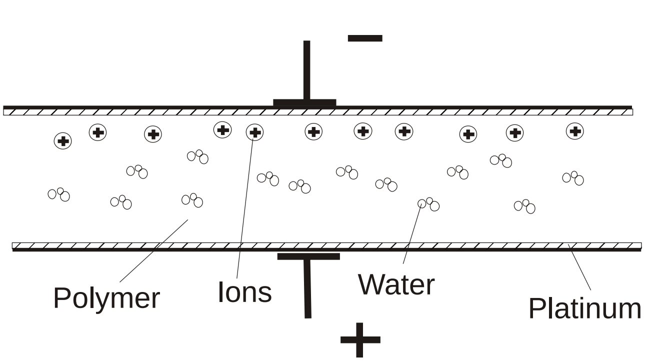

Fig. 3. EAP in a relaxing configuration**.**

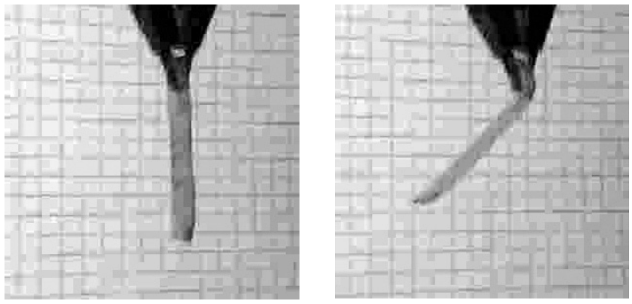

Fig. 4. A sample of an EAP sheet in an initial(left) and bent(right) configuration.

B Biological Background of Fish-Like Propulsion

Common kinematic variables that fishes and other aquatic animals modify to change swimming velocity include fin-beat frequency, amplitude, wave number and wavespeed [13].

Bottom-dwelling fishes like rays and stakes are characterized by a laterally compressed body (see Fig. 5 as an example). They propel themselves through water with large elongated pectoral fins. The swimming mode of rays is called rajiform swimming. In a rajiform swimming mode thrust is generated by passing vertical undulations along the pectoral fins. It is defined by having more than one wave present on the fins at the time.

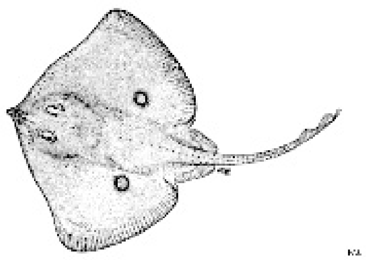

Fig. 5. African ray.

To our knowledge, there is only one study that attempts to model undulating pectoral fins using pneumatic actuators [14]. Compared to our research this study has complementary advantages and disadvantages. Pneumatics is a well established technology that permits building large and powerful devises. In the contrary, EAP actuators are an emerging field with immature control methods. EAPs are also better suitable for building small scale devices.

II. ROBOT DESIGN

A. The Pectoral Fins

The pectoral fins are shown in Fig. 6. Both of the fins consist of 8 muscle sheets. The length of the fin is 110mm. Each bottle-shape muscle is 40 mm long, 13 mm wide from the widest end that is attached to the frame and 4 mm wide at the narrowest place. The muscles of one fin are mechanically connected by a thin latex foil as shown in Fig. 6. The purpose of the bottle shaped form of the muscle is to prevent the latex foil from sliding over the tips of the muscles.

The muscles are cut from a 0.2mm - 0.5mm thick IPMC sheets provided by Musclesheet™. The sheet is an electroactive polymer film covered with a platinum coating.

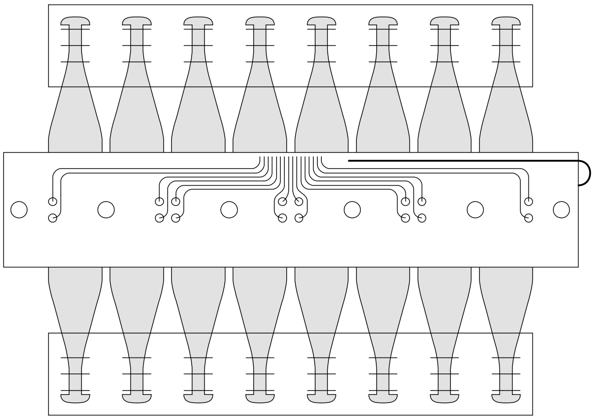

Fig. 6. The outline of the robot.

B. The Robot

Fig. 6 represents the design concept of the robot.

The fins of the robot are attached to a 28mm ×140 mm frame. The frame consists of upper and lower parts made of organic glass. The fin muscles are fixed to the frame with the help of textolite contacts. A 0.15μm thin layer of cold is evaporated to the surface of the textolite in order to confirm a reliable contact with the muscle and to prevent ion exchange with the polymer through the platinum cover of the muscle. The contacts at the lower organic glass frame are for a ground signal and are connected to each other. The upper contacts are separated and permit driving each muscle independently. The upper part of the frame has 16 openings for the signal wires and 6 large openings for screws that press the upper and lower part of the frame tightly against each other.

