

Freeform fabrication of ionomeric polymer-metal composite actuators

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Abstract

Purpose – To seek to produce low-voltage, soft mechanical actuators entirely via freeform fabrication as part of a larger effort to freeform fabricate complete electromechanical devices with lifelike and/or biocompatible geometry and function.

Design/methodology/approach – The authors selected ionomeric polymer-metal composite (IPMC) actuators from the literature and the authors' own preliminary experiments as most promising for freeform fabrication. The authors performed material formulation and manual device fabrication experiments to arrive at materials which are amenable to robotic deposition and developed an SFF process which allows the production of complete IPMC actuators and their fabrication substrate integrated within other freeform fabricated devices. The authors freeform fabricated simple IPMC's, explored some materials/performance interactions, and preliminarily characterized these devices in comparison to devices produced by non-SFF methods.

Findings – Freeform fabricated IPMC actuators operate continuously in air for more than 4 h and 3,000 bidirectional actuation cycles. The output stress scaled to input power is one to two orders of magnitude inferior to that of non-SFF devices. Much of this difference may be associated with process-sensitive microstructure of materials. Future work will investigate this performance gap.

Research limitations/implications – Device performance is sufficient to continue exploration of SFF of complete electromechanical devices, but will need improvement for broader application. The feasibility of the approach for producing devices with complex, non-planar geometry has not been demonstrated.

Practical implications – This work demonstrates the feasibility of freeform fabricating IPMC devices, and lays groundwork for further development of the materials and methods.

Originality/value – This work constitutes the first demonstration of complete, functional, IPMC actuators produced entirely by freeform fabrication.

Keywords Robotics, Actuators

Paper type Research paper

Introduction

There is a growing awareness in the engineering research community of the potential of solid freeform fabrication to greatly expand the space of manufacturable devices by enabling greater geometric freedom in designs and controlled spatial heterogeneity in material composition (Fuller *et al.*, 2002; Colvin, 2004; Bak, 2003; Dybala *et al.*, 2002; Liu *et al.*, 2004; Stampf *et al.*, 2002; Li *et al.*, 2000; Cooper *et al.*, 1999; Ouyang *et al.*, 2002; Smurov and Yakovlev, 2004; Noecker and Dupont, 2002; Duty *et al.*, 1999; Domack and Baughman, 2005). In light of this potential, we are developing a multiple-material freeform fabrication system, and a library of mutually compatible functional components which can be produced together to create fully integrated, active, electromechanical devices. The implied requirement for mutual compatibility of materials and processes, and the goal of spanning the largest possible space of functionality

with the smallest set of materials has motivated our selection of primarily polymeric active and passive materials and liquid-state deposition methods. It is our opinion that the majority of applications for this technology in the near term are in the biomedical device and biomimetic robotics fields, at roughly the centimeter scale. For this reason, we have chosen performance goals for functional components that are similar to the performance of biological functional analogs and more likely to be biocompatible – namely compliant structures and mechanisms, large strain actuation, and low voltage electronics. We have demonstrated a multiple material freeform fabrication platform (Malone *et al.*, 2004), and fabrication of batteries (Berry *et al.*, 2005), structures, joints and wiring (Malone *et al.*, 2004), and living tissue constructs (Cohen *et al.*, 2004). The focus of our research has shifted to the fabrication of actuators which are compatible with the aforementioned library and suitable for biomedical devices and biomimetic robotics.

In prior work (Malone and Lipson, 2004), we demonstrated that two types of soft electromechanically active materials – conducting polymer and ionomeric

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polymer-metal composite (IPMC) – plausibly can be freeform fabricated. We have also presented arguments based on electromechanical efficiency and actuation speed which motivate our decision that IPMC actuators are the superior choice for self-contained, meso-/macroscopic electromechanical devices (Malone and Lipson, 2005). Here, we demonstrate the feasibility of producing complete IPMC actuators via SFF. Materials have been formulated primarily to allow robotic deposition, and some tentative variation in performance with different formulations has been explored to lay the groundwork for future improvements. The actuation mechanism and traditional (non-SFF) method of manufacturing of IPMC devices is reviewed below.

Background

An IPMC actuator consists of a polymer film whose surfaces are partially penetrated by conductive (typically metal) particles. The surfaces are also typically chemically plated or electroplated with metal to increase the surface conductivity. IPMC's actuate by bending in response to an electric field applied via these conductive surface electrodes. The electromechanically active polymer is an "ionomer" – a polymer which has ionic termination, typically on a side branch. Several commercially produced ionomers are available (e.g. Nafion from Du Pont Inc., Flemion from Asahi Glass, Japan). Nafion is a modified PTFE (Teflon) with perfluorinated sulfonate anion side branches, and is typically produced in what is called "acid form," meaning that a proton is the associated counter-ion to the sulfonate anions in the polymer side chains (Figure 1(a)). The standard approach to IPMC fabrication (Kim and Shahinpoor, 2003) involves purchasing a solid membrane, and replacing the proton by

