An Energy-Autonomous Robotic Tadpole with Single Membrane Stomach and Tail.

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Abstract. We present an energetically autonomous robotic tadpole that uses a single membrane component for both electrical energy generation and propulsive actuation. The coupling of this small bio-inspired power source to a bio-inspired actuator demonstrates the first generation design for an energetically autonomous swimming robot comprised of a single membrane. An ionic polymer metal composite (IPMC) with a Nafion polymer layer is demonstrated in a novel application as the ion exchange membrane and anode and cathode electrode of a microbial fuel cell (MFC), whilst being used concurrently as an artificial muscle tail. In contrast to previous work using stacked units for increased voltage, a single MFC with novel, 0.88ml anode chamber architecture is used to drive artificial muscle actuation. This shows the suitability of the small forces generated by IPMCs for propulsion of a bio-energy source. Similarly, the work shows the suitability of MFCs for powering artificial muscles without the requirement for large voltage step up by showing actuation of an IPMC tail using voltages recorded from the MFC during the experiment with minimal step up. Therefore, the work demonstrates great potential for reducing the mass and complexity of bio-inspired autonomous robots. The performance of the IPMC as an ion exchange membrane is compared to two conventional ion exchange membranes, Nafion and cation exchange membrane (CEM). The MFC anode and cathode show decreased increased resistance following inclusion within the MFC environment.

Keywords Energy-Autonomy · Ionic Polymer Metal Composite · Microbial Fuel Cell · Soft Robots

1 Introduction

When compared to natural organisms, conventional rigid-body robots are notably inferior in their ability to survive in varied and unpredictable environments for prolonged periods of time. Complex multi-component systems with low mechanical compliance are ill-equipped to deal with the irregularities that characterise most real world environments. Consequently, biomimickry has become a driving feature in the design of autonomous systems. The goal is to develop robots which are more robust and adaptable, while being simpler in their construction than current multi-component systems.

The use of soft artificial muscles, including those comprising electro-active polymers (EAPs), to emulate the soft physical mechanisms of natural organisms, allows greater adaptability to irregular environments, low mass to power ratios and good thermodynamic efficiency compared to conventional electromechanical actuators [13]. Among these, ionic polymer metal composites (IPMCs) are capable of significant actuation at low voltages (1-3V) due to induced ionic migration within a polymer layer when a potential is applied across it. Previous work has documented their use in applications such as propulsion in small, soft robots [8] & [15], soft compliant mechanical grippers and stents [9] and as a diaphragm in a micro-pump [3]. Nafion is widely used as the polymer layer of an IPMC due to its high ionic conductivity. It is commercially available as both thin sheets and as a castable liquid, and offers geometric versatility in fabrication.

Previous work has also documented the use of Nafion as an ion exchange membrane in microbial fuel cells (MFCs) [11], a bio-inspired means of electricity generation using the redox reaction during microbial respiration. MFCs convert the chemical energy stored in raw decomposing bio-matter to electrical energy. This technology presents a promising option for self powering autonomous robots and emulates the foraging behaviour of natural organisms. Past work has used MFCs as 'artificial stomachs' to power the sensor and actuator systems of autonomous robots [6]. However, these robots have previously comprised large stacks of MFCs to multiply the low redox potential of MFCs, theoretically 1.14 V, maximum, [1], with real systems producing significantly lower operating voltages.

However, the low voltages associated with MFCs are ideal for the actuation of IPMCs. Systems showing the combination of these technologies has been documented in the literature [5], showing energy generation hardware, far greater in physical size than the actuator stage of the system.This work seeks to explore the use of these technologies in combination at a more complimentary scale.

This investigation considers the ability of a single Nafion membrane to function simultaneously as an ion exchange membrane in an MFC and as a soft robotic actuator in first generation design for an autonomous robotic tadpole (Figure 1). We evaluate the efficacy for ion exchange in an MFC of a Nafion 112 (Dupont) membrane, compared to an IPMC with a Nafion 112 polymer layer and gold surface electrodes and CMI-7000 cation exchange membrane (Membranes International Inc.) conventionally used in MFCs. The performance of the three membrane types is considered in both continuous flow and batch feeding modes in a novel, 0.88 ml anode chamber, MFC design. Furthermore, we investigate the functionality of the noble metal surface electrodes of the IPMC as the anode and cathode in an MFC, contributing to the design of a single-component system for both energy generation and robotic actuation.