The device is attached under a piece of foamed polystyrole to make it positively buoyant.

Fig. 7 represents the photo of the robot floating in the tank.

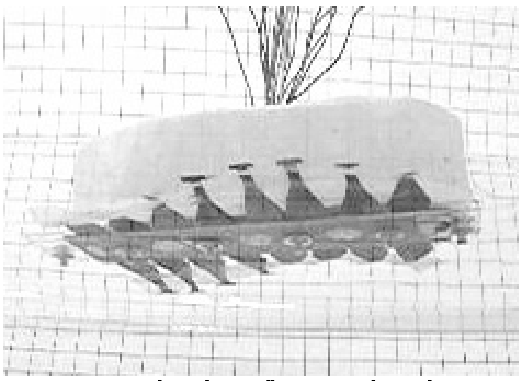

Fig. 7. The robot is floating in the tank.

C. Experimental Setup

The experimental setup is represented in Fig. 8.

The device lies in a tank filled with deionized water. Deionized water is used to prevent contamination of the polymer film through the platinum coating. Since deionized water does not conduct electricity, the contacts of the muscles do not have to be isolated.

To test the performance of the robot we control the muscles and record the signals with an off-board computer running National Instruments LabView 7.

The muscles of the fins oscillate with the period of 2.5s and with 40 degrees of a phase shift to generate thrust. Those signals are generated by NI PCI 6703 and measured by NI PCI 6304. The best shape of the signal was found during the experiments by trail and error. The wavelength is 144mm. The wave propagation speed is 50mm/s.

Because of the high current intensity of the muscles the data acquisition board cannot control the muscles directly. Instead, we use an additional power supply (for 12V car batteries) and a current amplifier.

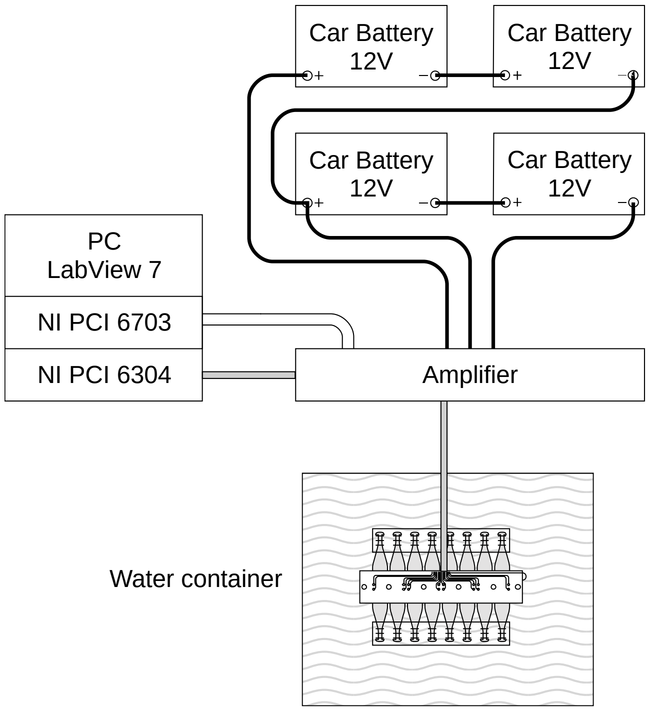

Fig. 8. Experimental setup.

III. EXPERIMENTAL RESULTS

The video clips of the experimental runs are available at http://simpol.mkem.uu.se/public/alvo/latest/DSCN0948.MOV.

The voltage and current are measured on the contacts of a muscle by NI PCI6034 during the propulsion. The characteristics of a single muscle are represented in Fig. 9.

The experiments show that the fins are able to propel the body forward.

During the experiments it was observed that the stiffness and torsional moment of the power supply wires considerably reduced the speed of the robot. We first planned to measure the thrust generated by the device but had to postpone these experiments until we have eliminated the influence of external forces.

Other parameters that characterize the trials are the following:

1) Average speed of the robot was measured by visually inspecting the videotapes and is approximately 0.005 mm/s. For comparison, swimming speed of a plaice is 0.34 m/s [15].

2) Speed with respect to the body length. The swimming speed of fishes is often measured with respect to their body length. The speed of this device is 0,038 BL/s. For comparison, typical swimming speed of a sting ray is 1-2 BL/s [16]. The swimming speed of this device is thus considerably lower than of the aquatic animals.

