Proceedings of the Towards Autonomous Robotic Systems (TAROS'08) Conference, University of Edinburgh, UK, 1-3 September 2008, pp 209-216.

Microbial-powered artificial muscles for autonomous robots

Ioannis Ieropoulos, Iain Anderson, Todd Gisby, Cheng Hung Wang and Jonathan Rossiter

***Abstract*— We consider the embodiment of a microbial fuel cell using artificial muscle actuators. The microbial fuel cell digests organic matter and generates electricity. This energy is stored in a capacitor bank until it is switched to power one of two complimentary artificial muscle technologies: the dielectric elastomer actuator and the ionic-polymer metal composite. We study the ability of the fuel cell to generate useful actuation and consider appropriate configurations to maximally exploit both of these artificial muscle technologies. A prototype artificial sphincter is implemented using a dielectric elastomer actuator. Stirrer and cilia mechanisms motivate experimentation using ionic polymer metal composite actuators. The ability of the fuel cell to drive both of these technologies opens up new possibilities for truly biomimetic soft artificial robotic organisms.**

***Keywords*— EcoBot, Artificial Muscles, Dielectric Elastomer Actuator, Ionic Polymer Metal Composite**

I. Introduction

Autonomous robots that can work in remote terrestrial and/or underwater environments present many design challenges for the engineer. Challenges include practical and efficient use and replenishment of power sources. For example, robots developed for underwater pollution monitoring will be expected to carry high density secondary power sources that can be recharged either onboard (through solar radiation or charging stations) or remotely by the human operator. In either case, the robot territory will probably be limited, as the distance between the farthest or deepest operating points cannot be greater than the distance that can be covered by the energy reserve available onboard. The same principles may apply to robots developed for terrestrial operation or even space exploration. In this context, energy becomes a scarcity and highly energy efficient modules become a necessity.

Nature provides many examples of biological agents that are successful energy managers in such environments. Animals are not only equipped with extremely efficient actuation mechanisms, but are also capable of extracting their energy from the environment in the form of food. Opportunistic examples of animals include the raccoon, which can survive in a wider range of habitats, utilizing almost anything edible and the salp, a urochordate oceanic drifter that is capable of feeding on virtually all microscopic life out of the water that filters through its body. The idea of developing autonomous robots that mimic how these animals operate, and maintain homeostasis is therefore very appealing.

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With nature as our inspiration we seek to design an autonomous robot with the ability to not only extract energy from the environment but also use it efficiently so that mission goals can be achieved in a timely manner. This will create a tool for scientists and engineers that will allow access to otherwise inaccessible areas thus offering the opportunity of performing functions that would otherwise be extremely difficult if not impossible to achieve. These systems will be designed according to a pre-defined mission and follow action selection rules that have the energy budget as the currency. Admittedly, the realization of such systems is still very far into the future.

Like a living animal, an autonomous robot will extract energy in the form of raw organic substrates from the environment and metabolise it into useful electricity. Such a robot would include in its duty cycle the collection of substrates such as plant material (fruits and vegetables) or even insect pests and other ingredients such as water to support an artificial-metabolism [1].

Current research is focused on producing a truly autonomous robot that harvests energy from its environment. The EcoBot project is developing an autonomous robot technology that employs microbial fuel cells (MFCs), as the onboard energy supply, which digest organic matter such as food waste and insects into useful power [1][2]. The low energy generated by the MFCs is stored in an on-board accumulator in order to be charged-up to a useful level, and then released to power the robot's systems for tasks such as environmental measurement, data processing, communication and locomotion. This of course implies that the robot's activity is limited by the amount of time it takes for the energy in the accumulator to reach the critical firing threshold and therefore results in a pulsated actuation [1][2].

Two exemplar robots have been developed as parts of the EcoBot project, namely EcoBot-I and EcoBot-II and the principle of operation is similar in both robots. Each robot is driven by 2 DC motors operated in a pulsed manner: each actuation interval is characterized by an active time, when the drive motors are on and an inactive time, when the system rests to allow the accumulation of electrical energy. Improvements to system performance are being sought through research into MFC technology, and the efficient utilization of devices such as the DC motors that drive the robot. However great benefits might arise from employing new and novel ways of actuation.