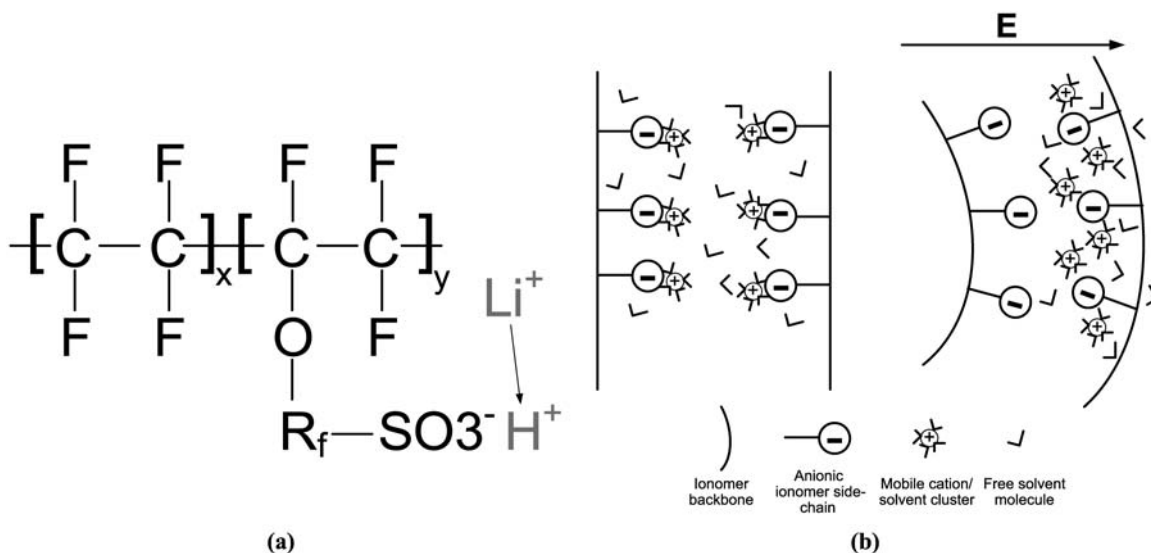
another cation (e.g. Li^+) to improve actuation properties (Figure 1(a)).

The surfaces of the membrane are given metallic electrodes typically by soaking in a platinum salt solution, then chemical reduction of the platinum salt to yield platinum nanoparticles in the outer few micrometers of the membrane. Platinum is the preferred metal because it is immune to corrosion over a larger range of electrochemical potential than other metals, and hence allows the use of higher driving voltages without damage. It appears to be essential to the actuation of the IPMC that these conductive particles be dispersed through a finite depth of the membrane in order to increase the depth of the electrostatic double-layers, and hence the fraction of the material which experiences the electric field (Nemat-Nasser and Li, 2002). The platinum reduction is then often followed by a surface chemical- or electro-plating, typically with gold, to reduce the surface resistance of the electrodes. The bending of an IPMC in response to an applied electric field seems to result from a combination of mechanisms. These include the field-driven diffusion of cations and associated solvent (the anionic side groups on the polymer being immobile) causing an internal pressure gradient (Figure 1(b)), a change in electrostatic forces between the anionic side groups, and reorientation of the (polar) solvent molecules (Shahinpoor and Kim, 2001; Nemat-Nasser and Li, 2002).

Experimental

The traditional approach to manufacturing IPMC described above is not readily adapted to freeform fabrication in that a prefabricated solid ionomer membrane must be chemically treated and metallized in several separate baths. Kim and Shahinpoor (2001a) present a method of producing IPMC devices which involves Nafion ionomer membranes made by

Figure 1



Notes: (a) Structure of DuPont Nafion polymer; schematic exchange of cation (from H^+ to Li^+) to improve actuation; R_f is proprietary fluorinated group, (b) possible IPMC actuation mechanism: pressure differential from electric field driven ion and solvent motion

Source: Adapted from Shahinpoor and Kim (2001)

casting a liquid dispersion (“Liquid Nafion”). The authors note that the cast dispersion is very prone to cracking unless an additive (typically a low vapor-pressure solvent) is added to the dispersion and solvent evaporation is gently performed. In addition, the resulting membrane must be annealed at elevated temperature in order to develop some crystallinity to prevent redissolution of the dispersion when hydrated for actuation. This “solution recasting” method permits the thickness of the membrane to be customized to the actuator application, and the authors present a 2 mm thick IPMC which demonstrates the significant output force increase which is possible (Table III). Note that this device is still given surface electrodes via metal reduction and plating methods. The authors suggest, but do not report results from, a method of producing the electrodes and the membrane entirely by casting stacked layers, wherein the electrode layers would be cast from an ionomer dispersion with suspended metal particles. This method would permit freeform fabrication of complete IPMC devices, and was taken as the starting point for the present efforts.

Initial formulation and hand-made IPMC

We performed an initial set of formulation and hand-fabrication experiments to identify a preliminary material set and problems likely to emerge in freeform fabrication. 5 wt% H⁺ Nafion dispersion in mixed alcohol and water (Sigma Aldrich prod. No. 527084) was used as the ionomer, and an initial electrode material consisted of silver powder (99.9 percent, 1–3 μm particles) mixed in the ionomer dispersion. Silver is used in these experiments as a lower cost alternative to platinum. An annealing schedule of 45 min at 70°C in air was found to eliminate solubility of the ionomer without causing brittleness from too high a degree of crystallinity. Casting the neat ionomer atop a dried film of the electrode material reveals some problems. Firstly, the dried ionomer in the electrode layer is highly hydrophobic, and causes subsequently deposited ionomer to migrate, bead up, and crack upon drying, and secondly, the dried electrode layer (whether annealed or not) absorbs solvent from the newly applied ionomer, causing swelling, buckling and cracking of both materials. It was found that the addition of ~2 wt% of a non-ionic surfactant (Du Pont Zonyl FSO-100) to the electrode material alleviates the first problem. The second problem can be reduced by deposition onto layers that have not completely dried, but with the consequence that suspended silver particles tend to settle during drying, and can penetrate the neat Nafion layer, causing internal electrical shorting of the finished IPMC.