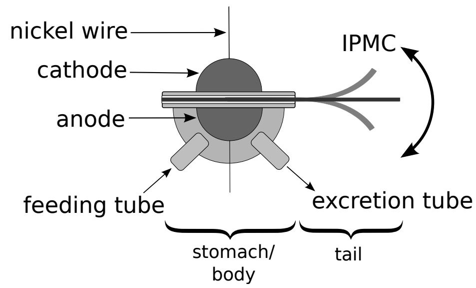
The effect of prolonged inclusion in the MFC environment on IPMC actuation and the power consumed per actuation is also considered. Additionally the effect on MFC performance of applying this electrical stimulus is documented. Furthermore, IPMC actuation, using the MFC anode and cathode as a means to deliver electrical charge for actuation is compared to use of electrodes which are external to the MFC environment. The study validates the combined use of EAP technologies for robotic systems combining bio-inspired energy generation and actuation.

This work will further the development of systems such as small swimming robots by providing energetic autonomy and propulsion from a single component.

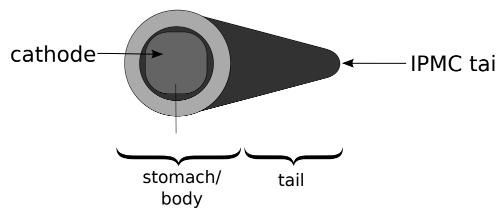
2 Methods and Processes

2.1 Energy Generation from MFC Artificial Stomachs

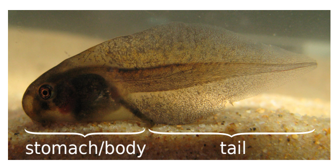
An MFC is a biological fuel cell that uses the redox reaction that takes place during bacterial anabolism to generate electrical charge. An MFC comprises an anode and cathode electrode,



(a) Side view



(b) Plan view



(c)

Tadpole

Fig. 1. Schematic: the tadpole robot comprising an MFC with IPMC membrane for ion exchange in artificial stomach and as tail actuator

usually with a separator to provide the electrical insulation and conduction of protons between the two electrodes required to generate cell potential. The reaction is fuelled by bacterial degradation of bio-matter in the anode chamber.

Table 1. MFC configurations investigated in the study

	Membrane	Carbon veil MFC anode and cathode	Protruding tail	Carbon veil electrodes at base of IPMC tail
Type 1	CEM	✓	X	X
Type 2	Nafion	✓	X	X
Type 3	IPMC with protruding tail	✓	✓	✓
Type 4	IPMC with protruding tail	X	✓	✓

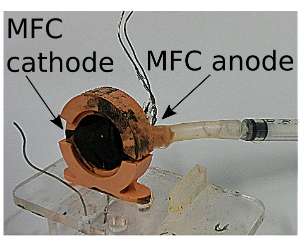
The anode chamber of each MFC had a 0.88mL capacity. A circular ion exchange membrane of 15mm diameter separated the anode and cathode. Three membrane types were investigated (Table 1); CEM (Type 1), Nafion (Type 2), and IPMC made from Nafion 112 with gold electrodes fabricated using electroless plating using the method described in [12](Type 3). MFC anode and cathode electrodes were made from carbon fibre veil, with surface areas of 1800mm^2 and 4500mm^2, respectively (Figures 2(a) and 2(b)). The open to air cathode of each system was coated with a conductive latex made using a method derived from [14], to maintain a continuous redox reaction without the need to hydrate the cathode electrode.

The performance of IPMC surface electrodes to function as the MFC anode and cathode, with the polymer layer used as the ion exchange membrane, was investigated in an additional configuration without carbon veil and conductive rubber MFC electrodes (Type 4).

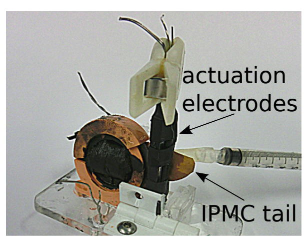
To maintain a consistent volume of anolyte with, Type 4 MFCs included a piece of cellulose (85%) blended with a bonding polymer (15%)(Dri-fresh cellulose, Siriane), of the same volume as the carbon veil anode in Type 1, 2 and 3 MFCs. The cellulose material was used due to its bio-compatibility and non-biodegradability in anaerobic environments.