Nature can provide the inspiration to find a means for improving the robot's performance: by giving it "muscle" power! A muscle is a structure that can produce and control motion. Natural muscles are soft and compliant. They can act as both springs and dampers and are capable of large strains of the order of 20% [3]. They can be organized to act in antagonistic pairs around a joint and configured into a system that can traverse difficult terrain. Even without a skeleton, a muscle system can provide controlled multi-degree of freedom movement for manipulation and locomotion.

One good example is the octopus arm that uses sets of radial circumferential and longitudinal bands of muscle in a hydrostat mechanism [4]. In addition to animal propulsion natural muscle systems enable peristalsis for food digestion, pumping of blood, valve control by sphincters and many other tasks necessary for animal survival. Muscles act directly without the need of a gearbox and are self-sensing: the forces they develop can be tailored to provide precise force and motion, enabling actions such as locomotion, mastication and violin playing.

II. ARTIFICIAL MUSCLES

To synthesize a muscle we can look to emerging electro-active polymer technologies. Two technologies are under consideration for EcoBot: the dielectric elastomer actuator (DEA) and the ionic polymer-metal composite (IPMC):

A. Dielectric Elastomer Actuators

Consider first the DEA that is essentially a compliant capacitor consisting of an incompressible soft polymer membrane dielectric with compliant electrodes applied on both sides. When a voltage is applied, the charge accumulated on the electrodes gives rise to electrostatic forces that generate deformation in the DEA. Charges of opposite polarity act to draw the positive and negative electrodes together while the charges of the same polarity act to expand the area of the electrode (Fig. 1). When the charge is removed, the elastic energy stored in the dielectric returns it to its original shape. The linear motion produced by this deformation response can be used for actuation purposes.

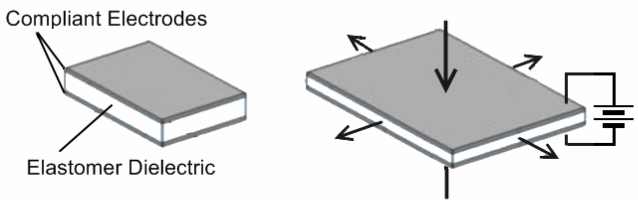


Fig. 1. Basic Operating Principle of a DEA

DEA's are driven by electric fields. The pressure capable of being generated by a DEA is defined by the following equation [5]:

$$P = \varepsilon_r \varepsilon_0 E^2 \quad (1)$$

Where P is the electrostatic Maxwell pressure, ε_r is the relative permittivity of the dielectric material, ε_0 is the permittivity of free space (ε_0 = 8.854 x 10^{-12} F/m) and E is the electric field strength with units (V/m). This is twice the pressure capable of being generated by a rigid plate electrostatic device due to the interaction of the area expansion and thickness compression upon activation. Also note that the pressure is related to the square of the electric field, and not the voltage. Minimizing the thickness of the dielectric membrane therefore reduces the voltage required to generate a given electric field.

The level of deformation achieved at any given field is dependent on the stiffness of the polymer dielectric and electrode materials combined. DEAs have demonstrated active strains in excess of 300%, strain rates up to 34,000%/s, pressures of 7.7MPa, and energy densities as high as 3.4MJ/m^3 [3].

Like natural muscles, DEAs can be controlled for position, speed or stiffness. DEA's are capable of maintaining a steady state position and, due to their capacitive nature, can store energy. By controlling the rate of charging of the device the speed of actuation can also be controlled. Similarly, utilizing the geometry of the device and the level of charge stored on the DEA, it is possible to determine the electroactive forces, which in conjunction with knowledge of the mechanical behaviour of the DEA itself, can be used to control stiffness.

Some of the issues associated with DEA are linked to stepping up the voltage from the accumulator bank to the level required for actuation. While DEAs are inherently low power devices and require very low currents, at current scales of membrane thicknesses voltages of the order of 2.5-3kV are necessary for significant actuation. It is necessary therefore to implement a DC-DC converter to step up the voltage from the accumulator bank to that required by the DEA for actuation. The output voltage of the DC-DC converter is proportional to the voltage across its input terminals, but will lag behind the input voltage. As the robot's capacitor discharges there will be a drop in voltage across its terminals. Below a certain voltage it might not be possible to produce satisfactory force or movement in the DEA. Thus there is a race against time to actuate before the voltage on the accumulator falls below a critical level. The required force/displacement will determine the effective size of the DEA artificial muscle and this in-turn has implications on the power delivery considerations described above.