Several devices were made by hand using these materials. Unfortunately, the devices are limited to only a few actuation cycles in air and the silver particles in the electrode material settle out of suspension very quickly making it difficult to dispense. Additionally, some means of confining the deposited liquids is required to allow freeform fabrication of an IPMC in an arbitrary planar shape. We require that this containment should allow the actuator to be fabricated as an embedded component of a larger freeform fabricated device.

Containment, and reformulation for freeform fabrication

Our second series of experiments focused on developing a means of freeform fabricating a container into which the

IPMC materials can be cast, and on modifying the electrode material formulation to improve dispensability.

RTV silicone was selected as a containment material. We can routinely achieve 250 μm resolution when fabricating structures with it, and can deposit it with good compatibility on most of the other materials that our system employs. Rectangular silicone wells (Figure 2(a)) with 1 cm by 3 cm by 2–5 mm internal dimensions were deposited onto glass microscope slides for use as containers for IPMC fabrication. When cast into these wells, we observed that there is a tendency for the ionomer to seep under the lower electrode material, and also to be drawn toward the boundaries of the well. This apparently produces stresses in the film as it dries, leading to cracking. With the addition of 33 wt% of DMF (N-N-dimethylformamide) to the ionomer, the cracking problem was eliminated at the cost of greatly increased drying time. Carbon black powder is used to help suspend the silver powder in the electrode material to improve dispensability. This formulation (Table I), dubbed electrode material 6, (EM6), can be dispensed from a 0.5 mm ID syringe needle without clogging. A four-probe measurement technique was used to obtain the resistivity of this material; the values for pure silver, carbon, and platinum are provided for reference.

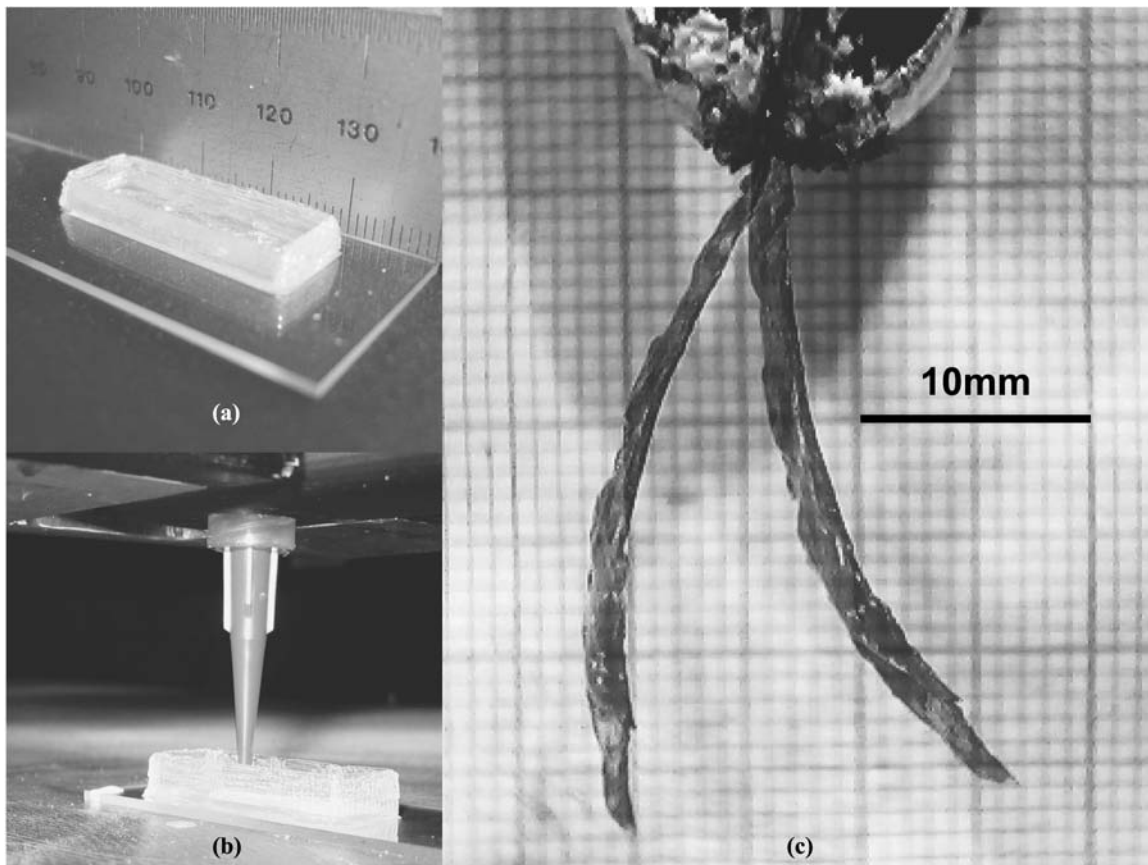
In order to be able to deposit liquid materials precisely into the silicone well, we extended the manufacturing planning software of our fabrication system to allow exceptions to strict layered manufacturing – a technique we call “backfill deposition.” Using backfill deposition, the silicone well can be assigned a higher fabrication priority than the materials to be deposited into it, and it will be completely fabricated to its full height before the deposition of the first electrode layer begins (Figure 2(b)). This greatly improves the speed of fabrication by reducing the number of material changes, and the quality of cast materials by allowing the deposition nozzle to be at its optimal height above the layer beneath.

We deposited the reformulated materials with our freeform fabrication system to produce several working IPMC devices. The actuation of these devices was verified qualitatively by videography (Figure 2(c)). The devices suffer from internal shorting, and have a very short service life in air – typically only 2 or 3 actuation cycles. Nevertheless, these are the first completely freeform fabricated IPMC actuators.

