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MULTI-MATERIAL FREEFORM FABRICATION OF ACTIVE SYSTEMS

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ABSTRACT

Current Solid Freeform Fabrication (SFF) technologies can manufacture, directly from digital data, end-use mechanical parts in an increasingly wide variety of engineering materials. However, commercial SFF systems remain costly, complex, proprietary, and are limited to working with one or two proprietary materials during the course of building a part, hindering their broader application and the impact of the technology.

The work we present here demonstrates (1) that SFF systems can employ many materials and multiple processes during the course of building a single object, (2) that such systems can produce complete, active, electromechanical devices, rather than only mechanical parts, and (3) that such multi-material SFF systems can be made accessible to, and are of interest to the general public. We have developed a research-oriented, multi-material SFF system and employed it to produce not only mechanical parts, but complete and functional Zn-air batteries, electrical wiring, flexible circuit boards, strain-gages, electromagnets, electroactive polymer actuators, organic-polymer transistors, and electromechanical relays. We have also developed and published the Fab@Home Model 1 open-source, multi-material, freeform fabrication system design. The Fab@Home project has received broad public and media attention, and more than 100 Model 1 machines have been built by individuals around the world.

multimaterial, multi-process, freeform fabrication, additive manufacturing, rapid prototyping, open-source

1. INTRODUCTION

Solid freeform fabrication (SFF) is the name given to a class of manufacturing methods, sometimes also known as Rapid Prototyping (RP), which allow the fabrication of three-dimensional structures directly from computer-aided design (CAD) data. SFF processes are generally additive, in that material is selectively deposited to construct the part, rather than removed from a block or billet. Most SFF processes are also layered, meaning that a geometrical description of the part to be produced is cut by a set of parallel surfaces (planar or curved) and the intersections of the part and each surface – referred to as slices or layers – are fabricated sequentially. Together, these two properties imply that SFF processes are subject to very different constraints than traditional material removal-based manufacturing. As has been demonstrated with various (but no single) SFF system, nearly arbitrary product geometries are achievable [1] and parts can be made without hard tooling, raw materials may be more efficiently used than in subtractive processes, mating parts and fully assembled mechanisms can be fabricated in a single step [2], exogenously produced components, such as integrated circuits, can be "dropped in" during fabrication [3], and multiple materials (including, electronic- [4], chemical-, and bio-materials [5-7] and even living tissues [8, 9]) can be combined to create graded material properties [10-13] and even complete functional devices [14-16]. Furthermore, one or more SFF processes can typically be implemented within a single small workcell [3, 14] – compacting enormously what might have once required many separate machines.

Given all of the above, it would seem possible that with some combination of SFF technologies, one could build a "compact factory", or "fabber" capable of building almost anything within a single workcell. Such systems could have tremendous value as flexible, portable manufacturing facilities for resource- or time-constrained situations such as catastrophe response, or polar or space exploration. Furthermore, such

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systems could enable invention, prototyping, and manufacturing of an entirely new space of product and device designs in which geometry and functionality (including active electromechanical, chemical, and biological functionality) can be continuously varied and intertwined.

A consumer-oriented fabber, coupled with the networked educational and technical resources already available today, could empower individuals with much of the innovative facility that would otherwise require an entire R&D laboratory. This could potentially lead to economic innovations such as neo-cottage industry manufacturing, an "eBay of designs" where individuals can market unique product designs as digital instructions and material recipes for others to execute on their own fabbers, and millions of people inventing technology rather than merely consuming it.

Despite the aforementioned potential, commercial SFF technology is still focused on producing passive mechanical parts in one or two proprietary materials, and the emphasis of commercial R&D has been on improving the quality, resolution, and surface finish of parts, and on broadening the range of useable materials. Growth in the market for and capability of commercial SFF technology has been disappointingly slow – commercial systems have been available for more than two decades [17], yet worldwide annual sales of systems are still measured only in thousands [18]. SFF systems remain very expensive and complex, and are used primarily by corporate engineers, designers, and architects for prototyping and visualization and for manufacturing a limited range of end use parts. These factors are linked in a vicious cycle which slows the development of the technology: Niche applications imply a small demand for machines, restricting commercial R&D and adoption of the new capabilities demonstrated in the laboratory, while small demand for machines keeps the machines costly and complex, limiting them to niche applications.