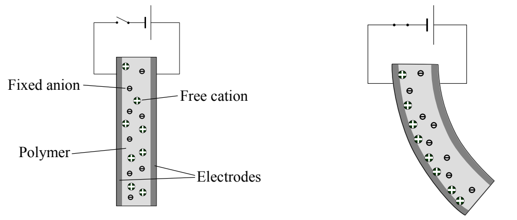
In this paper we have investigated the feasibility of MFC powered DEA actuators for EcoBot. In particular we have developed a robotic sphincter mechanism for controlling the outflow of waste effluent from its header tank. In the course of doing this we have identified key design features for the actuator and the circuitry that promote efficient and economic use of energy.

B. Ionic-Polymer Metal Composites

Now let us consider an artificial muscle material that can be considered as the compliment to the DEA described above. Ionic-polymer metal composites [7] are members of the family of electro-active actuator materials that rely on ion migration to achieve actuation. Other members of this group include ionic polymer composites of conducting polymers, and carbon nano-tubes. In contrast to DEA actuators, IPMCs operate at much lower voltages in the range 1-3V (in the order of $10kVm^{-1}$) and they undergo a bending action rather than the expansion action of the DEA. The lower operating voltage and contrasting actuation modality make this material an interesting prospect for integration into microbial fuel cell-powered soft robots.

IPMCs are tri-layer membrane devices consisting of two thin large-area electrodes sandwiching a polymer layer. Fig. 2a shows the structure of an IPMC in cross section. The electrode material is most commonly a noble metal such as gold or platinum which is electro-less plated onto the polymer layer. The polymer is an ion-exchange membrane such as the fluoropolymers Nafion (from DuPont) or Flemion (from Asahi Glass). The electromechanical actuation process requires the migration of mobile ions, thus an electrolyte is infused into the polymer to facilitate this migration. The electrolyte has traditionally been water or an alcohol such as ethylene glycol. More recently non-volatile electrolytes such as ionic liquids have been successfully used [6]. Ionic liquids have the advantage that they do not evaporate and as a result IPMCs fabricated using these liquids will operate for long periods in air, in contrast to those containing hydrous electrolytes which evaporate and result in a reduction in actuator performance over time.

The electro-mechanical actuation mechanism of IPMCs is illustrated in Fig. 2. When no electric field is applied to the electrodes the mobile cations and the immobile anions - which are bound to the polymer backbone - naturally form a distributed equilibrium (Fig. 2a). When a voltage is applied to the electrodes the cations migrate to the cathode but the anions remain fixed in place. The presence of a large concentration of ions at the cathode causes localized expansion of the cathode material due to inter-ion repulsions from Coulomb forces. The reduction in cation concentration at the anode causes a complimentary contraction of the anode. The net effect of these localized expansions and contractions is a bending of the IPMC towards the anode (Fig. 2b). This explanation is a simplification of the complete electro-mechanical process and does not consider the effects due to, for example, solvent flux. For a more complete description of the actuation mechanism see [8].



a. Unactuated state b. Actuated state

Fig. 2. Structure and actuation of an IPMC

We have used the EcoBot II energy harvesting system to explore the capacity of both technologies (DEA and IPMC) to produce useful actuation from MFC power.

III. Material and Methods

A. Microbial Fuel Cell Preparation

Energy harvested from MFCs was used for actuating the artificial muscle devices. A stack of 8 MFCs charged a bank of 64 x 6800µF capacitors up to 5V. The MFCs (see Fig. 3) were made from silicone rubber with 5mm diameter inflow and outflow ports on the top and bottom, to allow for continuous fluid flow. The MFCs had an open window on one side, to allow the fitting of a 30 x 40 mm cation-selective membrane (VWR International), on the outside of which the open to air cathode electrode was to be attached. Carbon fibre veil was used for both the anode and cathode electrodes, with a surface area of 270 cm^2. A 100mm length nickel-chromium wire was used to provide the connection point for the electrode. The microbes employed in these experiments were of the same type found in activated sewage sludge.

Activated sewage sludge samples were provided by the Wessex Water Scientific Laboratory (Saltford, UK). The samples were collected from the Cam Valley urban wastewater treatment plant, which mainly deals with domestic sewage. The plant is designed for a population equivalent of 6,000 (360kg BOD day^{-1}) and has a sludge age of hours. Activated sludge samples were taken from the aerobic process tank, in which suspended solids were 99.8%.