Reformulation for improved lifetime and efficiency

In a third sequence of experiments, we have focused on achieving reasonable service life and reducing input power requirements (internal shorting) of the freeform fabricated IPMC actuators. It is our experience that the primary limitations on the service life of IPMC devices in air are the loss of solvent, corrosion of the electrodes exacerbated by solvent electrolysis, and progressive electrical shorting. As described above, the IPMC actuation mechanism involves, in part, the generation of an internal pressure gradient by the electrophoretic transport of ions and solvent. This pressure gradient drives solvent out through the porous electrodes. Given time it can be reabsorbed into the actuator (Nemat-Nasser and Li, 2002), but while on the surface it is likely to be lost to evaporation, dripping, or contact transfer. Internal shorting causes resistive Joule heating which increases solvent evaporation. It has also been noted (Kim and Shahinpoor, 2003) that solvent leakage probably also reduces the

Figure 2



Notes: (a) A freeform fabricated silicone well, (b) “backfill” deposition of lower electrode layer into silicone well, (c) two superposed frames from video of actuation test of freeform fabricated IPMC-in air, 1.5V step, elapsed time 5s

maximum achievable force output from the actuator by limiting the internal pressure gradient that can be maintained.

In order to reduce the rate of solvent loss, we briefly explored the use of impermeable electrode materials which can trap the solvent inside of the IPMC. There are several essential requirements that such a material must meet:

- low modulus of elasticity;
- low electrical resistivity;
- solvent (water) impermeability;
- chemically inert to other IPMC materials;
- good adhesion to other IPMC materials; and
- easily deposited.

Table I Formulation and resistivity of EM6

Material	Value	Units
Ag powder, 99.9 percent, 1-3 μm	20	wt%
H ⁺ 5 wt% Nafion dispersion	70	wt%
Du Pont Zonyl FSO-100 surfactant	2	wt%
Carbon black	8	wt%
Resistivity		
EM6 (3 samples, 4-probe method)	$3.85(\pm 3.76) \times 10^{-3}$	$\Omega \text{ cm}$
Silver, pure solid (Matweb, 2005)	1.77×10^{-6}	$\Omega \text{ cm}$
Carbon, graphite (Matweb, 2005)	6×10^{-3}	$\Omega \text{ cm}$
Platinum, pure solid (Matweb, 2005)	1.06×10^{-5}	$\Omega \text{ cm}$

The impermeable material is intended to serve as a surface coating to the silver-filled ionomer electrode layers. As mentioned above, some conductive particle penetration into the membrane is essential to the actuation of IPMC.

We found Hydrin C thermoplastic (poly (epichlorohydrin-co-ethylene oxide), Zeon Chemicals L.P.) to be a reasonably good elastomer matrix for this application. Low resistivity is achieved without dramatic increase in stiffness, it is hydrophobic but soluble in several common solvents including toluene and DMF, and it adheres well to the IPMC materials. The main drawback to the material is a somewhat higher permeability to water vapor than some alternatives.

1-3 μm silver particles do not suspend well in dissolved Hydrin. A commercial “flexible silver ink” (EP403920-50, SRA Inc.), which uses specialty polymers to suspend colloidal silver particles without adversely affecting conductivity, was found to form a good alloy with Hydrin. Both materials are soluble in toluene, which evaporates quickly and does not attack the ionomer. The addition of surfactant was again necessary to prevent migration and cracking of subsequent layers cast atop this material. Table II presents our best formulation, referred to as electrode material 19 (EM19), its resistivity and that of some reference materials.

We have dealt with the internal shorting problems by increasing the thickness of the neat ionomer layer. Thus, a

Table II Formulation and resistivity of EM19

Material	Value	Units
Zeon Chemicals L.P. Hydrin C elastomer	6	wt%
Toluene	72	wt%
SRA Inc. EP403920-50 flexible silver ink	20	wt%
Du Pont Zonyl FSO-100 surfactant	2	wt%
Resistivity		
EM19 (3 samples, 4-probe method)	$6.96(\pm 0.96) \times 10^{-3}$	Ω cm
Silver, pure solid (Matweb, 2005)	1.77×10^{-6}	Ω cm
SRA Inc. EP403920-50 flexible silver ink (Stan-Rubenstein-Associates, 2005)	1×10^{-4}	Ω cm
Silicone Solutions Inc. SS-26 silver-filled RTV (Silicone-Solutions-Inc., 2005)	5×10^{-3}	Ω cm

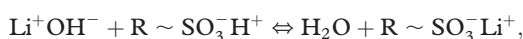
larger volume of liquid Nafion must be deposited and the drying time (especially given the low vapor pressure of the DMF additive) is very long. We employ a more concentrated ionomer dispersion to mitigate this. Switching to 20 wt% H⁺ Nafion dispersion (Sigma-Aldrich prod. # 527122) requires increasing the amount of DMF added up to 50 wt% to prevent cracking, but still results in greatly reduced time for evaporation. We modified the freeform fabrication process to employ these materials:

- 1 A silicone well is deposited onto a glass slide.
- 2 A layer of EM19 electrode material is deposited into the well and allowed to dry completely.
- 3 A layer of EM6 electrode material is deposited into the well and allowed to dry until matte in appearance.
- 4 The well is backfilled to the top with ionomer dispersion (with DMF additive) and allowed to dry until the surface does not flow.
- 5 Repeat step 3.
- 6 Repeat step 2.
- 7 The glass slide is placed in an oven and annealed at 70°C for 45 min.
- 8 The silicone well is filled with deionized water for 30 min to saturate the IPMC.
- 9 The device is lifted from the well with tweezers and tested.

