

Freeform Fabrication of a Complete Electromechanical Relay

Evan Malone, Hod Lipson

Mechanical and Aerospace Engineering, Cornell University

evan.malone@cornell.edu

Reviewed, accepted September 5, 2007

Abstract

Research Paper

Purpose

We seek to produce electromechanical relays entirely via freeform fabrication as part of a larger effort to freeform fabricate complete electromechanical devices. Relays which can switch using an input current of less than 100 microamperes, current gain greater than 10, and an open/closed resistance ratio of greater than 10^3 will make feasible the control of freeform fabricated actuators by printable organic polymer transistor circuits, opening up a design space of completely freeform fabricated electromechanical actuation systems.

Design/methodology/approach

We conceived a simple relay design which makes use of our prior successes in freeform fabrication of ionomeric polymer-metal composite actuators (IPMC). The electrically conductive surface electrodes of an IPMC serve to selectively close or open a load circuit as the actuator deforms, and the mold used for casting the actuator materials also serves as the relay housing. We are seeking candidate switch contact materials, IPMC electroding materials, candidate housing and contact designs, and manufacturing sequences to find combinations which result in functional IPMCs which when hydrated release themselves from the load contacts while maintaining signal contact, yet have low contact resistance with the load contacts. Candidate housings with contacts were fabricated using a Fab@Home Model 1 desktop fabricator. We manually cast variants of IPMC materials into these housings, and tested these partially freeform fabricated relays using a PC-based data acquisition system.

Findings

Partially freeform-fabricated relays achieved a controllable load path resistance change of a factor of two at switching frequencies up to 0.05 Hz with a 1.2V control input and an RMS input current of 3.8mA. At 1.2V load potential, load/input current gain is roughly 1.05. The device functions above 1Hz, but current gain falls below 1.

Research limitations/implications

Incompatibilities between the tested relay contact materials and the IPMC materials lead to IPMCs of low quality which have internal shorting, resulting in reduced force output, and poor switching performance. Our “wet-contact” design limits devices to operation below 1.2V for both the control signal and the load. Device gain is barely greater than 1. Additional design and materials optimization is required.

Practical implications

This work demonstrates the feasibility of completely freeform fabricating electromechanical relays, and suggests that the stated performance goals are attainable with further work.

Originality

This work constitutes the first demonstration of complete, functional relays which can feasibly be produced entirely by freeform fabrication without manual assembly.

Keywords

electromechanical, relay, IPMC, biomimetic, robotics, freeform fabrication, rapid prototyping, printable

Introduction

The frontier of research in freeform fabrication is pushing outward to encompass ever larger and smaller dimensions, ever more materials, and now increasingly toward fabricating in multiple materials with multiple processes, all within the same fabrication system. We claim that the implicit and valuable drive behind all of this research is to reduce the cost and complexity of infrastructure and the level of technical training required to build essentially anything – both to expand the realm of what can be built, and to allow smaller companies, even individuals, to build or invent almost anything for themselves. The ultimate expression of this drive is a compact

manufacturing system including materials and software tools which together will make the building of a functional device as simple and accessible as printing a digital photograph is today.

We have been working toward this goal both from the direction of simplifying and popularizing multimaterial SFF technology, and through developing hardware, software, and materials which allow the integral freeform fabrication of complete electromechanical devices, food, engineered tissues – essentially anything. Along the first line, we have created the Fab@Home Project (Malone and Lipson, 2007), which develops and publishes open-source, open-architecture, multimaterial SFF system designs – including hardware, software, materials, and applications ideas - and promotes them to the public via a user-modifiable wiki-website, collaborative open-source software development, online discussion groups, and support of commercialization efforts. Pursuant to the second avenue of research, we have demonstrated freeform fabrication of batteries (Berry et al., 2005), structures, joints and wiring (Malone et al., 2004), soft polymer “artificial muscle” actuators (Malone and Lipson, 2006a), and living tissue constructs (Cohen et al., 2006). The burgeoning fields of organic electronics and “printed” electronics have demonstrated that complex integrated circuits can be made entirely through solution processes (Nilsson et al., 2005, Paul et al., 2003), and from our preliminary efforts at producing single transistors with our fabrication systems (Malone and Lipson, 2004), we believe it will soon be possible for us to fabricate integrated circuits with them as well.

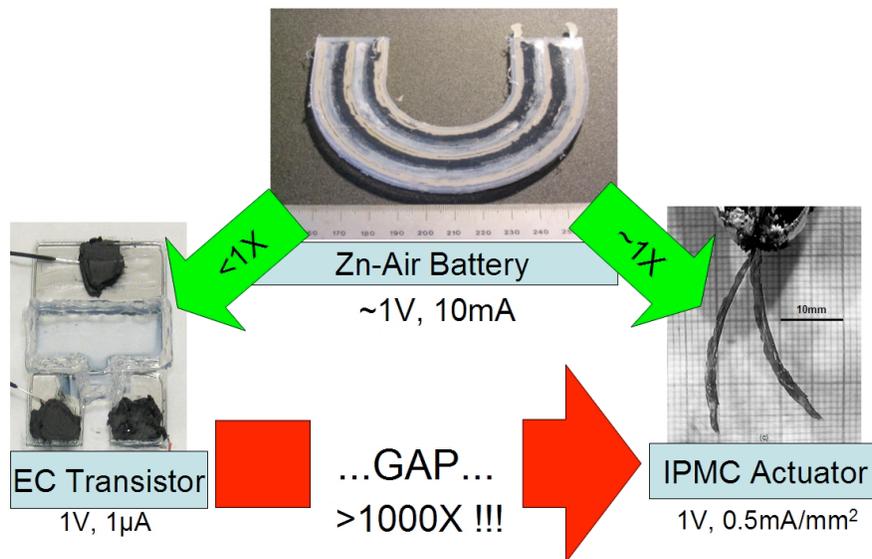


Figure 1. The "electronics gap": freeform fabricated actuators have input current and voltage requirements compatible with a freeform fabricated battery, but exceed the current capacity of organic transistors by 3 orders of magnitude

Our own frontier of research is now moving beyond demonstrating the fabrication of single device types toward multi-device integration – for example, an entirely freeform fabricated actuator subsystem including a battery, IPMC actuator, and organic electronics control circuitry. While the batteries we have been able to fabricate can supply sufficient current to actuate an IPMC, that current is three orders of magnitude larger than what can be controlled by a printable transistor. This “electronics gap” (Figure 1) would require us to build 1000 transistors in parallel to control one actuator, or to find or develop some kind of amplifier which can be completely freeform fabricated.