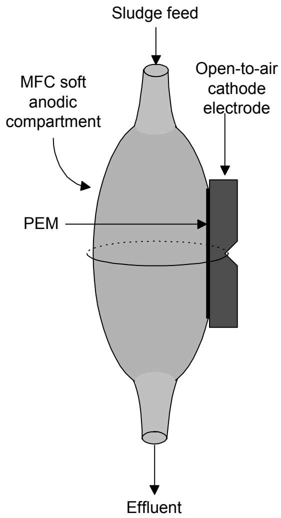


Fig. 3. The microbial fuel cell

The collected samples were pre-processed, during treatment at the water works in order to remove pathogenic viruses. Samples were kept in their original water-based suspension, at 4°C anaerobically, and used within 3 weeks following anaerobic treatment. The sludge samples (pH 7.3) were mixed with sterile nutrient broth (25 g/L) (Oxoid, Basingstoke, U.K.) and given 24 h at room temperature prior to usage as start inocula in the experiments.

The open to the air cathode electrodes were moistened with 0.1M potassium hexacyanoferrate (a.k.a. ferricyanide, K_3Fe_3-[CN]$_6$), mixed with 0.1M potassium buffer (K_2HPO_4). The pH of the electrolyte was adjusted to 7.

The microbial power was used for actuating two types of artificial muscle: DEA membrane actuators in two stretch ratios and bending IPMC devices in three sizes.

The experiments were set-up as shown in Fig. 4 below. The stack of 8 MFCs joined in series was connected to a bank of 64 x 6700mF (6.3V dc) capacitors, giving a total capacitance of 0.428F. The energy generated by the MFCs was accumulated in the bank of capacitors up to a predefined threshold, at which point the actuator was connected. The capacitor voltage drop, as a result of driving the actuator, was also recorded.

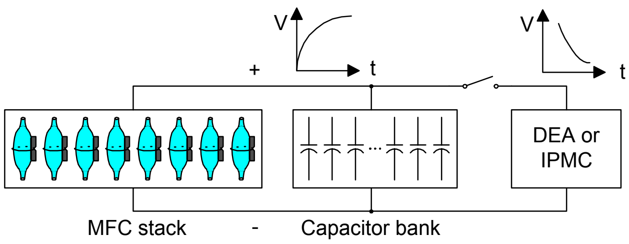


Fig. 4. Connecting the MFC and artificial muscles

B. *Dielectric Elastomer Actuator Preparation*

A DEA sphincter (Fig. 5) was prepared and used for the actuation of a valve mechanism that was to function as a proof-of-concept sphincter on the EcoBot robot. This consisted of an acrylic membrane (3M VHB 4905) that was stretched equi-biaxially to nine times its original area and supported in a rigid plastic frame. Stretching reduced the membrane thickness to approximately 56µm. Electrically conductive carbon loaded grease was applied top and bottom to one half of the membrane area. At the center of the membrane was clamped a circular plate with a hole through which a post protruded. A thin walled rubber tube was pinched between the post and the inner surface of the plate. Actuation of the membrane shifted the circular plate sideways relieving pressure of the inner plate against the tube, thus allowing fluid stored in the tube to flow downwards by gravity feed. Two voltage converters were trialed: an EMCO Q50 DC-DC converter with the ability to boost voltage by 1000 times and an Artificial Muscle Inc. unit (serial T-3005) that could boost voltage by 600 times.

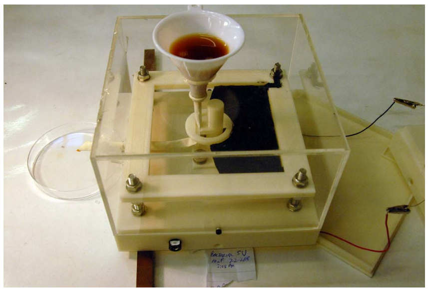


Fig. 5. Photograph of the DEA sphincter that was actuated using the MFC capacitor.