Figure 3 shows the CAD model of the devices that we produced with our fabrication system, and the appearance of a finished device. Initial qualitative testing of these devices indicates a substantial improvement in service life. Quantitative testing results are presented below.

Reformulation for improved performance

It has been observed (Kim and Shahinpoor, 2003) that by exchanging the proton in the as-purchased Nafion membrane with another cation, most notably Li⁺, gains of a factor of two or more can be achieved in IPMC blocked force and speed of response. Having successfully developed a set of materials and a manufacturing process which yield functional IPMC's in our initial experiments, we proceeded to modify the liquid Nafion by exchanging the proton cation for Li⁺. Traditionally, this cation exchange has been carried out by soaking a commercially produced membrane in a concentrated salt solution. To avoid the extra steps of solidification of the liquid Nafion, cation exchange, and redissolution, we exchange the cation by means of the reaction:



which can be carried out entirely in solution. Aqueous LiOH is added to the liquid Nafion dispersion and the pH monitored until neutrality has been achieved. The required quantity of LiOH can be estimated from the "acid capacity" (the density of anionic side branches on the PTFE backbone) and the molar mass of the Nafion molecules.

We discovered that the Li⁺ form of liquid Nafion is more prone to cracking, and is generally more brittle than the as-purchased material. This was successfully managed by increasing the concentration of DMF in the solvent blend to about 60 wt%.

Three- and five-layer devices were successfully freeform fabricated as above using the Li⁺ liquid Nafion. Quantitative characterizations are presented below.

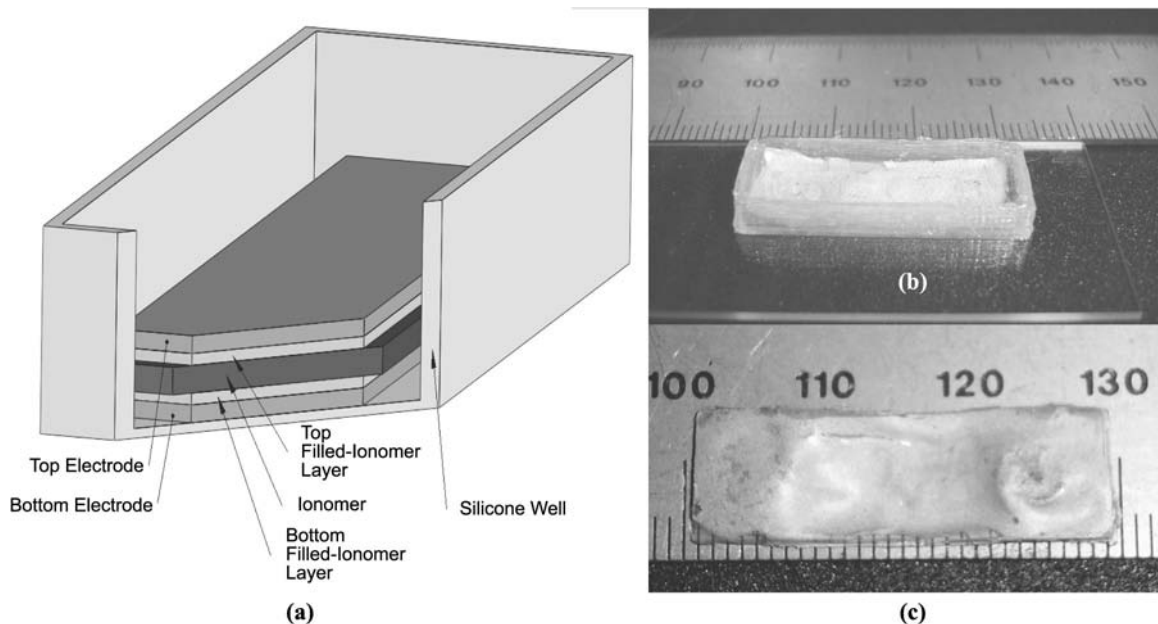
Apparatus

To enable quantitative testing of the performance of the IPMC devices being produced, we developed a test apparatus (Figure 4) which interfaces with a PC-based data acquisition system (IOtech DAQBoard 2000, running DASyLab DAQ software).