We have conceived of an electromechanical relay which employs an IPMC as the mechanical switch, and which in principle can fill our electronics gap. Here we present the relay design, and partial freeform fabrication and characterization of some units.

Background

Standard electromechanical relays are binary amplifiers – a small electrical current supplied to a coil electromagnetically actuates a mechanical armature as a switch, which in turn controls a much larger current through some useful load. The ratio of the change in load current from “on” to “off” to the current required to actuate the relay can be defined as the relay’s (current) gain, G . Maximum load current is limited by resistive power dissipation in the metal-to-metal switch contacts, while minimum coil current is limited by the need to move the switch armature quickly to minimize switching noise and/or arcing at the load contacts – modern DC relays have $G \sim 100$ (Omron, 2006, Tyco-Axicom, 2006).

Relays have been produced before in part through SFF processes (Palmer et al., 2006), but that work involved metal machining processes as well as assembly of parts. Here, we seek to produce such a device entirely through additive manufacturing processes that are compatible with all of the other freeform fabricated devices we can produce so that a single compact fabrication system can build up complete electromechanical devices without any assembly of parts.

An Ionomeric Polymer-Metal Composite (IPMC) actuator is a branched polymer-electrolyte (ionomer) film which has been given parallel electrically conductive surface electrodes. When saturated with an appropriate solvent, an electric field applied via these conductive surface electrodes causes the IPMC to bend toward the more positive electrode through a combination of electrostatic (mutual repulsion of anion-terminated branches) and ion-driven pressure gradient (electrophoresis of solvated mobile cations) mechanisms (Nemat-Nasser and Li, 2002, Shahinpoor and Kim, 2001). After this initial rapid motion, and depending upon the choice of solvent (Hyoung-Tae et al., 2006, Nemat-Nasser and Zamani, 2003), ionomer (Nemat-Nasser and Li, 2002), and possible nanocomposite additives (Nguyen et al., 2006, Paquette et al., 2003), the IPMC may or may not relax back toward the negative electrode, putatively because of solvent back-diffusion (Nemat-Nasser and Zamani, 2003).

The standard approach to IPMC fabrication (Kim and Shahinpoor, 2003), and that which results in the highest actuator performance, involves purchasing a solid membrane from a commercial source, and applying surface electrodes to it via metal-salt reduction to metal nanoparticles, usually followed by a chemical or physical metal plating to reduce surface resistance.

As first demonstrated by Kim and Shahinpoor (Kim and Shahinpoor, 2002), it is also possible to produce IPMCs entirely through solution processes. Cast IPMCs can be made to greater thickness than commercially available membranes which allows an increase in force output (Kim and Shahinpoor, 2002, Nguyen and Yoo, 2007), although at least anecdotally, solution processing of the ionomer seems to result in reduced electromechanical efficiency relative to IPMCs made with commercial (extruded) membranes (Kim and Shahinpoor, 2001). Based on these successes, we developed formulations of Electroding or Active Materials (formulations with “EM”, and “AM” designations) and solution processable ionomer Interior Materials (formulations with “IM” designations), all of which are syringe dispensable and tolerate being cast into silicone molds, and succeeded in producing both molds and IPMCs in a single freeform fabrication process (Malone and Lipson, 2006a). This is significant because it

allows an IPMC to be integrally fabricated with other devices, such as batteries and wiring, as part of an electromechanical subsystem or complete electromechanical device. One material particularly important for this success is an electrically conductive elastic vapor barrier material, designated EM19, which serves as an electroding material. EM19 not give our IPMCs the longest reported operation in air without rehydration (> 4 hours, 3000+ actuation cycles (Malone and Lipson, 2006a)) by preventing solvent loss through the actuator surfaces, but also improves the quality of films of the solution processed ionomer material when cast into silicone molds by acting as a hydrophilic intermediary.

Given that an IPMC generally has high-conductivity electrode surfaces, and can be caused to bend by a relatively small electrical signal, it can act as both coil and armature in a relay if it can be actuated in order to selectively close a load circuit with sufficiently small resistance (Figure 2). Our concept is to fabricate a relay housing which contains electrical contacts for the load circuit and for the IPMC and has a recess into which the IPMC materials can be cast and the entire housing annealed to remove the water solubility of the materials. Additional contacts can then be deposited atop, the cavity filled with water and capped, creating a sealed device (to prolong the IPMC service life) with three or more electrical terminals.