In a complimentary study we subjected the AMI converter to different capacitive loads, representing large and small DEA. We also fabricated additional sphincter membranes to investigate the influence of stretch ratio (3 and 4 times equibiaxial) versus MFC capacitance on membrane actuation. For this final study, actuation was characterized as the free displacement of the central valve on the membrane (pillar removed) for different actuation voltages.

C. *IPMC preparation*

The IPMC samples used in this study were fabricated from Nafion 112, 117 and 1110 ion-exchange polymer membranes. These membranes were five times chemically coated with gold using Asaka and Oguro's method [9] to yield a dense fractal-like electrode structure with point-to-point surface resistance of less than 0.5Ωcm^{-1}. After final cleaning with HCl the membranes were soaked in a doping solution of NaCl overnight so that the majority of mobile H+ ions within the membranes were exchanged for larger

Na+ ions. The membranes were kept in a purified water bath when not in use.

Since the actuation mechanisms of DEAs and IPMCs are so different it is clear that they have their own niche applications within the EcoBot platform. The low force, high displacement bending actuation of IPMCs makes them suitable for application within a microbial fuel cell as a stirrer mechanism and as a cilium. The stirrer is needed within the MFC to ensure that organic matter and microbes are uniformly mixed. The cilia mechanism can be used for fluid transport and control within the MFC digestive system and also as an external propulsion mechanism for the EcoBot body. To study the suitability of IPMCs as stirrer and cilia mechanisms within the EcoBot we have performed a set of experiments to assess the amount and form of actuation of IPMCs when driven by a charged MFC capacitor bank. Three sample IPMCs were used. The characteristics of these samples are detailed in Table 1.

TABLE 1
THE THREE IPMC SAMPLES USED

Sample number	Base Material	Length (mm)	Width (mm)	Dry thickness (μm)
1	Nafion 112	12	2	51
2	Nafion 117	32	2.5	183
3	Nafion 1110	47	10	254

These three samples cover the typical dimensions and base material used in state-of-the-art IPMC actuators. Note that it is also possible to fabricate these actuators to a much smaller size (In [10] gold coated Nafion actuators of dimensions 30μm wide, 300μm long and 0.4μm thick were fabricated.)

Tests were conducted to determine the amount of fluid mixing that could be achieved using each of the samples 1-3 when powered by the MFC. The test setup in Fig. 4 was modified slightly with the inclusion of a polarity reversing switch SW2 as shown in Fig. 6.

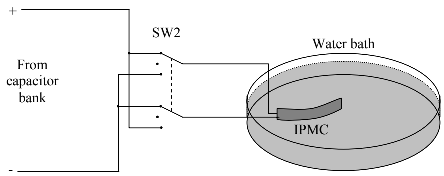


Fig. 6. Setup for MFC powered IPMC experiments

The IPMC sample was electrically connected and mechanically fixed at one end, and was suspended in a bath of purified water.

Two capacitor bank sizes were used for the IPMC experiments: the same 64 x 6800μF capacitor bank as for the DEA experiments, and an additional smaller 10,000uF capacitor. The capacitor banks were charged to either approx 2.6V or approx 5.0V.

IV. Results and Discussion

A. Dielectric Elastomer Actuator Results

For the DEA sphincter the effectiveness of converting the low voltage energy of the robot's accumulator bank into useful mechanical work depends on the inherent electrical characteristics of the DEA and the efficiency and dynamic response of the driving circuitry. During testing we charged the MFC capacitor up to 4.3V and this was boosted up to one thousand times by the EMCO voltage converter. The unit operated successfully but discharging the MFC electrical power into the DEA circuitry highlighted important leakage issues. In particular, once the output voltage of the converter dropped below the voltage across the DEA, the DEA discharged through the converter. Minimizing leakage mechanisms such as this would be beneficial to performance. This was demonstrated during our initial experiments. Despite having a lower peak voltage than the EMCO DC-DC converter, the AMI DC-DC converter proved to be more suitable for actuating the DEA sphincter due to its higher output impedance.

Our subsequent study of the AMI voltage converter demonstrated how its performance can be affected by DEA size. Size is associated with the effective capacitance of the DEA: the larger the surface area of the DEA, the larger the capacitance. The sphincter membrane had a capacitance of approximately 4nF. A range of stock capacitors in the range 2-10nF were coupled to the AMI voltage converter. The outcome of these tests depicted in Fig. 7 suggests that as capacitance on the output increases (i.e. a larger DEA), so more energy will be required from the voltage converter to drive the voltage rise across the artificial muscle membrane. This is evidenced by the time taken to charge in fig. 7. Thus the capacitance of the DEA can influence voltage converter performance and must be taken into account when designing a DEA mechanism for an autonomous robot.