As will be presented, we are working to free SFF technology from this trap, and to accelerate the development of fabbers by:

1. developing a research SFF system which is capable of employing multiple SFF processes and many materials in the course of building a single object,
2. developing materials and designs which allow us to produce a wide variety of functional products and even complete electromechanical devices entirely within this single SFF system, and
3. involving the public in developing novel applications for and innovations in fabbing technology by designing the Fab@Home Model 1 Personal Desktop Fabricator– an inexpensive multi-material fabber which individuals can build from a kit, operate, and experiment with, using free and open-source designs, instructions, and software we provide via a website.

2. RESEARCH SFF SYSTEM

Our multi-material freeform fabrication research platform (Figure 1) consists of a 3-axis Cartesian gantry robot, two changeable material-deposition tools, and a software application which processes assemblies of STL files into a multi-material manufacturing plan and executes the plan on the system hardware. Since our first publication on the system [14], we have reengineered both tools and improved the software to enhance deposition control, speed up changes of material, and simplify manufacturing of complex multi-material objects.

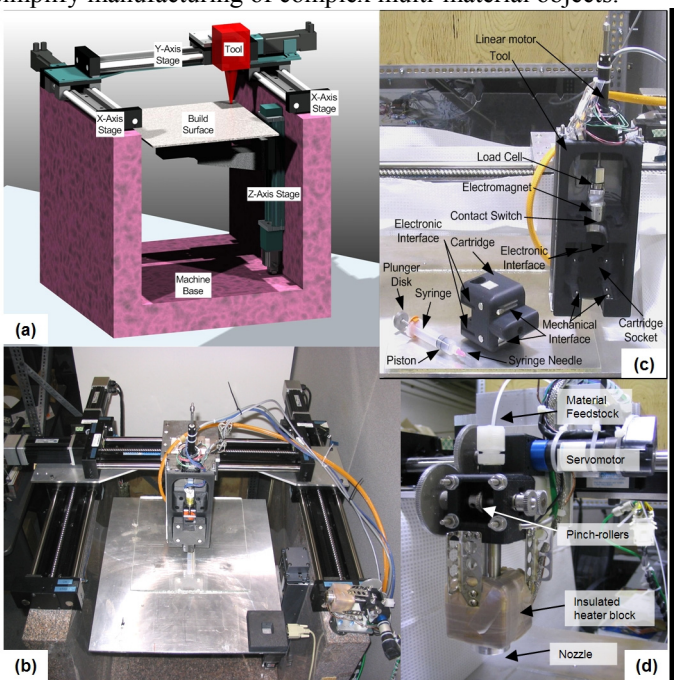


Figure 1. Multi-material SFF research platform; (a) CAD rendering of the Cartesian gantry positioning system, (b) photograph of actual system with syringe-deposition tool mounted, (c) components of syringe-deposition tool, and (d) components of molten-extrusion tool.

The XY-axis gantry moves the mounted tool along planned deposition paths, while the Z-axis table moves downward to accommodate deposited material layers (Figure 1(a, b)). One tool (Figure 1(c)) employs syringe-deposition ("robocasting") to deposit streams ("roads") of material 250-1500µm in diameter, depending on material properties and resolution/fabrication speed tradeoff. It is compatible with an enormous range of liquid, gel, or paste materials, and employs a linear stepper motor to achieve volumetric dispensing, at up to 1.1MPa (160PSI). We have redesigned it to dispense from 10mL disposable syringes mounted in easily changeable cartridges in order to facilitate rapid material changes. The second tool (Figure 1(d)) employs a molten-extrusion (FDM®) process, which entails feeding thermoplastic or low-melting point eutectic alloy feedstock in wire-form into a heated nozzle. This tool extrudes a fine strand (typically 150-200µm diameter) of molten material which quickly solidifies, and now has active feedstock cooling, an optimized pinch roller tooth design, and a

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modular, finger-safe heating block. Tools are mounted to the XY gantry via a pneumatically-actuated robotic tool changer, which allows quick and accurate exchanges of tools.