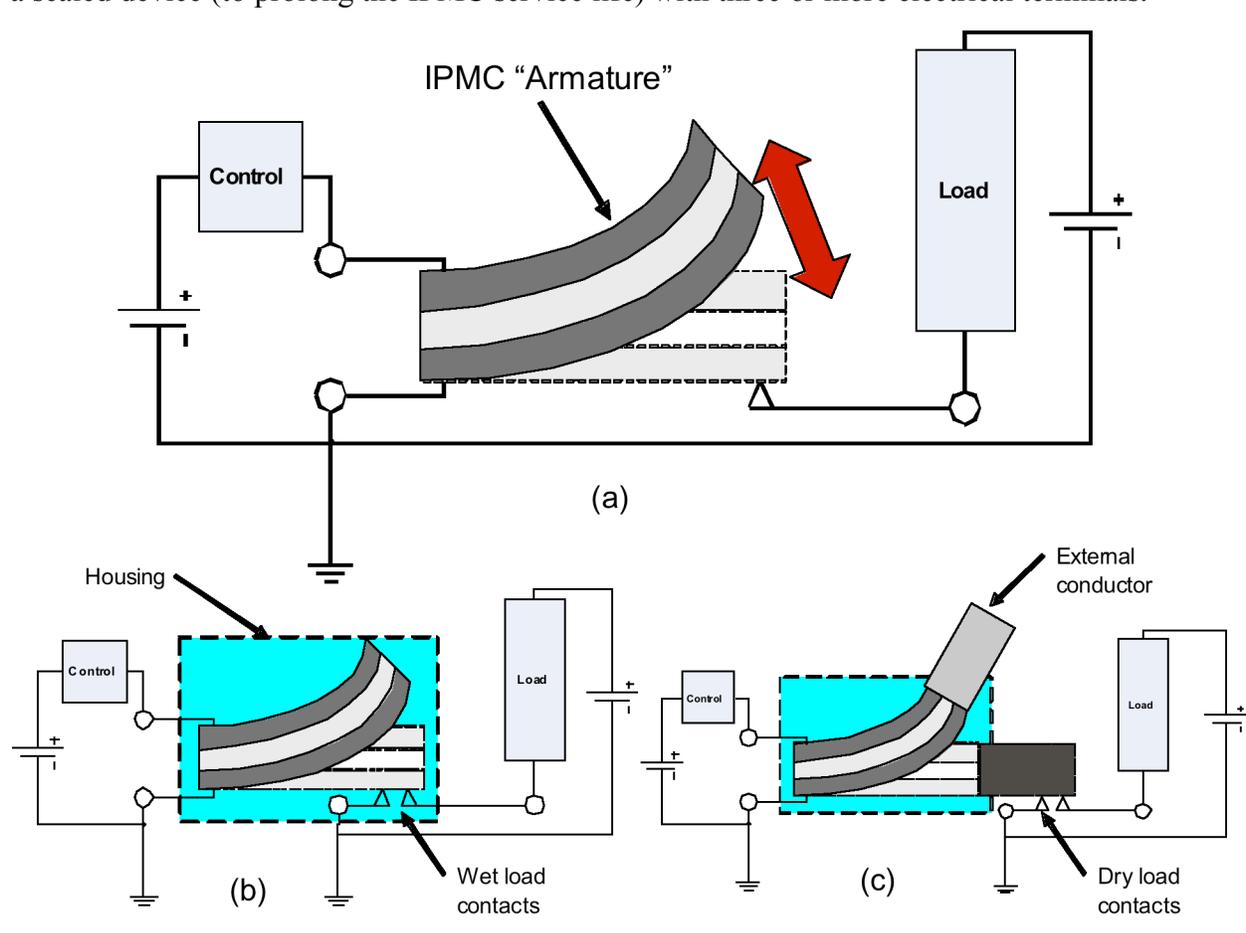


Figure 2. (a) Schematic of IPMC relay concept; (b) “wet contact” design in which load contacts are within the solvent-filled housing; (c) “dry-contact” design in which IPMC is extended with an external conductor which passes through the housing to interact with the load contacts in dry conditions.

Several design issues must be considered which affect the performance and mode of operation of any relay, including whether it should be normally conducting or not (normally

closed or normally open), how to maximize the current gain (minimize the input current requirement, minimize the load current when the device is not conducting, and minimize the resistance to the load current when the device is conducting), and how to achieve rapid switching. Several additional issues must be considered when the relay will employ an IPMC as the switching armature, and the entire device must be additively manufactured with no assembly. These include: whether the load contacts should be wet or dry (as the IPMC must be wet to operate), whether an IPMC of good quality, with good dimensional tolerances and high performance can be cast into the same structure that will house the relay, and whether the IPMC, once cast from solution, can free itself from its mold automatically so that it can operate without needing manual removal and reassembly.

A very simple design for a “normally closed” IPMC relay would be one in which one IPMC electrode (the “anode”) is grounded and acts as the load path to ground (Figure 2(a)). If in the unactuated “relaxed” state, the IPMC closes the load circuit, then a positive potential applied to the upper electrode (the “cathode”) will bend the IPMC upward, breaking the load circuit.

A “normally open” version cannot be made simply by placing the load contact above the upper electrode, as in this configuration the signal current source and load current source must be the same, and $G > 1$ is not possible. Maximizing gain is a matter of ensuring that the IPMC is of good quality – hence high electromechanical efficiency, and that the contact resistance between the load contacts and the armature (IPMC anode, or perhaps some conductor attached to the IPMC) is as small as possible when conducting, and as large as possible when not. This is largely a material properties issue (e.g. intrinsic resistivity, hydrophobicity if the contacts are wet), but also depends upon the pressure that the IPMC can apply to close the load circuit. Switching speed is tied to manufacturing tolerances (how far the IPMC must move to open/close the circuit), electromechanical efficiency of the IPMC (force/charge transfer), and the allowable control signal amplitude (in water, limited to $< 1.24\text{V}$, above which electrolysis occurs, wasting power and corroding electrodes; other solvents can tolerate higher potential). Wet contacts are conceptually simpler (Figure 2(b)) – one of the IPMC electrodes (which will be wet) acts to close the load circuit by pressing against the load contacts, but many materials have high contact resistance when wet, and wet contacts limit the load supply voltage to $< 1.24\text{V}$ for electrolysis reasons. In addition, when one of the IPMC electrodes acts as part of the load’s path to ground, the load current will generate a resistive potential in this electrode, possibly counteract the input control signal to the IPMC. Dry contacts (Figure 2(c)) require encapsulating the IPMC to prevent solvent loss (which sacrifices efficiency) and/or coupling some external conductor to the IPMC to switch the load circuit – complicating the manufacturing process. The quality of cast IPMCs, and whether they self-release from the mold/housing is dependent upon the IPMC material formulations, additives, etc., and the choice of mold/housing materials.

Experimental

In our prior work on freeform fabrication of IPMCs, we employed a large, non-portable multimaterial freeform fabrication system (Malone et al., 2004). One drawback of that system was that at the time we lacked fume extraction facility proximate to the system, and hence had to transport IPMC specimens to a fume hood and back to the machine repeatedly during the fabrication process, complicating the positional registration of fabrication steps. For the freeform fabrication processes in the present research, we are employing a Fab@Home Model 1 personal fabrication system (Malone and Lipson, 2007) which is compact and portable enough to setup in

a wetlab environment. This permits us to extract fumes directly from the system without removing the samples. The Model 1 dispenses materials from disposable 10cc polyethylene syringe barrels (EFD, Inc.) by the action of a linear stepper motor coupled to a disposable neoprene syringe piston (EFD, Inc.). The software application accepts 3D model data, allows the user to associate each model component with a material type, and then plans and executes the multimaterial fabrication process based on user supplied material data, prompting the user to change the material at the appropriate points in the process. Material changes are simply a matter of removing one syringe barrel and replacing with another. More details on the Model 1 can be found online (Malone et al., 2007).

Micrographs of IPMC specimens were captured with an AmScope ZM-1TZ-FOR-GT-3M Stereo Inspection Microscope with 3-megapixel camera, (AmScope, Inc.).

