Towards a biomimetic EAP robot

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Abstract

This paper describes preliminary experiments with an EAP (electro-active polymer) robot. The research reported here serves two purposes. First, we aim at building a testbed to investigate control methods of EAP actuators. Second, we wish to build an underwater robot that mimics undulating motions of pectoral fins. The prototype described in this paper has two pectoral fins. The tests confirm that the fins are able to generate thrust and move the robot forward. The mechanical design of the fins is reliable but the results largely depend on the properties of the electroactive polymers.

1. Introduction

Underwater vehicles almost exclusively use propellers or jets to move in water and are powered by electromechanical devices. At the same time, most of marine habitants use radically different means of locomotion. Smart materials, like EAP, which can be used as artificial muscles, pave the way to a great variety of biomimetic approaches for underwater vehicle design.

Theoretically, robots with EAP actuators have several advantages over their conventional counterparts. They are lightweight, have a high number of degrees of freedom, consume little energy and are environmental friendly. Due to the material, their electromagnetic field is practically undetectable. Fish-like propulsion would also generate a less conspicuous wake. The last two properties together with the noiseless motion make these robots especially valuable for reconnaissance, military inspection and intelligence gathering.

At the same time, EAP actuators have several disadvantages compared to conventional underwater vehicles with DC motors and rigid links. The electrochemical processes taking place in EAP materials are not yet thoroughly understood and therefore efficient control methods of EAP actuators have not yet evolved. Only very few studies address the problem of the closed-loop control of EAP actuators (Richardson et.al., 2002). Low energy density and softness of the EAP material makes building large and powerful machines difficult.

This research reports preliminary attempts to build a biomimetic fish-like EAP robot. The aim of the research is twofold. First, we aim at using the robot as a testbed to develop control algorithms for EAP actuators. Second, we aim at replicating the undulating motions of ray fins to discover effective ways of locomotion for biomimetic underwater vehicles.

The rest of this paper is organized as follows. The rest of the introduction motivates our research by describing swimming modes of ray-like fishes and by giving an overview of electroactive materials. Section 2 describes the design of the robot and the experimental setup. Section 3 describes the experimental results. The paper ends with conclusions about the current research and future work directions.

1.1. Biological Inspiration

Aquatic animals use a great variety of means for propulsion and maneuvering, see (Sfakiotakis et.al., 1999) for an overview.

Rays belong to the group of batoid fishes that are characterized by flattened bodies and pectoral fins (see Figure 1.). While the swimming behaviour among different species of batoid fishes varies considerably, it can be by and large divided into two major swimming modes (Rosenberger, 2001). Axial-based locomotion means propelling through the water by moving body and tail. Pectoral-fin-based swimming means locomotion with help of greatly expanded pectoral fins.

Pectoral-fin-based locomotion is in turn divided into rajiform locomotion and mobuliform locomotion. 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. Mobuliform locomotion is the oscillation of the pectoral fins. The fins move up and down with less than half of a wave on the fins and locomotion is similar to flapping the wings in birds.

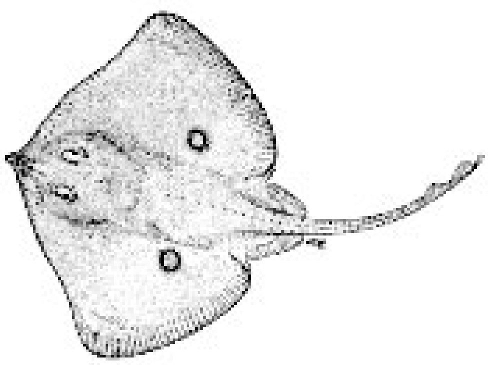

Figure 1. A batiod fish, African ray *(raja africana)*.

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

Apart from swimming, batoid fishes demonstrate remarkable acceleration, great maneuverability and ability to hover in mid-water to compensate changes in temperature, currents and pressure. A recent study suggests that batoid benthic species use hydrodynamic ground effect to increase their swimming efficiency (Webb, 2002).

All these properties suggest that batoid fishes can be excellent models of an underwater vehicle. Oscillatory locomotion of fishes has been replicated in several studies (Kato and Inaba, 2001), (Mojjarad and Shahinpoor, 1997), (Manson and Burdick, 2001). To our knowledge, there is only one study that attempts to model undulating pectoral fins using pneumatic actuators (Sfakiotakis et.al., 2001).

1.2. Electroactive Polymers

Electroactive polymer actuators change their geometry in respond to electrical potential. Elasticity, damage tolerance and large actuation strains make them functionally similar to biological muscles. See (Bar-Cohen, 2001) for a thorough overview of EAP artificial muscles and actuators.

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 electro-active 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 Figure 2). The this 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 water molecules (Figure 3).