The open circuit voltage of the MFCs was recorded using a Pico Technology ADC-24 data logger. The MFCs were inoculated weekly with 2mL sludge (Wessex Water, Cam Valley UK 13/01/14) mixed w/ 2.5% nutrient broth, for a period of five weeks. A peristaltic pump was used to deliver anolyte (5mM acetate solution w/ 0.2% tryptone, 0.1% yeast) at a constant flow rate of 0.002 mL/min to each MFC through an individual feed tube from a reservoir of anolyte. This mode of feeding required regular intervention to prevent blockage of supply micro-tubes and was terminated at 174 days.

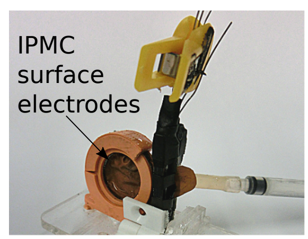
Each Type 3 and 4 IPMC membrane featuring a tab that protruded from the MFC forming the tadpole tail (Figures 2(b) and 2(c)). Two additional carbon veil actuation electrodes (surface area 1500mm^2) for actuation of the IPMC tail (surface area 140mm^2, length 14mm) were held either side of the tab at its base and pressure was applied using a small hinged clip to press them to the gold surface in order to supply electrical charge for actuation of the IPMC.



(a) Type 1 (CEM) and Type 2 (Nafion) MFCs



(b) Type 3 (IPMC) MFCs



(c) Type 4 (IPMC) MFCs

Fig. 2. MFC configurations using different membrane types

Previous work has examined the resistance of MFCs to prolonged periods of anolyte starvation [14]. Such conditions reflect the likely fluctuations in available fuel that an autonomous system would have to survive in an unstructured environment. Hence, termination of continuous flow feeding at 174 days months was used as an opportunity to evaluate the capability of the MFCs to withstand starvation. From 174 days the MFCs were starved for 168 days. At 342 days, the MFCs were revived by feeding batch feeding with 2mL of anolyte through a syringe, at 2 day intervals.

2.2 Actuation of IPMC Tail

Actuation in water of the area of the IPMC tail was recorded with the complete system submerged in deionised water, mimicking the undulatory swimming mechanism of a tadpole [10]. Actuation was recorded before inoculation of the MFC and, subsequently, at 349 days, while under batch feeding conditions, to study the effect of the MFC environment on the actuation of the artificial muscle. Tip displacement was recorded using a laser displacement sensor (Keyence). The neutral plane of the IPMC was orthogonal to the laser displacement sensor.

Power consumption during delivery of a 1Hz square wave for a total time of 10s using a potentiostat (Hokuto Denko) was recorded using a National Instruments PCI-6229 data acquisition board. Displacement relative to the laser source was documented at voltages of amplitude +/-1V and +/-3V. The effect of driving the IPMC using carbon veil electrodes positioned at the base of the tab was compared to using the anode and cathode electrode inside the MFC, as well as using both sets of electrodes simultaneously.

3 Results

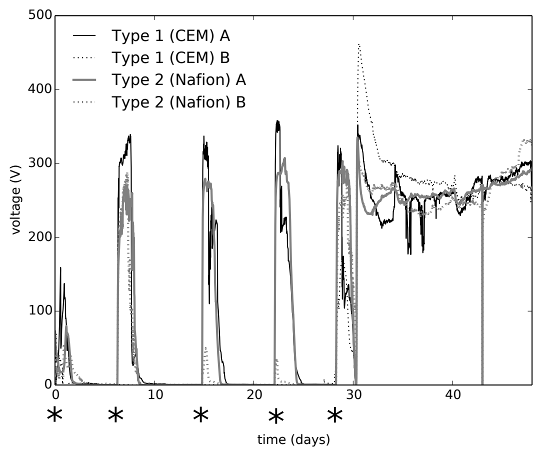
3.1 MFC Performance

During inoculation, large variation was shown in the behaviour of different MFCs of same membrane type 3. However, the conventionally used membranes, Nafion and CEM, in general, showed a significantly higher open circuit voltage than the MFCs with IPMC membranes (Table 2). The behaviour of MFCs with conventional membranes (Type 1 and 2) was notably more consistent between like systems than under continuous flow feeding conditions, and showed superior performance to MFCs with IPMC membranes (Type 3 and 4).