We have created a custom computer-aided manufacturing (CAM) application which imports individual or assemblies of tessellated geometry (polyhedra) as STL files, generates hardware executable manufacturing plans, and controls their execution on the fabrication hardware. The system operator uses a graphical interface (GUI) to specify with which material/tool combination each polyhedron should be fabricated. The toolpath planning consists of slicing each polyhedron according to the road thickness associated with its particular material/tool combination, offsetting resulting boundary polygons by ½ of the road width for the material/tool, and filling enclosed areas with raster (hatch) paths. Slices (containing paths) are then sorted by their height and executed, with the software prompting the operator to change the material and/or tool as required. Our hardware currently allows only one tool/material combination to be mounted at a time, and changes are manually executed, so time and labor become a significant factor for complex products, such as batteries.

To reduce the cost associated with tool/material switching, we have developed a fabrication process extension, dubbed "Backfill Deposition", which allows overriding the layer height-ordering of the process plan to fabricate some parts of the structure before others. In practice, as geometry data describing component parts of a product such as a battery are imported into the fabrication system software, the operator may use the GUI to assign a sequential "fabrication priority" to each of the parts. Our SFF system will fabricate higher priority parts of an assembly *to their full height* prior to fabricating lower priority parts, in contrast to strict layered fabrication. This can reduce the number of tool changes in some cases from one per layer, down to one per STL file (or part). Additionally, this option facilitates fabrication of products which contain or are made from liquid materials – it allows the fabrication system to construct a container *before filling it*.

3. FUNCTIONAL PRODUCTS AND DEVICES

In order to prove the principle that multi-process, multi-material SFF systems can begin to approximate the capabilities that we have envisioned for future fabbers, we have used our SFF systems to produce a wide variety of functional products and electromechanical devices, with the eventual goal of being able to freeform fabricate an entire mobile robot as a capstone demonstration. Each of these products required a significant R&D effort which included developing or adapting product designs for compatibility with SFF manufacturing, and formulating functional raw materials which are compatible with SFF processes without sacrificing their essential functionality. The key observation from the sum of these efforts is that once the designs and materials have been proven successful, *a single SFF system can produce any of these objects*, and we intend to show in future work, can produce many of them integrated into a single multifunctional product.

3.1. Batteries

In prior work [14], we demonstrated the first freeform fabrication of complete, macroscopic Zn-air batteries – a milestone in SFF not only for being a functional battery, but also for the number of separate materials (five) involved. We have continued to refine the materials and techniques, including backfill deposition, required to produce Zn-air batteries, and have since achieved cylindrical batteries (Figure 3(a)) with energy density and power density about 10% that of commercial, mass-produced batteries (Figure 2) [19].

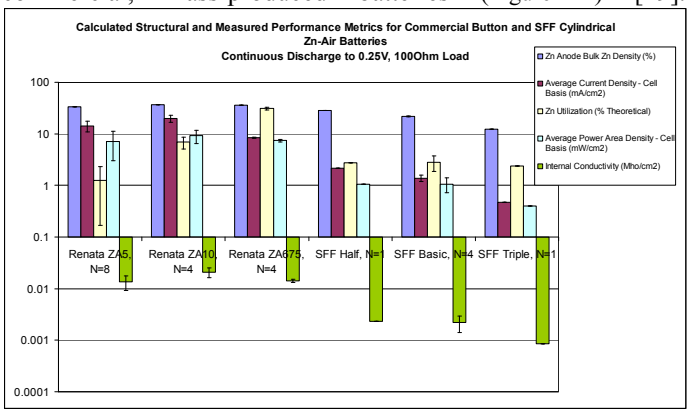
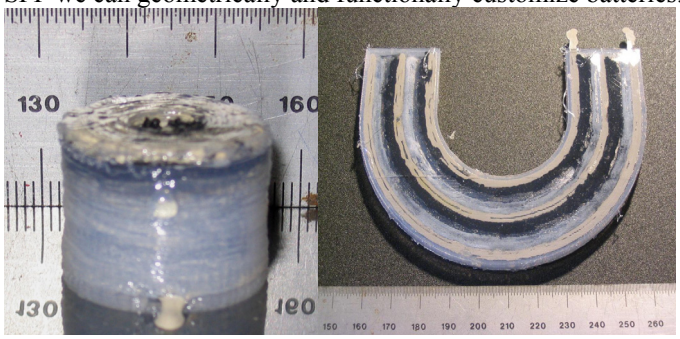