3) Wave propagation speed. The average distance between two muscles is 13.6 mm. The phase shift of two muscles is 40 degrees. So the wavelength is (360/40)*13.6 mm = 122.4 mm. The period was 2.5 s. The wave propagation speed is thus 122.4 mm / 2.5 s = 48.96 mm/s ≈ 0.05 m/s. In comparison, the mean wave speed of a sting ray is 0.23 m/s, e.g. approximately an order of magnitude higher [16].

4) Swimming efficiency is the ratio of the overall swimming speed and wave propagation speed [4]. The speed of the fish is 0.005 m/s. Thereby the swimming efficiency is (0.005 m/s) / (0.05 m/s) = 0.1.

5) The wave amplitude is approximately 15mm.

6*) Total weight/ muscle weight ratio.* The wet muscles with the latex foil device weight approximately 6 g while the robot weights approximately 60g (without wires). The device is thus able to carry about 10 % of its own weight. At the same time, in many fishes the muscle tissue comprises 50% - 60% of their body mass.

7) Frequency of muscle oscillation was adjusted by trial and error to give the maximum actuation strain. The near-optimal frequency is 0.4 Hz. Frequency of a biological muscle at maximum power is 1.9Hz – 173Hz [17].

8) The average power consumption of one muscle is 2.2W.

9) The peak power consumption is 20.7W.

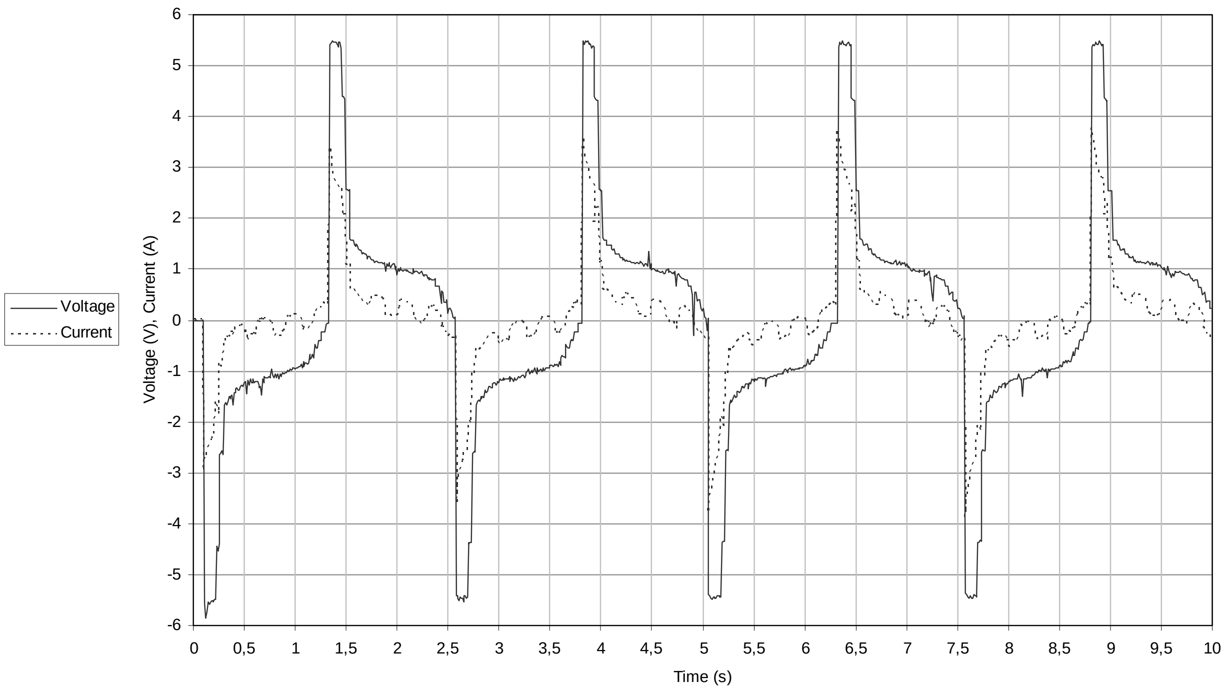

Fig. 9. Voltage and current measured on the contacts of a muscle by NI PCI6034 during the propulsion. After every 0.28s a pair of muscles reaches a phase, where they consume 3.5 A of current. Small oscillations on the current waveform are the outcome of that.

IV. CONCLUSIONS

This paper describes an electroactive polymer underwater robot with two pectoral fins. Both of the fins consist of eight EAP muscles that generate undulating motion. The test confirmed that the undulating fins can propel the body forward with the speed of 5 mm/s.

The speed of the device is also decreased because of the stiffness of the power supply wires and we therefore did not manage to measure the force generated by the actuators. This remains a topic of our future experiments.

The speed of the device and the swimming efficiency is considerably lower than that of aquatic animals. At the same time, the muscle mass and total mass ratio is considerably less than of animals.

The further goal of our studies is to use this experimental platform in a future to develop more sophisticated control methods of EAP actuators.

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