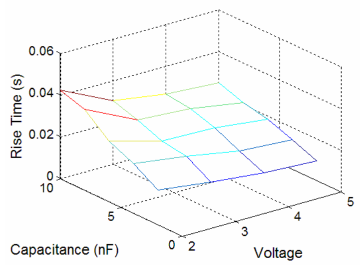


Fig. 7. Simulated DEA rise time for AMI voltage converter vs DEA size represented by capacitance.

Another key issue is stretch ratio in the membrane. We measured the displacement of the central part of our sphincter membrane for two prototypes with equibiaxial stretch ratios of 3 by 3 (final thickness 56μm) and 4 by 4 (final thickness 31μm). The results are displayed in Figs. 8

and 9 vs time. These measurements were conducted for a range of simulated MFC capacitors from 18.8 to 75.6 mF, each charged to 5V. While these capacitances were much smaller than the capacitor on EcoBot the experimental results indicate a trend that as capacitance increases so does displacement. They also show that increased stretch ratio, despite introducing greater membrane forces also results in larger actuation. This is in part due to the greater electric field and corresponding Maxwell stress within the thinner membrane. There is also evidence that the viscoelastic response is subdued in the tauter membrane as demonstrated by the sharper increase in displacement with the voltage onset.

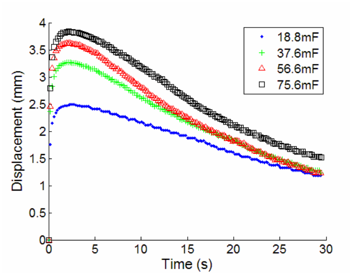


Fig. 8. Central 3×3 membrane displacement vs time for a range of simulated MFC capacitances. Each was charged to 5 volts.

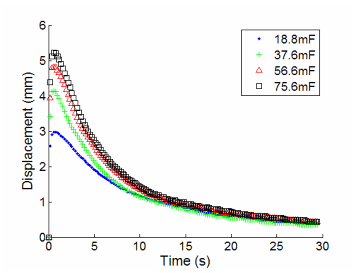


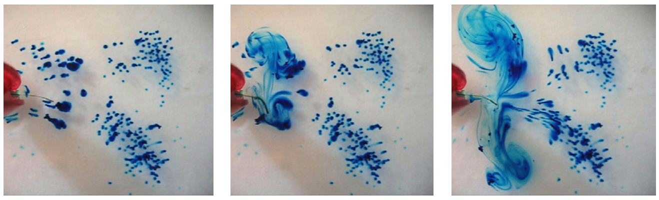
Fig. 9. Central 4×4 membrane displacement vs time for a range of simulated MFC capacitances. Each was charged to 5 volts.

B. *Ionic-Polymer Metal Composite Results*

To assess the ability of MFC powered IPMCs to act as fluid mixing and fluid transport devices, (i.e. stirrers and cilia) each sample was actuated in a still H_2O bath. Just prior to actuation a small amount of Methylene Blue dye (in crystal form) were sprinkled on the water surface. The slow dispersal of Methylene Blue enabled the observation of fluid flow patterns and hence the assessment of mixing ability. The experiments are outlined in Table 2.

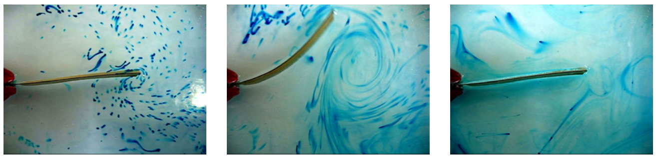
The qualitative assessment of mixing ability in the final column is a rough guide to the performance of an IPMC sample when coupled with a specific capacitance and voltage, and is derived from visual assessment of videos of the IPMCs taken during the experiments. The number of effective actuations refers to the number of times the voltage polarity could be switched, resulting in step actuation, before the actuation became too small to have a measurable mixing effect.