Figure 2. Structure and performance comparison between several sizes of commercially manufactured Zn-air batteries and solid freeform fabricated (SFF) Zn-air batteries. Error bars are provided for cases in which multiple batteries were tested - N indicates the sample size.

We have also demonstrated, by producing a flexible, "U" shaped Zn-air battery containing 2 cells (Figure 3(b)), that via SFF we can geometrically and functionally customize batteries.



(a) (b)

Figure 3. Functional Zn-air batteries produced entirely by SFF: (a) a cylindrical battery containing one cell; (b) a flexible, "U" shaped battery containing 2 cells.

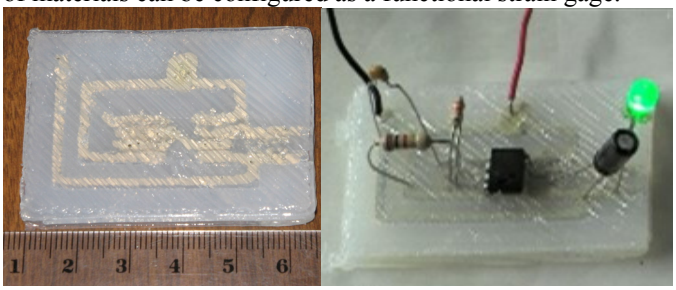
We believe that SFF allows design freedom and packaging density superior to what can be achieved with packs of mass produced batteries, and thus expect SFF to become a competitive technique for custom batteries if we can achieve performance within about 20% that of mass-produced batteries. We have identified likely performance bottlenecks, and are actively seeking solutions for them.

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3.2. Wiring, Circuit Boards, Strain Gages, & Electromagnets

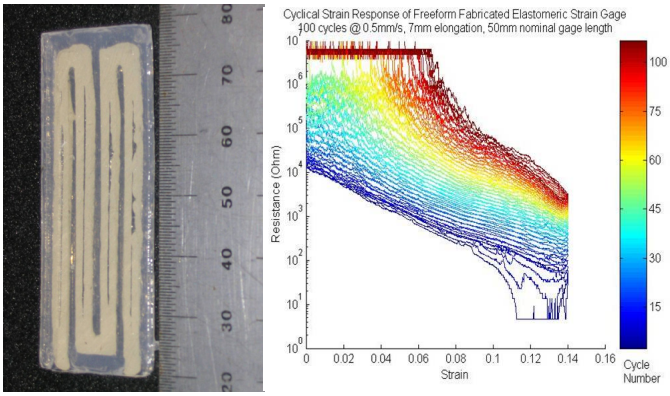
An essential functionality for any electromechanical device is electrical circuitry – wiring. We have developed two approaches to freeform fabrication of wiring, based on two types of materials, each with particular benefits and drawbacks.

The first class of materials could be described as conductive composites, e.g. polymers filled with a granular conductive phase. These include commercially available silver inks, our own ink formulations, and silver-filled silicone rubber. These materials have the benefit of simple, room-temperature processing, and are typically flexible, or even elastic, but the drawback of having relatively high resistivity – typically ~ 10^{-3} Ω-cm. Their "soft" nature immediately suggests novel applications beyond simple wiring. Figure 4 shows a freeform fabricated functional, flexible printed circuit board comprising Ag-filled silicone traces embedded in insulating silicone. Figure 5 shows how with a simple change of the CAD model sent to the SFF system, the same combination of materials can be configured as a functional strain gage.