The bent conformation is an imbalanced situation. Water starts to diffuse in an opposite direction and the polymer sheet relaxes after some time (Figure 4). These materials do not keep their position under direct current. However their action length is remarkable, 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.

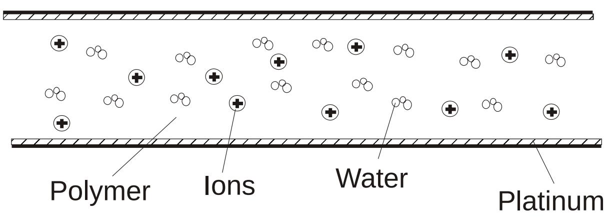

Figure 2. EAP in an initial configuration.

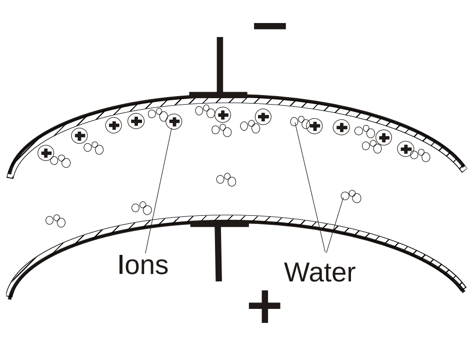

Figure 3. EAP in a bended configuration.

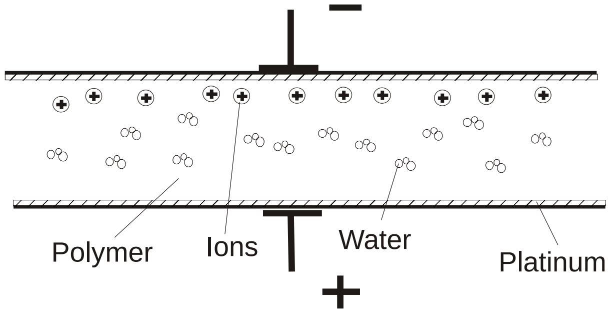

Figure 4. EAP in a relaxing configuration.

Applications of EAP reported so far include a dust wiper of a planetary rover (Bar-Cohen et.al., 2000), an application in an entertainment industry (Hanson et.al., 2001) and a hexapod robot (Eckerle et.al., 2001). Since EAP materials usually operate in a solvent environment it is not surprising that biomimetic EAP devices are inspired by a starfish (Otake et.al., 2003), tadpole (Jung et.al., 2003), mollusk (Tadokoro et.al. 2002) or mimic a caudal fin (Mojarrad 2000), (Guo et.al. 2003).

2. Robot Design

2.1. The Pectoral Fin

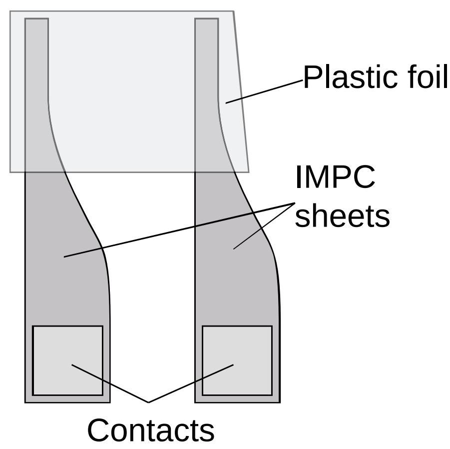

Figure 5. The pectoral fin.

The pectoral fin of the robot is composed of two 0,2 mm - 0,5 mm thick stripes of the IPMC sheets provided by Musclesheet™. The IPMC sheet is an electroactive polymer sheet covered with a platinum coating.

The length of each IPMC sheet is 50 mm. The width of the stripe is 12 mm at one end and 3 mm at the other end.

Contacts are attached to the wider end. They are made of gold foil to prevent ion exchange with the platinum coating of the muscle sheets. The fin operates in a tank of deionized water, therefore the contacts do not have to be electrically isolated.

Thinner ends of the two stripes are connected together with a thin plastic foil (see Figure 5).

2.2. The Robot

The robot consists of two pectoral fins on both sides of a 0,5 mm thick plastic frame (see Figure 6). The size of the frame is 27 mm × 35 mm. The frame is used to attach the gold contacts tightly against the platinum coating of the muscle sheets. The body is made buoyant by fixing the frame under a piece of penoplast. The device lies in a tank filled with deionized water (see Figure 7).