Figs. 10 and 11 show captured images of the fluid mixing experiments. For each of experiments 2 and 6 three images show the state of fluid mixing at three time points. The Methylene Blue clearly highlights the fluid mixing vortices generated by the actuating IPMCs.



a. t=0s b. t=7s c. t=30s

Fig. 10. Fluid flow images from experiment 2 (smallest IPMC)



a. t=0s b. t=14s c. t=30s

Fig. 11. Fluid flow images from experiment 6 (largest IPMC)

As can be clearly seen from Figs. 10 and 11, the most mixing occurs when the largest and strongest IPMC was coupled to the larger capacitor bank charged to 5V. The mixing is extremely effective and rapid. This is most clearly shown in Fig. 11b where the actuation generates a very large vortex which is efficient at mixing the fluid. After full discharge of the capacitor bank the fluid is almost completely mixed, with only some remaining undissolved crystals of Methylene Blue showing in Fig. 11c.

TABLE 2
SUMMARY OF IPMC FLUID MIXING EXPERIMENTS

Experiment number	IPMC sample used	Capacitance bank (μF)	Charge voltage (V)	Number of effective actuations	Mean energy per actuation (mJ)	Mixing ability (1=worse, 6=best)
1	1	10000	2.6	20	1.6275	1
2	1	10000	5.1	20	6.44	4
3	2	10000	2.56	10	3.1518	3
4	2	10000	5.0	10	12.375	5
5	3	10000	5.0	1	123.75	2
6	3	435200	5.0	8	673.2	6

It is clear from both Figs. 10 and 11 that, when actuated in water, vortices are generated at the tip of the IPMC. In these experiments we are operating in the region of a high Reynolds number where inertial forces dominate over viscous forces. These same vortices, while effective at mixing fluids, also indicate the potential for thrust generation when IPMCs are configured as cilia. Additionally, from Fig. 10, we observe that the actuation of the IPMC resembles the flapping of a fish tail and the vortices generated can be expected to generate a significant component of thrust. Artificial cilia made from IPMCs have the potential to act not only as external actuators for MFC-powered swimming robots but also as internal fluid transport mechanisms. A MFC soft robot will require the pumping of digestive and waste fluid about the body and arrays of IPMC micro cilia can be configured to beat in a controlled traveling wave pattern to push these fluids along internal vessels or tubes.

Although the large IPMC has been shown to be most effective at fluid mixing, the consumption of such a large (for a MFC) amount of energy in mixing is likely to be unnecessary and too energy expensive. More suitable mixing mechanisms are likely to be found in smaller and thinner IPMCs which, although not able to mix fluid quite so well, consume far less energy.

Now let us consider the energy consumption profile of these IPMCs when connected to a capacitor bank. The actuation of an IPMC is dependant on both the voltage applied to it and the charge that can flow into it. The greater the voltage, the more rapid the ion and electrolyte movement within the IPMC, the faster the actuation and the greater the tip displacement. While accurate impedance modeling of an IPMC is difficult due to the complex electro-chemo-mechanical coupling of the material all equivalent circuit models share a very large capacitive component together with a parallel resistive component. It is these two components that characterize the gross current flow when actuated. In the MFC application therefore, the capacitance bank effectively discharges into a parallel circuit of a capacitor and a resistor. Unlike the DEA, though, the polarity of the equivalent circuit determines the direction of actuation, and as such a reversal of potential is required to achieve a reversal of actuation. In applications such as fluid mixing or micro cilia a repeated beating action is used, which requires the repeated polarity reversal of the IPMC and hence the repeated charge reversal of the capacitive component of the equivalent circuit. Clearly there is some scope to scavenge this charge during the reversal process, but due to the resistive component the amount of energy that can be scavenged is small. It is this resistive component that also represents the route for energy conversion from electrical to kinetic during actuation.

As the MFC capacitor bank discharges into the IPMC, voltage across the actuator falls, thus reducing the actuation speed and displacement. In our experiments, when the voltage across the IPMC fell to approximately 0.5V there was no effective mixing action. We also note from the first four rows of Table 2 that increasing the voltage of the capacitor bank increased the actuation of the IPMC, and hence increased the mixing effect of each stroke, but did not increase the number of actuations. This is illustrated in Figs. 12 and 13 which show voltage traces for IPMC sample 1 when the 10,000μF capacitor bank was charged to 2.56v and 5.0v respectively. Here we see voltage decay of the capacitor bank to approximately the same voltage after 10 cycles (20 actuations), despite different starting voltages.