(a) (b)

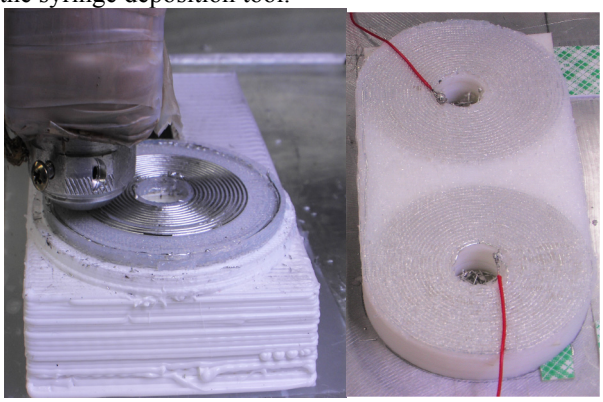
Figure 4. A two-dimensional flexible printed circuit: (a) as fabbed (dimensions in centimeters); (b) with components inserted and power supplied.



(a) (b)

Figure 5. (a) A silver-filled silicone strain gage (dimensions in mm); (b) resistance vs. strain data over 100 cycles.

The second class of materials is fusible metals which have low melting points, such as alloys of Pb, Sn, Bi, Sb, or In. These materials of course require elevated-temperature processing, but have the benefit of very high conductivity – typically ~ 10^{-5} Ω-cm. By careful tuning of deposition parameters, we have achieved continuous deposition of Sn-Sb alloy strands 0.5mm in diameter and more than 5m long. This combination of high conductivity and fine gage has enabled us to freeform fabricate coils of sufficient density and number of turns to produce functional electromagnets (Figure 6). Our best result so far has been three consecutive stacked layers of 20 turns each at about 1 turn/mm of radius. To amplify the magnetic field, we have employed a core material consisting of 80wt% iron filings in lithium grease, which is readily deposited via the syringe deposition tool.



(a) (b)

Figure 6. Freeform fabrication of an electromagnet: (a) depositing multiple layers of Sb-Sn alloy wire coils atop a freeform fabricated silicone base via the molten-extrusion tool; (b) a complete electromagnet assembly.

3.3. Electroactive Polymer Actuators

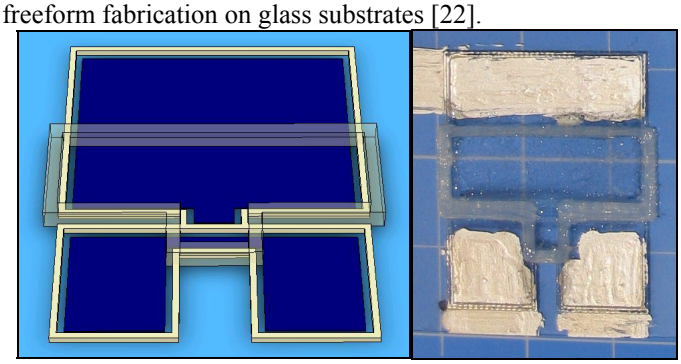
Rotary electromagnetic motors are the dominant form of electromechanical actuator in the world today. Despite our success with electromagnets, which are a key subsystem of rotary motors, freeform fabrication of a complete rotary electromagnetic motor remains a "grand challenge" for SFF due to the complexity of moving coils, bearings, etc. Fortunately, electromechanically active materials exist which can be configured as mechanical actuators in a relatively simple fashion. We have investigated a particular type of device, known as an Ionomeric Polymer-Metal Composite (IPMC) Actuator, which typically comprises two or three materials, and which bends in response to a low voltage electrical signal. We adapted the IPMC solution-processing research of Kim and Shahinpoor [20] by formulating materials compatible with SFF processes, and developed the technique of fabricating the container for the actuator materials along with the actuator – a key innovation which enables actuators to be embedded within more complicated freeform fabricated devices. Using these innovations, we have successfully demonstrated freeform fabrication of complete IPMC actuators, and documented the longest reported operating life in air for IPMCs manufactured by any method [21]. As with batteries, however, freeform fabricated IPMCs have inferior performance in several metrics – blocked stress, bandwidth, and range of motion – to those produced by established laboratory methods. We are continuing

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to refine the materials and the control of their deposition with the goal of closing the performance gap and allowing greater freedom in the shape and orientation of freeform fabricated IPMCs.