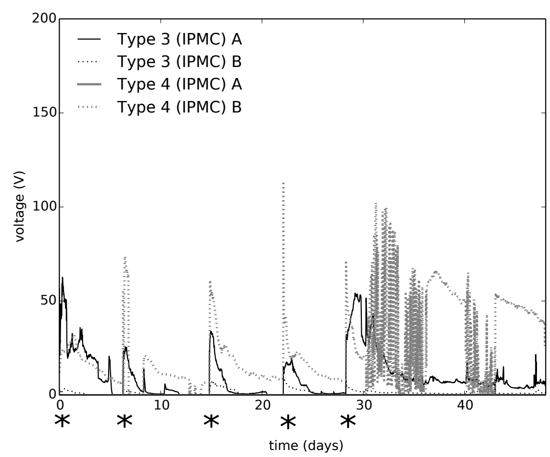
During the 168 days that the MFCs were left unfed, negligible voltage was output from all MFCs. The MFCs were revived at day 342 with a single batch of anolyte. Initially, this resulted in lower performance than the previous feed conditions (Figure 4). Cell polarity reversal indicated an increase in the internal resistance of the MFCs. However, improved open circuit voltage was shown by the second batch, demonstrating the ability of the MFCs to recover quickly from periods of starvation. Peak voltage per batch for Type 1 (CEM) and and Type 2 (Nafion) MFCs showed comparable voltage to average voltages under continuous flow by the third batch (Table 2), showing the resilience of MFC performance to the effect of long term anolyte starvation. While, performance of MFCs with IPMC membranes (Type 3 and 4) was inferior to those with conventional membranes (Type 1 and 2), under the new batch feeding mode, both MFCs with IPMC membranes of Type 4 showed a significant improvement in open circuit voltage. This could indicate development of the biofilm during the months over which the systems were left unfed. This showed the potential for significantly downsizing the combined MFC-actuator system by removal of the carbon veil anode and cathode electrode, showing the viability of a single component IPMC system for use in an energetically autonomous tadpole robot, or diaphragm pump fed MFC. Furthermore, MFCs with IPMC membranes of Type 3 showed negligible voltages suggesting that this conventional electrode configuration was detrimental to the performance of the IPMC for ion exchange in an MFC.

Table 2. Open circuit voltage produced by each MFC type under inoculation, continuous flow and batch feeding modes.

	Type 1 (CEM)		Type 2 (Nafion)		Type 3 (IPMC)		Type 4 (IPMC)	
	A	B	A	B	A	B	A	B
Inoculum, peak voltage per batch (mV) (average of 5 batches, day 1-29)	249.1	143.5	307.2	56.5	41.0	6.6	1.3	81.9
Continuous flow (mV) (average continuous voltage, day 29-48)	260.9	263.4	261.1	283.7	9.5	1.0	0.05	37.6
Batch feeding, peak voltage per batch (mV) (average of 6 batches, day 342-355)	217.2	170.3	225.0	225.9	46.5	10.94	75.2	54.5

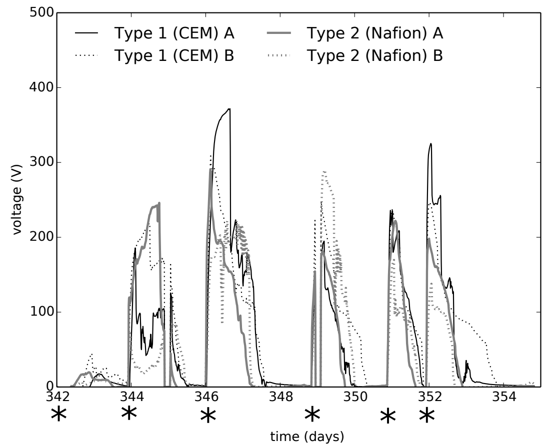


(a) Conventional membranes (Type 1 and Type 2)

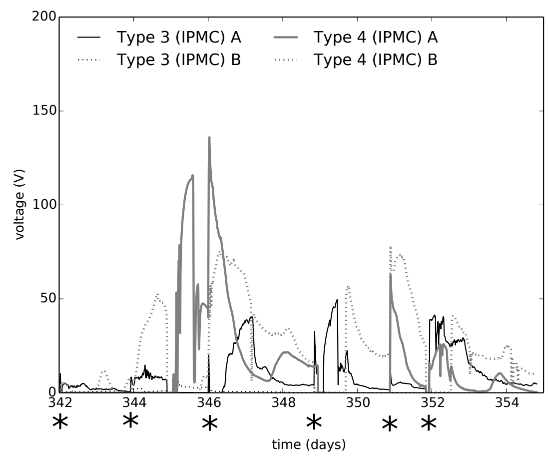


(b) IPMC membranes (Type 1 and Type 2)

Fig. 3. Temporal open circuit voltage of MFCs during inoculation (day 0-29)and continuous flow feeding (day 29-48). Stars indicate feed times during inoculation.