The structural material employed for IPMC molds and relay housings is GE Silicone II RTV (General Electric, Inc.) The candidate anode, cathode and load contact materials included Leit-C CCC, a commercial conductive carbon cement (SPI Supplies, Inc.), SPI 05002-AB, a high purity silver paint (SPI Supplies, Inc.), and SS26F, a silver-filled silicone RTV (Silicone Solutions, Inc.). Candidate IPMC electrode materials (designation EM or AM) included AM1, carbon black-filled Nafion composite (Malone and Lipson, 2006b), EM19, a thermoplastic rubber/silver colloid composite material (Malone and Lipson, 2006b), EM22, Ag-nanoparticle-filled Nafion composite, and EM23, a composite of 0.7-1.3 μm Ag powder-filled Nafion. All candidate IPMC internal materials are based on a 20wt% “liquid Nafion” dispersion in a blend of alcohols and water (Sigma-Aldrich #527122), which has been converted to Li^+ cation-form via a LiOH treatment (Malone and Lipson, 2006b). IM1 (Malone and Lipson, 2006b), , with 50wt% *N,N*-Dimethylformamide (Sigma-Aldrich) as a film-quality additive, and 2 wt% of fumed silica, and IM2, which is 50wt% of the 20 Li^+ .

The details of materials formulation and methods for freeform fabrication of IPMCs can be found elsewhere (Malone and Lipson, 2006b).

We performed automatic testing of complete relay devices using a PC-based data acquisition system (DAQBoard 2000 PCI, IOTech, Inc.) and DASyLab software (measX GmbH & Co. KG). Data is collected at 100Hz sampling rate, and data analysis performed with MATLAB (The MathWorks, Inc.).

Figure 3 provides a schematic of the automatic test setup. The relay load path (e.g. from load terminal 1 through the IPMC anode – if it is in contact with the load terminals – to load terminal 6) is connected as the lower leg of a voltage divider, with the resistive load, $R_{\text{Load}}=115\Omega$ +/-1%. We use separate, isolated, power supplies for the load and the IPMC actuation signal to ensure that the load circuit resistance signal is not contaminated by current leakage from the IPMC control signal. All testing is performed with $V_{\text{Load}} = 1.2\text{VDC}$, and an IPMC input square wave signal with 1.2V amplitude and frequency ranging from 0.005Hz to 1Hz.

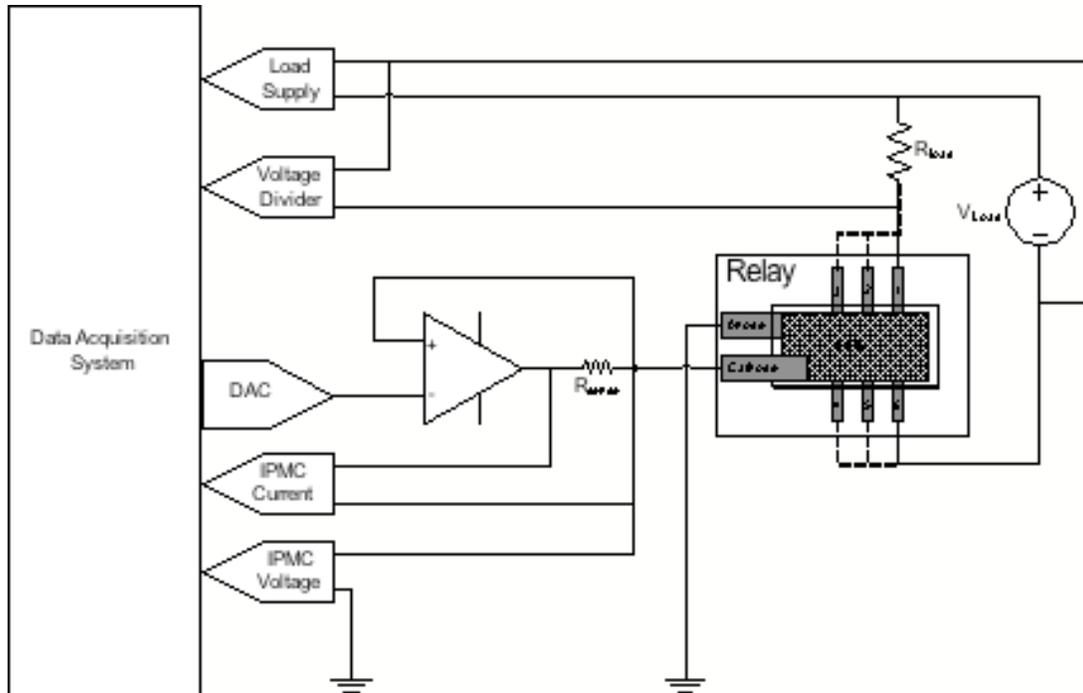


Figure 3. Data acquisition setup for automatic testing of IPMC relay; $R_{Load}=115\Omega$, $V_{Load} = 1.2VDC$ at all times, and the IPMC input signal is a square wave of 1.2V amplitude and frequency typically in the range 0.005-1 Hz.

Candidate Materials Selection

Given the aforementioned relay design issues of contact resistance, self-release, and IPMC performance, we evaluated candidate materials for the relay housing, anode, cathode and load contacts, and IPMC electrodes.

We performed a simple evaluation of relative contact resistance between IPMC electrode materials and candidate contact materials by pressing cast specimens of IPMC electrode materials against two electrically isolated traces of candidate contact material deposited manually on a glass slide. A small mass (2.2g) is used to generate a consistent, moderate pressure between the materials for a more fair comparison, and the total path resistance from one trace, through the electrode material, and back to the other trace was measured with a digital multimeter.

Measurements were performed with the materials fully dry, and again with them saturated in deionized water, in order to inform the tradeoff between wet and dry contact relay designs. Figure 4 shows the data from these experiments.