3.4. Organic Polymer Transistors

Solution-processable organic semiconductor materials can be used to print transistors under ambient conditions which are robust enough to function on flexible substrates, and are useful for inexpensive, disposable, and/or flexible applications. Specifically, organic electrochemical transistors (ECT) function at low voltages and with large feature sizes, making them good candidates for freeform fabricated devices. In prior work, we have reported the first functional ECTs produced via freeform fabrication on glass substrates [22].



(a) (b)

Figure 7. (a) A 3D CAD model of a printable transistor. The yellow material indicates silicone boundaries, while the dark blue material is PEDOT:PSS. The liquid electrolyte is held within the partially transparent boundary. (b) A completed transistor set up for characterization (the grid size is 1cm).

Our freeform fabricated transistors (Figure 7) are made by depositing boundary patterns of silicone on a glass substrate, via the syringe deposition tool, to define the source and drain regions.

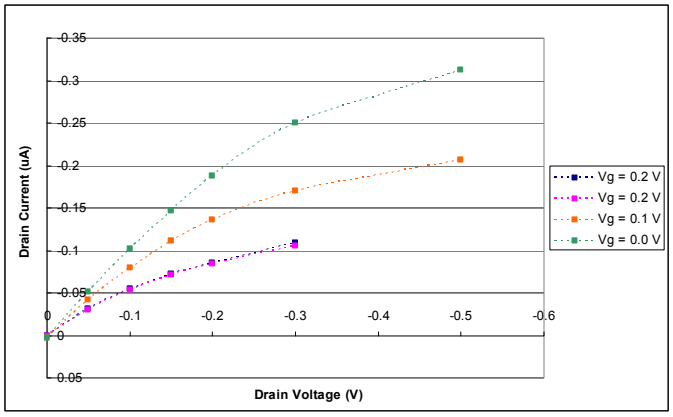


Figure 8. Drain current vs. drain voltage curves for a single printed transistor for various gate voltages. The transistor was measured twice at 0.2V applied to the gate, then once at 0.1V, and once at 0V.

The same tool is then used to deposit our preferred organic semiconductor, PEDOT:PSS dispersed in water, into the source and drain boundaries. A silicone boundary to define the gate region is then deposited and filled with $CaCl_2$ electrolyte. Silver-ink contact pads are hand-painted and devices are connected to a data acquisition system for testing.

Our freeform devices show stable operation in air over at least one hour and several measurement cycles, have a source-drain current of 0.1μA at -0.5Vsd, which is an order of magnitude larger than the gate (leakage) current, and an on/off ratio of 2 at 0.2Vgate (Figure 8). These preliminary devices have source-drain current three orders of magnitude lower than literature values for similar ECTs. This work has enabled us to study ECT behavior on printable substrates, necessary to ultimately incorporating ECTs into fully integrated freeform fabricated electromechanical devices.

3.5. Electromechanical Relays

We have investigated producing electromechanical relays entirely via freeform fabrication as part of our 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. Relays have been produced before in part through SFF processes [16], but that work involved metal machining processes as well as assembly of parts. We need to produce such a device entirely via SFF 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.

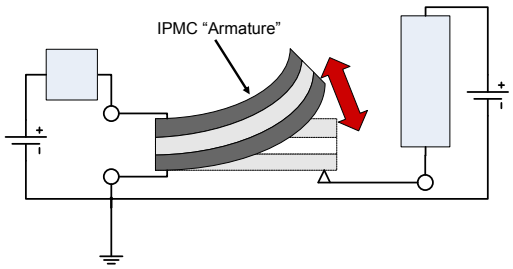


Figure 9. Schematic of an IPMC-based electromechanical relay

We conceived a simple relay design (Figure 9) 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 have explored candidate switch contact materials, IPMC electroding materials, candidate housing and contact designs, and manufacturing sequences to find

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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. Thus far, we have freeform fabricated test housings, and then manually cast variants of IPMC materials into these housings, and tested these partially freeform fabricated relays using a PC-based data acquisition system. Given our success with complete freeform fabrication of IPMC actuators, this manual casting for expediency during testing should not be considered evidence of any additional difficulty in automating the casting for this application.