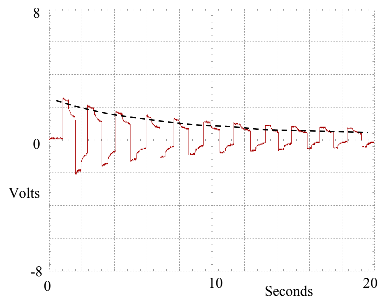


Fig. 12. Experiment 1, IPMC sample 1 driven by 10,000μF charged to 2.6V

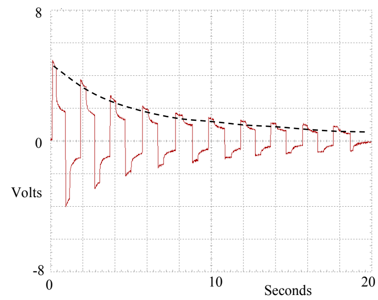


Fig. 13. Experiment 2, IPMC sample 1 driven by 10,000μF charged to 5.1V

Table 2 also lists the mean energy per actuation stroke for each experiment, which varied from 1.627mJ to 673.2mJ. Note that the total energy E used in each experiment is calculated as in Equation 2.

$$E = \frac{1}{2} CV_{init}^2 - \frac{1}{2} CV_{final}^2 \quad (2)$$

where V_{init} and V_{final} are the initial and final voltages across the capacitor bank respectively and V_{final} is taken to be 0.5V.

We observe a monotonic relationship between mean energy used per actuation and the fluid mixing ability of an IPMC. The one exception is experiment 5 where the

10,000uF capacitor can only drive the large IPMC with one very small actuation. In this case the charge in the capacitor is simply too small to be transferred to the large IPMC and maintain a sufficient voltage for a sufficient length of time to achieve an effective actuation. When the larger 0.428F capacitor bank is charged to the same 5V the number of actuations rose from 1 to 8. The voltage profiles in Figs. 14 and 15 respectively illustrate these two cases.

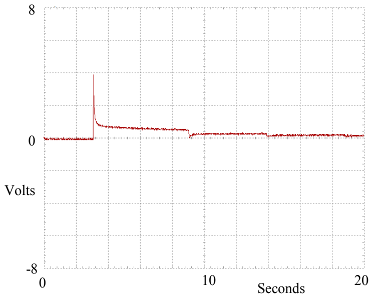


Fig. 14. Experiment 5, IPMC sample 3 driven by 10,000μF charged to 5V

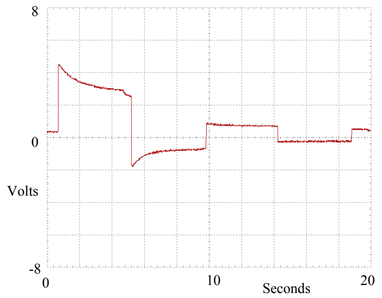


Fig. 15. Experiment 6, IPMC sample 3 driven by 435,200μF charged to 5V

V. CONCLUSION

Actuation efficiency plays a pivotal role in the design of autonomous agents, for which viability greatly depends on their success in collecting their energy from the environment. For this reason it is very important to invest in new technologies that move away from traditional designs. In this study, two different novel technologies were investigated as possible actuation mechanisms for EcoBot and both demonstrated the feasibility of such an approach and outlined areas with room for further improvement. It is envisaged that such systems will form the core of future robot hardware design.

We have shown that the microbial fuel cell can generate enough electrical energy to power the complimentary artificial muscle technologies of dielectric elastomer actuators and ionic-polymer metal composites. This ability enables the possibility of a truly soft EcoBot, one where the MFC forms a soft stomach and gut and the artificial muscles form a soft pliable body. We have shown application of DEAs in this domain through a prototype sphincter mechanism that can control the flow of waste fluid from the MFC. We have also shown the application of IPMCs through a prototype stirrer and cilia configuration. Experimental results with respect to actuation and electrical power consumption have also been shown. Clearly there is much work needed in this area and future research will focus on isolating the key mechanisms in the EcoBot that can be converted to artificial muscle power and efficiently using the small amounts of electrical energy that the MFC can generate.

ACKNOWLEDGEMENTS

The authors would like to thank Prof. Andy Levy for producing the silicon-rubber Microbial Fuel Cells.

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