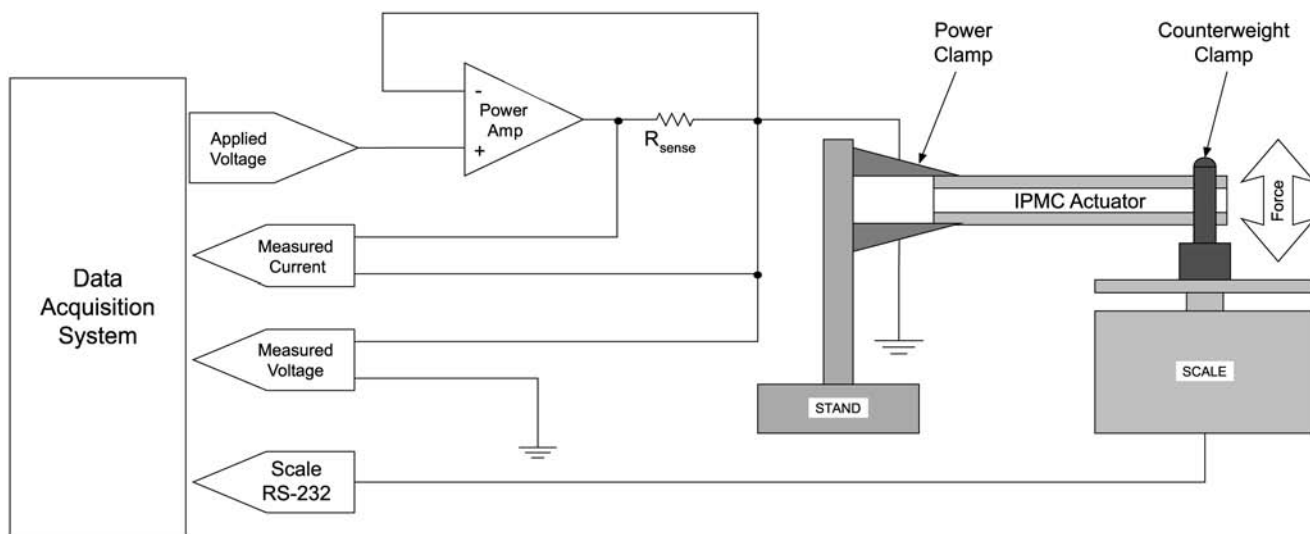
This apparatus allows the application of a controlled voltage waveform to the actuator, while simultaneously collecting applied voltage, current, and force output by the actuator. The actuator is clamped on one end to a 12 g counterweight which rests atop a laboratory scale with a 5 mg resolution (ADAM ACB Plus-150). The other end of the actuator is held in a spring clamp, the tips of which form isolated electrical contacts. The spring clamp is held in a laboratory ring stand. A power operational amplifier receives a voltage command from the DAQ system, and attempts to maintain this voltage across the actuator electrodes by applying a current to the actuator via the spring clamp contacts. The applied current is sensed by the data acquisition system by analog to digital (A/D) conversion of the voltage drop across a current sensing resistor in the current path. The actual voltage achieved by the amplifier is also measured by A/D at the output of the amplifier. The force output is sensed by the scale, which streams readings via serial communications at about 40 Hz to the DAQ system. The simultaneous collection of these data allows us to calculate applied power, and to measure blocked output force and service life.

Results/discussion

We have tested several three- and five-layer freeform fabricated devices, including H⁺ and Li⁺ devices, using the

Figure 3 Freeform fabricated five-layer IPMC

Notes: (a) Cutaway of CAD model showing layer sequence, (b) IPMC in its well, and (c) after hydration and removal

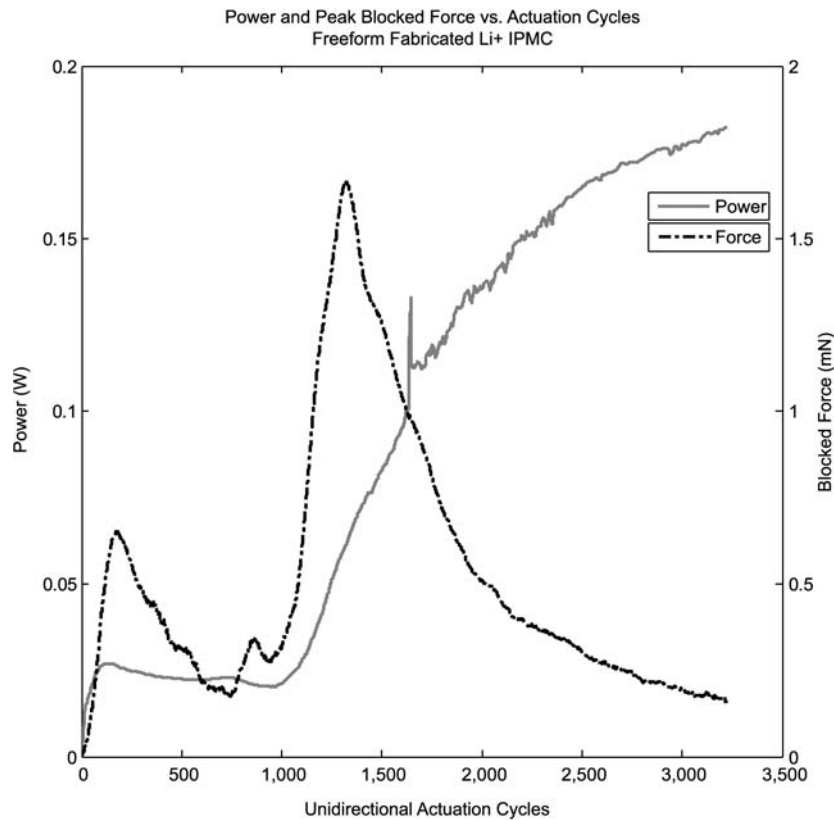
Figure 4 Schematic of test apparatus for acquiring force output, voltage, and current versus time

above apparatus. For these devices, there is a large variation in the output force and power consumed over time (Figure 5).

This is probably a result of the particulate nature of the conductive phases of the electrode materials making and breaking conductive paths as the device bends, and electrical coupling of the device to the test apparatus varying as solvent migrates and evaporates. At this time, for comparisons, all testing takes place with a 0.1 Hz, 1.5 V square wave applied signal. Our longest lasting device, a five-layer, Li^+ IPMC, achieved more than 3,000 bi-directional actuation cycles, cycles in air, operating continuously without rehydration for about 4 h. At the termination of testing, the device showed

significant localized delamination and corrosion of the electrode materials, suggesting that a 1.5 V stimulus may still be too large relative to the electrolysis potential of water (1.23 V). Despite this, the device was still operational after being rehydrated, and showed visible actuation response up to 1 Hz in a frequency sweep. This suggests that loss of solvent is still the primary service life limitation, followed by electrode degradation.