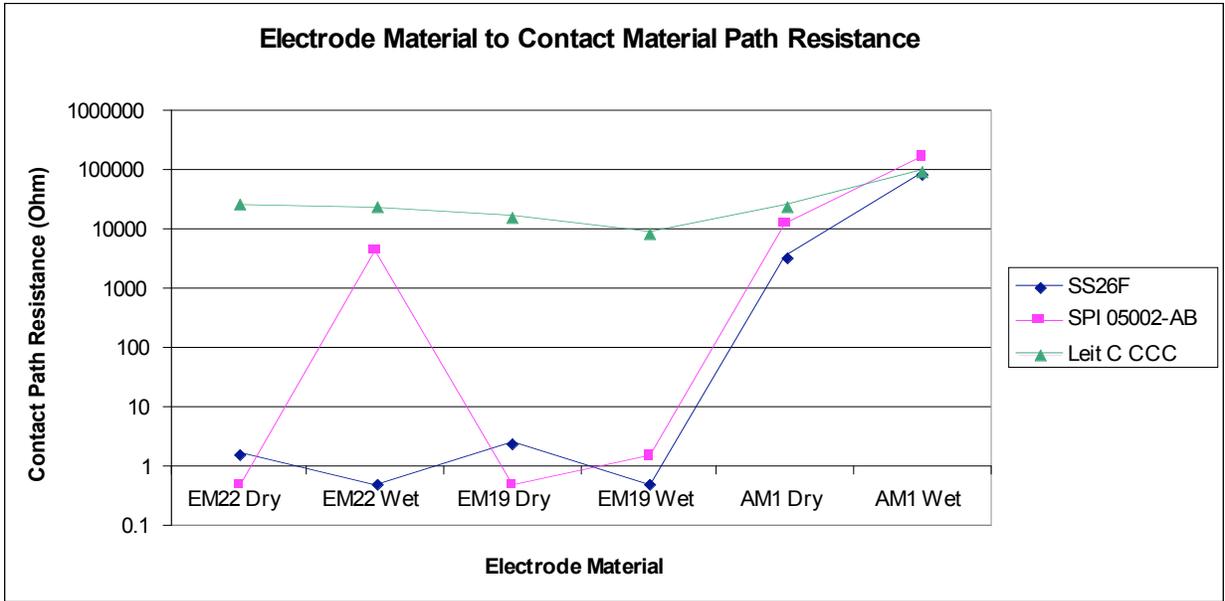


Figure 4. Data from wet and dry resistance tests of candidate IPMC electrode materials against candidate relay load contact materials

Note that the data are not adjusted to compensate for the resistance of the traces themselves or for the instrument contact to the traces, and were used for relative comparisons of material pairs only. It is clear that in dry conditions, either the EM22 or the EM19 electrode material against the SPI 05002-AB silver paint is the best combination, while for wet conditions, the combination of EM19 and SS26F is superior. The Ag-nanoparticle filled electrode material, EM22, is not included in these tests as it was found to be essentially non-conducting, and hence not a viable material for closing the load circuit.



Figure 5. Poor casting results for IPMC materials in (Design 1) relay housings constructed of GE Silicone II RTV, and electrical contact material SS26F; note the thick rims, curled and/or cracked surfaces

We examined the issues of self-release and IPMC quality by proceeding to fabricate candidate relay housing designs, and then casting IPMC materials into them. We evaluate self-release qualitatively by observing whether the IPMC is in substantial contact with the walls of the housing, and quantitatively by measuring the resistance from the anode terminal to each of the load terminals. IPMC quality is evaluated qualitatively by visual inspection for cracks, pinholes, and visible anode to cathode shorting and by optical microscopic inspection of internal structure, and quantitatively by measuring the anode to cathode resistance.

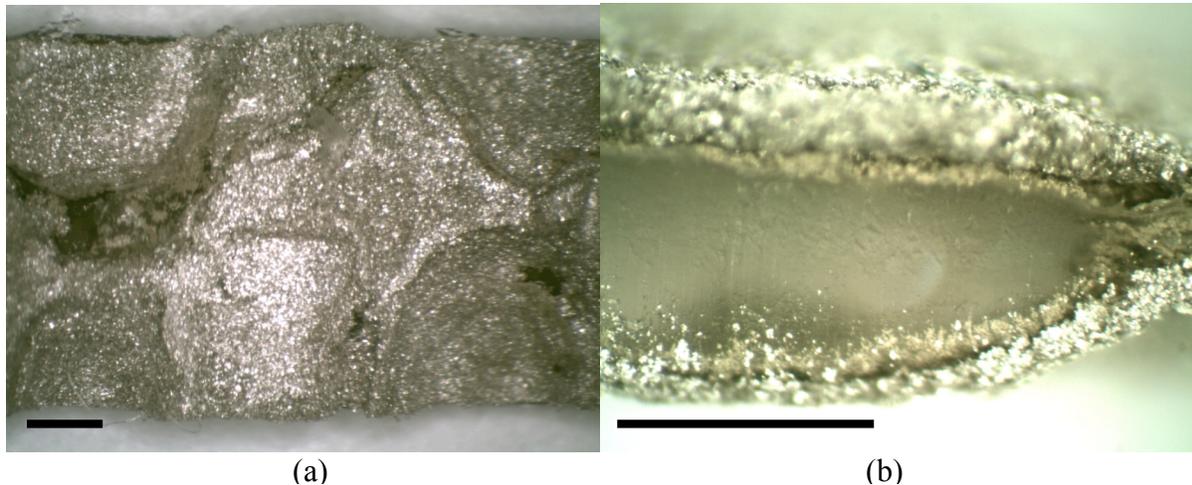


Figure 6. Optical micrographs of a poor-quality cast IPMC extracted from relay housing; (a) top down view showing irregular surface and impressions left by load contacts, scale bar 1mm; (b) edge-on view of cleaved IPMC showing well-formed and separated layers of EM19, EM23, and IM1 toward center (left), but anode to cathode shorting at edge (right), scale bar 500 μ m.

Design 1 (Figure 5) uses the single load contact design shown in Figure 2(a), and the majority of the housing base surface area consists of SS26F – roughly $\frac{1}{2}$ of the area for the anode contact and $\frac{1}{2}$ for the load contact. With this design, it became apparent fairly quickly that the IPMC materials do not cast well atop the SS26F/GE Silicone II combination of which the housings are constructed (Figure 5). None of the previously viable IPMC material combinations resulted in high-quality IPMCs – all tended to have very thick and cracked rims which were frequently the sites of anode to cathode shorting, and irregular internal material layer thickness (Figure 6). Several design modifications were used to attempt to improve the casting quality and to reduce cathode-to-anode shorting, including reducing the fraction of the surface area occupied by the SS26F material (Design 2), switching to the multiple load-contact design (Design 3) shown schematically in Figure 2(b), adjusting the height of the conductive contacts relative to the inside bottom surface of the housing/mold (Design 4), and depositing the anode electrode layer prior to depositing the housing walls, so that the anode layer could perfectly cover the bottom surface of the housing cavity, but the cavity walls are completely devoid of anode material (Design 4 variant).

After each design modification, a new set of set of relay housings was produced with the Fab@Home Model 1. We cast IPMC materials by pipette into these housings, varying the choices of electrode material(s), internal materials, and the number of layers (from 3 to 5). All casting attempts were dried at 35C in flowing air, and then annealed at 70C for 45 minutes. After annealing, all devices were inspected to select those with the best IPMC quality. These were made into complete relay devices by hand, by manually depositing (from syringe) a cathode insulator (of GE Silicone II) and a cathode terminal (of SS26F or EM19). For all finished devices, the resistance between anode and cathode, and between anode and electrode was measured with the device at ambient humidity, and also fully saturated with deionized water.