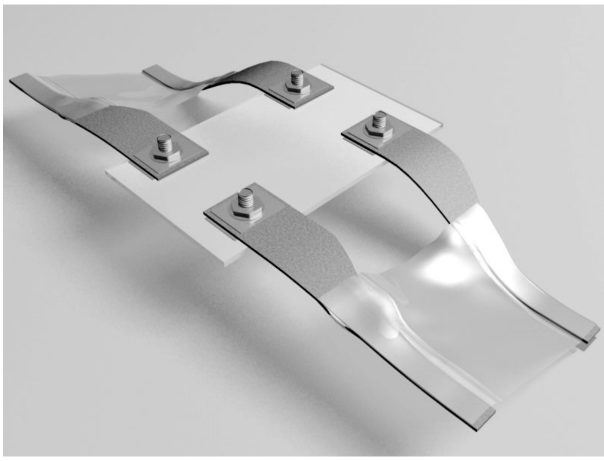

Figure 6. Computer generated image of the robot.

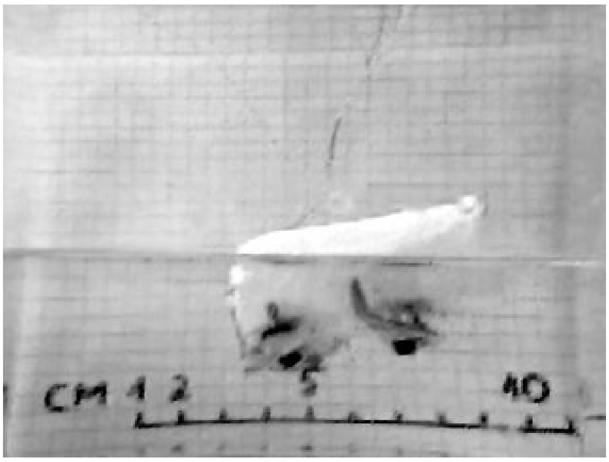

Figure 7. Photo of the robat floating in the tank.

2.3. Robot Control

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.

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 (TTi EX752M) and a current amplifier.

The muscles of the fins are powered with a 50 degrees phase shift to generate thrust. The control signals to steer a single fin are provided in Figure 9. Those signals are generated by NI PCI 6703. The best shape of the signal was found during the experiments by trail and error.

The maximum current of TTi EX752M power supply unit is limited by 4A. During experiments, we found that to be a big problem, because the robot needed more current than 4A to run properly. The IPMC sheets also have a high capacity. As a result, the original control signal was changed considerably. Figure 10 provides the voltage and current characteristics measured from the contacts of a single muscle.

3. Experimental Results

Video clips of test runs are available at http://www.ut.ee/~maarjakr/ray

With the experimental setup in Figure 8, the fins generated thrust and moved the robot forward. The speed of the robot varied in different experiments from approximately 3mm/s to 9 mm/s.

The final version of the robot weighed 9,6g. The weight of the fins (wet muscles and the plastic foil) weighted 1,5g. The muscles were thus able to move ca 6 times of their own weight with a speed up to 1/4 body length per second.

We experienced some difficulties with the vehicle design and experimental setup. While we were able to eliminate problems caused by the vehicle's mechanical design, like the influence of the torsional moment of the wires to the vehicle's motion or uncertainty caused by surface tension, we could not affect the properties of the polymer sheet. Therefore, the robot was rather unstable and hard to control.

The properties of the muscles diverge largely from each other and change over time. They depend on the geometry of the muscles and the shape of the control signals. All these parameters were adjusted during the experiments by trail and error.

Because of the varying properties of the muscles, the thrust generated by the fins was always uneven, and therefore the robot rather appeared turning than moving forward.

To restore the electroactive properties of muscles we heated them in 1M HCl solution and kept in 1M NaOH or LiOH solution. The result varied depending on the duration of reaction and the solvent used. At about 1,3V between the electrodes water electrolysis will start and we are not yet certain about how much it influences the behaviour of the system.

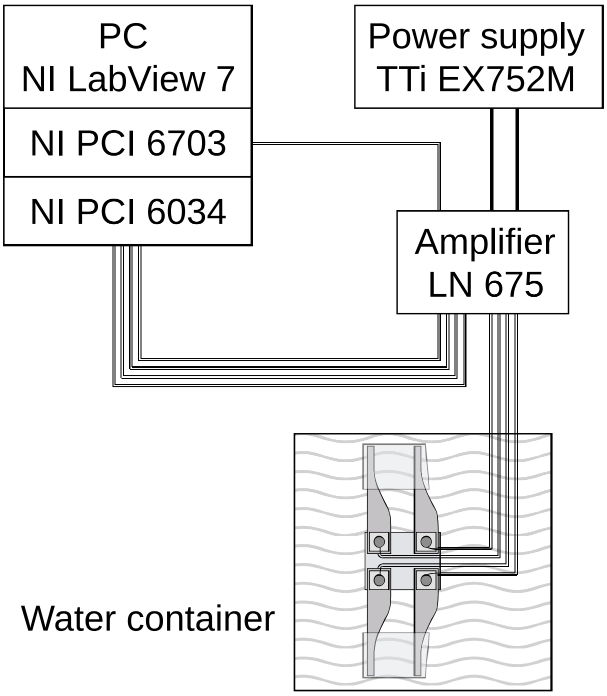

Figure 8. Experimental setup.