Table III presents a summary of the results of testing in comparison to some of the best results published for IPMC actuators produced by any means. Associated with the change of cation in the liquid Nafion from H^+ to Li^+ , we observe a

Figure 5 Peak blocked force and consumed power vs time for best five-layer, Li⁺ freeform fabricated IPMC**Table III** Comparison of performance of freeform fabricated IPMC to other published IPMC results

Type	Dimensions (mm)	Test conditions (Hz ²)	Force (mN)	Est. shear stress (MPa)	Est. shear stress/power (MPa/W) ^a	Service life (cycles)
Freeform fabricated five-layer Li ⁺ Nafion IPMC	16 × 9 × 0.8 mm	1.5 V, 0.1	1.89	5.2 × 10 ⁻³	2.2 × 10 ⁻¹	3,222
Freeform fabricated three-layer Li ⁺ Nafion IPMC	16 × 9 × 0.5 mm	1.5 V, 0.1	0.916	6.2 × 10 ⁻³	3.2 × 10 ⁻¹	1,384
Freeform fabricated five-layer H ⁺ Nafion IPMC	20 × 9 × 1 mm	1.5 V, 0.1	0.678	1.5 × 10 ⁻³	1.6 × 10 ⁻¹	513
Recast Li ⁺ Nafion IPMC, standard Pt/Au (Kim and Shahinpoor, 2002)	15 × 5 × 2 mm	2 V, 0.5	60	4.5 × 10 ⁻²	9.0 × 10 ⁻¹	
Standard Li ⁺ Nafion IPMC, standard Pt/Au (Shahinpoor and Kim, 2001)	20 × 5 × 0.2 mm	1 V, 0.5	16	1.6	6.4 × 10 ¹	
Stretched Li ⁺ Nafion IPMC, standard Pt/Au (Kim and Shahinpoor, 2003)	10 × 5 × 0.2 mm	1.5 V, 0.5	60	3.0	8.0 × 10 ¹	

Note: ^aThe referenced literature does not contain simultaneous data for force and power, nor for force, voltage and current. We have used selected 25 mA as a reasonable average current based on Kim and Shahinpoor (2003), Figures 11-13

performance increase in output shear stress for five-layer devices of almost 3.5 times – even greater than expected. Note that while there is a performance gap of two orders of magnitude between the best freeform fabricated device and the best published results for IPMC's made with commercial Nafion membranes, the published performance for devices made with Nafion cast from the liquid dispersion (Kim and Shahinpoor, 2003) is only superior by a factor of two, despite using the Pt salt electroding process applied in the best published results. This suggests that the dispersion-cast membrane is somehow inferior for actuation applications. Kim and Shahinpoor (2002) report that passive tensile stress/

strain behavior is different for cast and commercial membranes. Figure 6 shows these comparison data in graphical form.

Figure 7 shows a comparison between three- and five-layer freeform fabricated IPMC's on the basis of a "lifetime performance metric," namely the blocked shear-stress multiplied by service life per unit input power. As mentioned above, the conductive impermeable encapsulant layer possessed by the five-layer devices was investigated as a means of limiting solvent loss, and possibly also as a means of increasing peak blocked force. The data (from a single five-layer device, and two three-layer devices) suggest that the

Figure 6 Comparison of freeform fabricated IPMC's to published results by maximum shear stress scaled to input power