Finished devices have 36AWG copper wire bonded to their anode and cathode terminals with silver paint (SPI 05002-AB) to improve the repeatability of electrical connection to the data acquisition system.

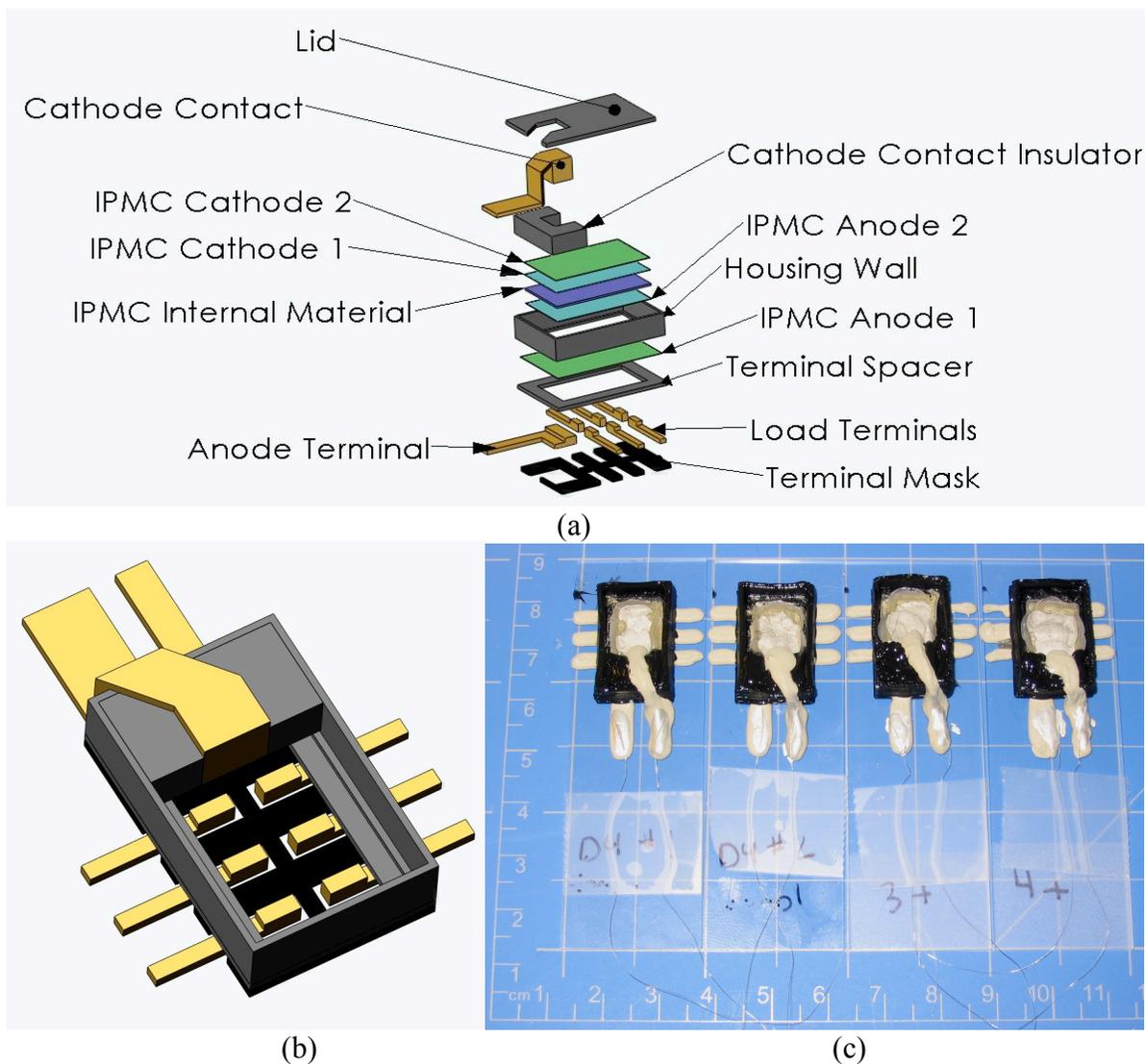


Figure 7. Design 4 - successful IPMC-based relay; (a) an exploded view of Design 4, showing the sequence of fabrication from bottom to top; (b) assembled view with cap and IPMC removed to show multiple load contacts and mold-recess in housing; (c) four examples of Design 4 relays with automatically fabricated housings and contacts, manually cast IPMCs, manually deposited cathode contact and contact insulator, and bonded electrode wires for testing. Note: the lid is not included in these test samples to allow for post-testing disassembly and analysis.

In total, to date, we have performed 27 different casting attempts of 12 different IPMC material/stacking options, in 4 different housing designs. Of the 27, 8 were deemed to be of good enough quality for completion to testable relays. In testing these, we have thus far had only 1 definite success, with marginally detected response in a few other instances. Figure 7 shows the most successful design of housing. It includes 6 total load terminals to increase the probability

of finding a pair that experience the largest change in resistance as the actuator oscillates during testing, and the heights of the terminals have been designed protrude about $500\mu\text{m}$ above the interior of the housing cavity floor as a compromise between excessive disruption of the planarity of IPMC materials during casting, and insufficient protrusion to make contact with the IPMC electrode. The cathode contact insulator, which is deposited immediately prior to the cathode contact, prevents the cathode contact material from flowing around the edges of the IPMC and shorting to the anode contact.

The most successful single device employed the combination: housing, Design 4; 5-layers (EM19, EM22, IM1, EM22, EM19); cathode conductor material, SS26F. Results of testing this device are presented below.