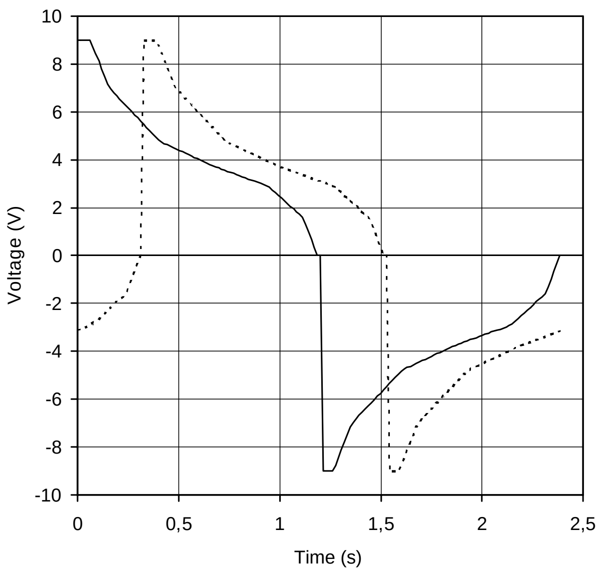

Figure 9. Control signals generated by NI PCI 6703 for two muscles during one period. The length of the period is 2,4 sec.

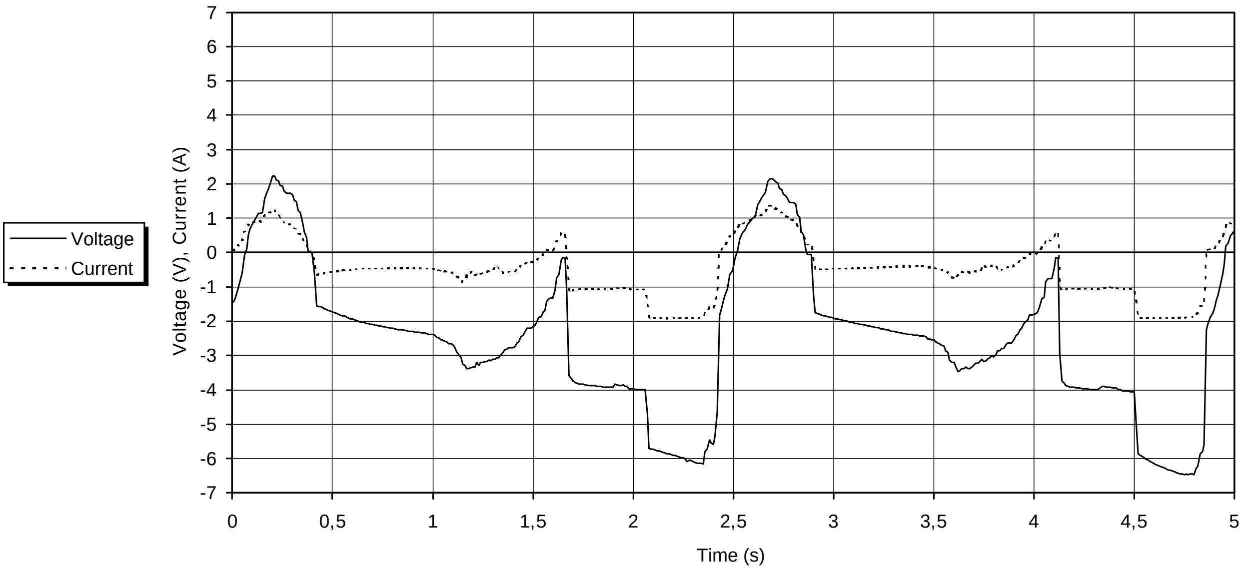

Figure 10. Voltage and current measured on the contacts of a muscle by NI PCI6034 during the propulsion.

4. Conclusions and Future work

The main result of the experiments reported here is that the fins are able to generate thrust and move the body forward. We conclude that rajiform swimming is an effective means of underwater locomotion that can be mimicked with the help of EAP muscles.

Mechanical design of the fins was reliable but the largely varying properties of the EAP muscles made the robot unstable.

There are two complementary ways to overcome this problem. The first possibility is to develop better control mechanisms, e.g. in a feedback loop. The second alternative is to improve the electromechanical properties of the EAPs.

In our future work, we aim at elongating the fins by adding more muscles. The elongated fins permit observing propagation of waves in the fins. Our next aim is to measure the generated forces quantitatively to develop fins that are more efficient and to make the device fully autonomous.

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