(a) Conventional membranes (Type 1 and Type 2)



(b) IPMC membranes (Type 3 and Type 4)

Fig. 4. Temporal open circuit voltage of MFCs during batch feeding mode. Stars indicate feed times.

During the second batch, all MFCs were removed from the data logging hardware to allow actuation of the IPMC using external hardware to be recorded. On completion of actuation tests, the open circuit voltage of all MFCs with IPMC membranes had not suffered, showing the ability of the MFC bacterial culture to withstand significantly larger applied voltage than those generated by the MFC.

3.2 IPMC Actuation

Actuation was exhibited by the IPMC tail protruding from each Type 4 MFC in response to a square wave voltage (1V and 3V) of 1Hz, applied for 10s (Tables 3 and 4). This showed actuation at voltages achievable using the MFCs in this study. Capacitors could be charged in parallel from an MFC, then configured in series to supply a multiplied voltage to an actuator. Only four capacitors would need to be charged from Type 1 and 2 MFCs to achieve voltages over 1V. This demonstrates the potential for a relatively simple system comprising few components to use the charge generated by the MFCs for actuation of the IPMC tail. Furthermore, the superior performance of Nafion membranes compared to IPMC membranes could result in Nafion membranes, selectively plated to optimise particular areas for either power generation or actuation.

By considering the energy required per IPMC actuation stroke (Tables 3 and 4) capacitors could be charged from the MFCs to the total energy required,

$$E = CV^2 \tag{1}$$

where V is the voltage to which the capacitor of capacitance, C is charged. Further work will therefore compare the charge times provided by the different MFC membranes considered and hence their suitability for pulsed, charge-actuation cycles. Additionally, voltage step up hardware will be investigated.

Prior to use as an MFC, displacement of the protruding IPMC tail was greater when charge was supplied using the anode and cathode electrodes of the MFC relative to when electrodes external to the MFC environment were used. This may have been due to a lower resistance coupling of the electrodes to the IPMC due to the larger contact surface supplied by the carbon veil and conductive rubber coating on the cathode, as higher power was drawn when using the MFC electrodes to actuate (Table 3). Use of both sets of electrodes simultaneously further reduced the resistance of the electrical coupling resulting in increased power consumption and larger displacement. Hence, future work should seek to further reduce the resistance of the electrical coupling to the IPMC actuator in order to achieve actuation at a suitable amplitude for propulsion.

Table 3. Amplitude of IPMC tail displacement, maximum power per stroke and energy per stroke, average of two replicate systems (A and B) over 20 actuations, prior to inoculation of MFCs. Response using actuation electrodes considered for Type 3 and 4 IPMC membranes. Response using carbon veil MFC electrodes and combining both sets of electrodes considered for Type 3 IPMC membranes.

	Displacement (mm)		Power (mW)		Energy (mJ)	
	1V	3V	1V	3V	1V	3V
actuation electrodes	0.01	0.02	5	58	2	97
MFC electrodes	0.01	0.09	10	166	3	260
both electrodes	0.07	0.21	13	184	5	308

When actuated at 349 days, the period of MFC batch feeding, lower power was drawn by all electrode configurations during IPMC actuation. This suggested an increase in the resistance of the MFC. This may have been caused by biofouling of the IPMC. The displacement and power recorded when using the MFC electrodes was greater then when using the actuation electrodes, but showed a relative decrease in performance suggesting an increased

Table 4. Amplitude of cantilever displacement, maximum power per stroke and energy per stroke, average of two replicate systems (A and B) over 20 actuations, while MFCs active. Response using actuation electrodes considered for Type 3 and 4 IPMC membranes. Response using carbon veil MFC electrodes and combining both sets of electrodes considered for Type 3 IPMC membranes.