Results / Discussion

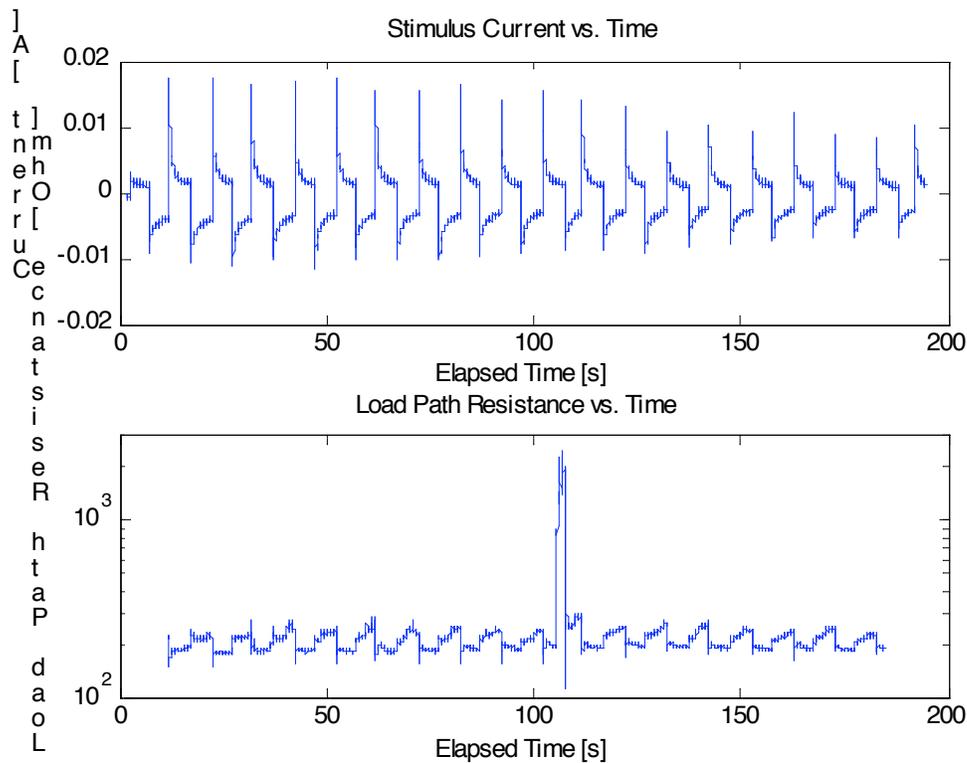


Figure 8. Successful test of partially freeform fabricated relay; IMPC input signal 1.2V, 0.05Hz square wave, $V_{\text{Load}} = 1.2\text{VDC}$

Figure 8 shows time-series data of current input to the IMPC, and load path resistance calculated from the load circuit voltage divider potential. The input signal is a 0.05Hz, 1.2V square wave. The RMS input current to the IMPC, $I_{\text{RMS,In}}$, for this particular sample is 0.0038A, and the RMS power, $P_{\text{RMS,In}}$, is 0.0039W. The open/closed resistance ratio achieved is roughly 2 ($\sim 300\Omega/150\Omega$). With a minimum resistance, R_{min} of 150Ω , the current gain, G , for this device is 1.05. The large “glitch” at $t \sim 110\text{s}$ is unexplained.

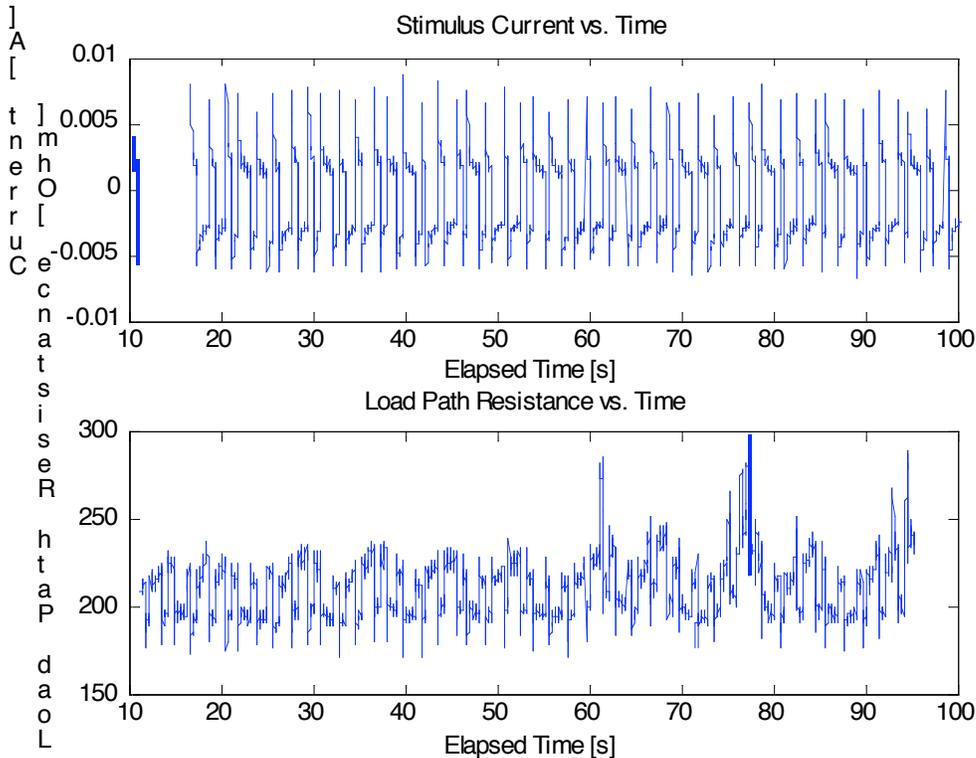


Figure 9. Successful test of partially freeform fabricated relay; IMPC input signal 1.2V, 1Hz square wave, $V_{Load} = 1.2VDC$

As can be seen in Figure 9, at 1Hz, this same device has a smaller response. $I_{RMS,In} = 0.0031A$, $P_{RMS,In} = 0.0035W$. The resistance ratio becomes 1.2 ($\sim 220\Omega/180\Omega$), and $G \sim 0.39$.

Future Work

The present results are not sufficient to fill our need for an amplifier which can connect the microampere domain of organic polymer semiconductors to the milliampere domain of the IPMC used as a macroscale actuator. Given the difficulties we have experienced with casting of IPMC materials into the housings we have fabricated, we propose to explore additional viable housing and electrical contact materials, including epoxies and hydrophilic thermoplastic polymers both with and without conductive fillers. Improvements to IPMC casting will improve the dimensional tolerances and electromechanical efficiency of the resulting IPMCs, enabling a reduction of their size and input power requirements and thus the current gain of the relay. IPMC performance can be enhanced through nanocompositing with activated silica (Nguyen et al., 2006, Paquette et al., 2003), which will also reduce the relay input current, as well as the driven actuator's input requirements.

Conclusion

We are confronted by significant barrier to our goal of developing multimaterial freeform fabrication systems capable of “printing” complete electromechanical devices. We can print batteries capable of supplying sufficient power for the actuators we can print, and it is feasible to produce integrated circuits entirely through solution processing within our fabrication system.