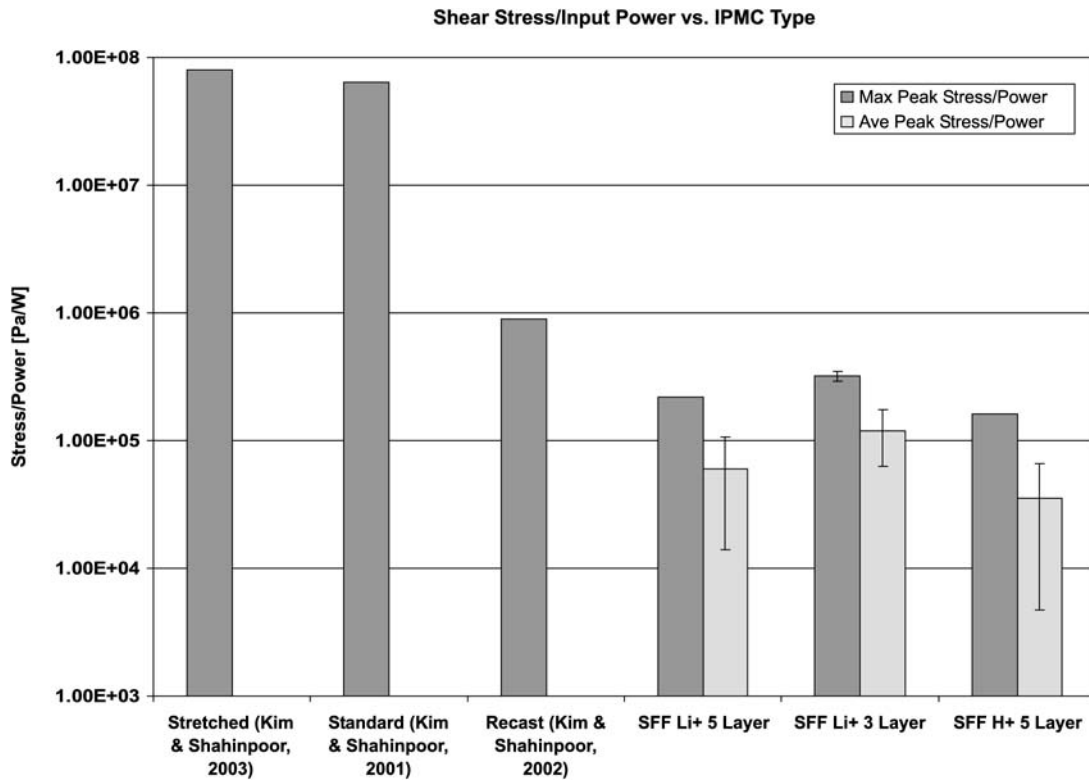
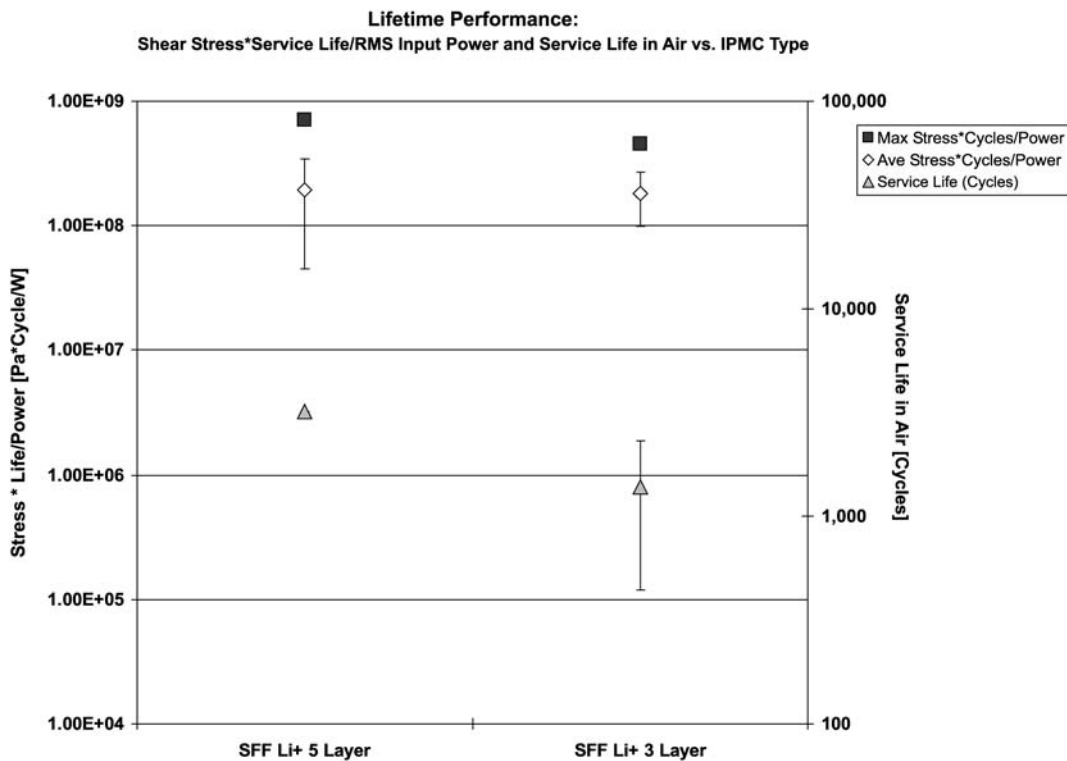


Figure 7 Comparison of three- to five-layer freeform fabricated devices by "lifetime performance," conductive encapsulant layer prolongs life at a cost to output stress



encapsulant does indeed prolong service life, but does not seem to produce any increase in output force. If this holds true with more significant sample sizes, then the encapsulant may be viewed as a design alternative which allows a tradeoff between force output and service life in air.

Future work

We are investigating means of surmounting the large performance gap between the best reported results for IMPC's, and our freeform fabricated devices. The change of cation from H^+ to Li^+ yielded a factor of 3.5 improvement in shear stress, and there are several materials modifications which may also yield large improvements in performance. These include reducing the size of conductive particles used in our electrode materials to the nanometer scale (Kim and Shahinpoor, 2001b), forming a nanocomposite of the ionomer with montmorillonite clay particles (Paquette *et al.*, 2003), and using a lower modulus, more vapor impermeable elastomer in a conductive encapsulant layer. Most importantly, we will investigate the microstructural differences between dispersion-cast and commercially extruded Nafion membranes in order to identify the cause of the performance differences between IPMC's made with each type of material. We also intend to continue our efforts at increasing the geometric freedom with which we can make these devices. Currently, the most promising approach to achieving truly three-dimensional actuators is to fabricate assemblies of small planar actuators joined by inert material.

Conclusion

We have developed new material formulations and manufacturing processes which have allowed us to produce the first ever completely freeform fabricated IPMC actuators. We have quantitatively measured and compared the performance of our freeform fabricated devices to that of devices produced by other methods as reported in the literature. We have also presented a conductive encapsulant material which tentatively prolongs service life in air, presumably by reducing the rate of solvent loss. We have presented the first cycle life measurements for in-air operation of an IPMC, and have demonstrated devices operating continuously in air for more than 4 h and 3,000 cycles. The output stress measured for our freeform fabricated devices is substantially inferior to that of IPMC devices produced in the standard manner, but is sufficient to allow our continued exploration of freeform fabrication of complete electromechanical devices. In addition, this performance gap seems to be correlated with the use of Nafion materials cast from liquid dispersions, suggesting that some microstructural difference between extruded and cast Nafion is the cause. The freeform fabrication process developed includes the fabrication of wells to contain the liquid active materials during their casting. In that these wells can be deposited at an arbitrary location, atop almost any other material, this represents a major step toward fabricating actuators as integral components of complete, freeform fabricated electromechanical devices.

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