	Displacement (mm)		Power (mW)		Energy (mJ)	
	1V	3V	1V	3V	1V	3V
actuation electrodes	0.02	0.06	4	21	4	30
MFC electrodes	0.02	0.07	6	28	6	23
both electrodes	0.02	0.08	6	20	1	32

resistance of the electrodes due to inclusion within the MFC environment, potentially due to biofouling. However, the resistence of the IPMC actuator to significant deterioration in performance was The order of magnitude of IPMC displacement was the same before and after long term exposure to the MFC environment showing resilience of the actuator to biodegradation.

Future work could exploit the multi-functional behaviour of the IPMC for energetic autonomy and actuation in tadpole inspired robots and other autonomous systems. For example, the actuation of an IPMC micro-pump, powered by a small MFC, could be used to deliver the low flow rate of anolyte that is required by small MFCs [7].

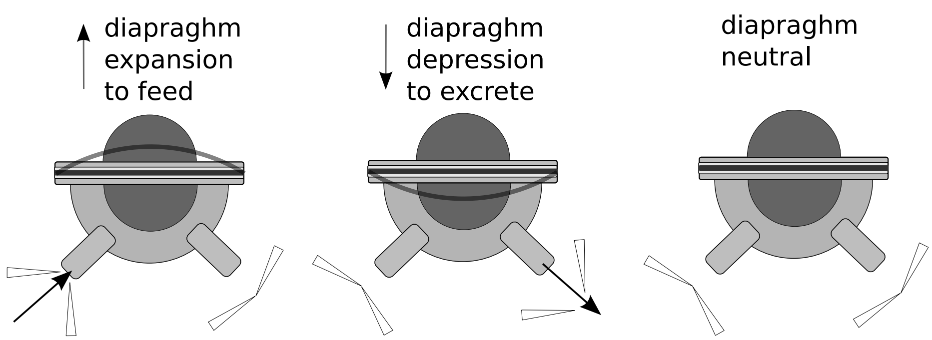
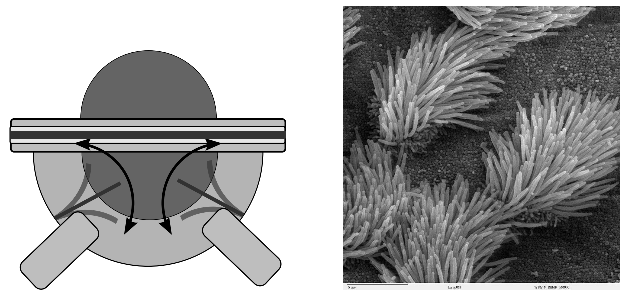


Fig. 5. Schematic of design for a self-feeding MFC with IPMC diaphragm pump with one way valves conrolling direction of fluid flow through feeding and excretion tubes

Previous studies have combined energy generation with actuation in a single component of a fuel cell by the chemical gradients present in a fuel cell to drive gradual actuation, for example, [2] considers components dual functionality as electrodes and actuators for mixing in the anolyte chamber. Agitation of anolyte within the MFC has been shown to increase mass transfer of the anolyte to the biofilm, stimulating increased power production [4], hence by inclusion of an IPMC within the MFC bacterial environment this study evaluates the suitability of IPMCs for use in internal mixing of MFC anolyte (Figure 6).



(a) Schematic of design using IPMCs for mixing within the anode chamber of an MFC, inspired by the motion of cilia

(b) Cilia in the lung trachea. Charles Daghlian, Scanning electron microscope image of lung trachea epithelium, October 7, 2006, Licensed under PDM via Wikipedia.

Fig. 6. MFC configurations using different membrane types

4 Conclusion

This work shows an ionic polymer metal composite (IPMC) membrane functioning as both an actuator and the anode, cathode and separator in an MFC. This study demonstrates the feasibility of an autonomous robot fabricated from a single, electroless plated membrane, for both electrical energy generation using an MFC and actuation using minimal multiplication of the generated voltages. Further work will allow the use of this multi functional component to enable energetic autonomy in small soft, IPMC-based robots. The report shows better performance of an IPMC as an ion exchange membrane in an MFC. Furthermore, a reduction in IPMC actuation is associated with development of the biofilm. Future work will exploit the multi-functional behaviour of the IPMC to reduce the mass and complexity of the current system. Additional study will further characterise the behaviour of the novel MFCs under load.

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