However, the foreseeable circuits, based on organic polymer semiconductors, will not be able to directly control the level of power required to operate a meaningful actuator. Hence there is a gap between what needs to be controlled and what can do the controlling. To bridge this “electronics gap” we are developing a relay which employs an IPMC actuator in lieu of the electromagnet and armature of a normal DC relay. Here we have demonstrated complete, functional IPMC-based relays produced entirely by solution/extrusion processes, with the relay housing and electrical contacts fabricated automatically with a Fab@Home Model 1 system, and the remainder deposited by hand from pipette or syringe. Despite substantial effort at optimizing materials and exploring designs, our current material suite does not yet yield the level of performance that we require, but we are actively pursuing several obvious approaches to enhancing device performance, and confident of eventual success. Relays with sufficiently high performance will allow us to fabricate complete actively controlled electromechanical devices within a single, compact freeform fabrication system, without assembly, opening up an entirely new design space for engineering and product innovation.

Acknowledgments

This work was supported in parts by the U.S. Department of Energy, grant DE-FG02-01ER45902.

References

- BERRY, M., MALONE, E. & LIPSON, H. (2005) Freeform Fabrication of Zinc-Air Batteries with Tailored Geometry and Performance. IN BEAMAN, J. & BOURELL, J. (Eds.) *16th Solid Freeform Fabrication Symposium*. Austin, TX, USA.
- COHEN, D. L., MALONE, E., LIPSON, H. & BONASSAR, L. J. (2006) Direct freeform fabrication of seeded hydrogels in arbitrary geometries. *Tissue Engineering*, 12, 1325.
- HYOUNG-TAE, L., JANG-WOO, L. & YOUNG-TAI, Y. (2006) Actuation behavior of a carbon nanotube/nafion™ IPMC actuator containing an ionic liquid. *Journal of the Korean Physical Society*, 49, 1101.
- KIM, K. J. & SHAHINPOOR, M. (2001) Development of Three-Dimensional Polymeric Artificial Muscles. IN BAR-COHEN, Y. (Ed.) *Proceedings of the SPIE 8th Annual Symposium on Smart Structures and Materials: Electroactive Polymer Actuators and Devices*. San Diego, CA, USA, SPIE Press.
- KIM, K. J. & SHAHINPOOR, M. (2002) A novel method of manufacturing three-dimensional ionic polymer-metal composites (IPMCs) biomimetic sensors, actuators and artificial muscles. *Polymer*, 43, 797-802.
- KIM, K. J. & SHAHINPOOR, M. (2003) Ionic polymer-metal composites: II. Manufacturing techniques. *Smart Materials and Structures*, 12, 65-79.
- MALONE, E. & LIPSON, H. (2004) Solid Freeform Fabrication for Autonomous Manufacturing of Complete Mobile Robots. IN COLOMBANO, S. (Ed.) *Robosphere 2004*. Mountain View, CA.
- MALONE, E. & LIPSON, H. (2006a) Freeform Fabrication of Ionomeric Polymer-Metal Composite Actuators. *Rapid Prototyping Journal*, 12, 244-253.
- MALONE, E. & LIPSON, H. (2006b) Freeform fabrication of ionomeric polymer-metal composite actuators. *Rapid Prototyping Journal*, 12, 244.
- MALONE, E. & LIPSON, H. (2007) Fab@Home: The Personal Desktop Fabricator Kit. *Rapid Prototyping Journal*, Accepted.
- MALONE, E., LIPSON, H., PERIARD, D. & YAO, J. (2007) Fab@Home.
- MALONE, E., RASA, K., COHEN, D., ISAACSON, T., LASHLEY, H. & LIPSON, H. (2004) Freeform fabrication of zinc-air batteries and electromechanical assemblies. *Rapid Prototyping Journal*, 10, 58-69.
- NEMAT-NASSER, S. & LI, J. Y. (2002) Micromechanics of actuation of ionic polymer-metal composites. *Journal of Applied Physics*, 92, 2899-2915.
- NEMAT-NASSER, S. & ZAMANI, S. (2003) Experimental study of nafion- and flemion-based ionic polymer-metal composites (IPMCs) with ethylene glycol as solvent. *Proceedings of the SPIE - The International Society for Optical Engineering*

- Smart Structures and Materials 2003. Electroactive Polymer Actuators and Devices (EAPAD)*, 3-6 March 2003, 5051, 233-44.
- NGUYEN, V. K., LIM, H.-T., LEE, J. W. & YOO, Y. (2006) Effect of nanoparticulate fillers on the deformation behavior of Nafion-based ionic polymer metal composite. *Smart Structures and Materials 2006: Electroactive Polymer Actuators and Devices (EAPAD)*. 1 ed. San Diego, CA, USA, SPIE.
- NGUYEN, V. K. & YOO, Y. (2007) A novel design and fabrication of multilayered ionic polymer-metal composite actuators based on Nafion/layered silicate and Nafion/silica nanocomposites. *Sensors and Actuators, B: Chemical*, 123, 183.
- NILSSON, D., ROBINSON, N., BERGGREN, M. & FORCHHEIMER, R. (2005) Electrochemical logic circuits. *Advanced Materials*, 17, 353.
- OMRON (2006) General Purpose Relay MJN Technical Datasheet. Omron Electronic Components LLC.
- PALMER, J. A., JOKIEL, B., NORDQUIST, C. D., KAST, B. A., ATWOOD, C. J., GRANT, E., LIVINGSTON, F. J., MEDINA, F. & WICKER, R. B. (2006) Mesoscale RF relay enabled by integrated rapid manufacturing. *Rapid Prototyping Journal*, 12, 148.
- PAQUETTE, J. W., KIM, K. J., NAM, J.-D. & TAK, Y. S. (2003) An equivalent circuit model for ionic polymer-metal composites and their performance improvement by a clay-based polymer nano-composite technique. *Journal of Intelligent Material Systems and Structures*, 14, 633-42.
- PAUL, K. E., WONG, W. S., READY, S. E. & STREET, R. A. (2003) Additive jet printing of polymer thin-film transistors. *Applied Physics Letters*, 83, 2070.
- SHAHINPOOR, M. & KIM, K. J. (2001) Ionic polymer-metal composites. I. Fundamentals. *Smart Materials and Structures*, 10, 819-833.
- TYCO-AXICOM (2006) P2 V23079 Relay Technical Datasheet. Tyco Electronics / Axicom.