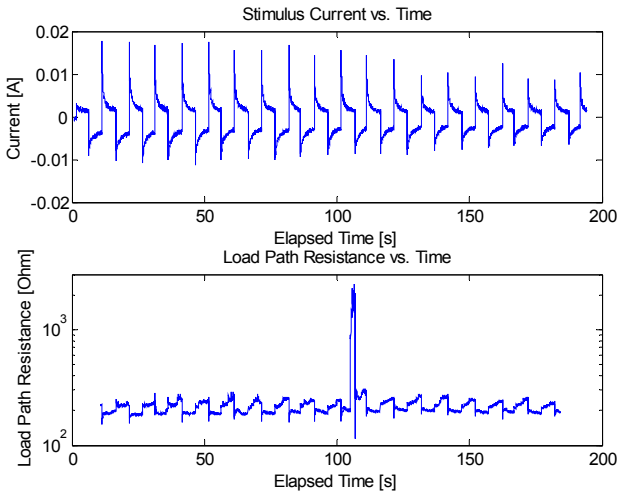


Figure 10. Successful test of partially freeform fabricated relay; IMPC input signal 1.2V, 0.05Hz square wave, V_{Load} = 1.2VDC

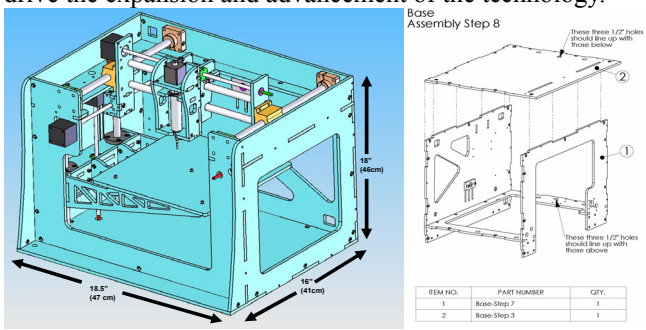
These partially freeform-fabricated relays achieved a controllable load path resistance change of a factor of two at switching frequencies up to 0.05 Hz with a 1.2V control input and an RMS input current of 3.8mA (Figure 10). At 1.2V load potential, load/input current gain is roughly 1.05. The device functions above 1Hz, but current gain falls below 1.

4. THE FAB@HOME PROJECT

Future fabricator systems that can produce complex functional artifacts comprising many materials will transform the way we design, make, deliver and consume some products, and enable the creation of entirely new products that will be literally impossible to produce otherwise.

Unfortunately, the key to these future fabbers, SFF technology, is trapped in a "chicken and egg" paradox, in which having only niche applications keeps SFF technology expensive and little known, and being expensive and little known, few new applications for SFF systems are developed, and the demand for SFF systems is too small to reduce their cost.

In order to escape this paradox, and to accelerate the spread and development of personal fabrication technology, we have developed the Fab@Home Project, and an open-source, low-cost, personal fabricator system kit, which we call the "Fab@Home Model 1" (Figure 11(a)). Our project has been inspired by the open-source approach employed by Bowyer's RepRap Project [23] toward the goal of developing self-replicating fabbers. The aim of our project is to put SFF technology into the hands of the maximum number of curious, inventive, and entrepreneurial individuals, and to help them to drive the expansion and advancement of the technology.



(a) **(b)**

Figure 11. The Fab@Home Model 1 Design. (a) 3D CAD model of an assembled Model 1; (b) An example of assembly instructions available via the project website

The Model 1 kit has a parts cost of roughly $2300, includes a free, open-source application to control the fabber, requires only basic hobbyist tools and skills to assembly and use, and can be used to deposit almost any room-temperature liquid or paste. It is essentially a simplified version of our research platform, but uses only a syringe deposition tool, and is slower and has lower resolution. We have used Model 1 machines to make multimaterial objects, and it could certainly be used to make most of the functional devices that we have produced with our research platform.

We have endeavored to make obtaining, assembling, using, and experimenting with the Model 1 as simple and intuitive as possible – the website provides step-by-step ordering, assembly (Figure 11(b)) and operational instructions, and the application has an animated graphical user interface (Figure 12).

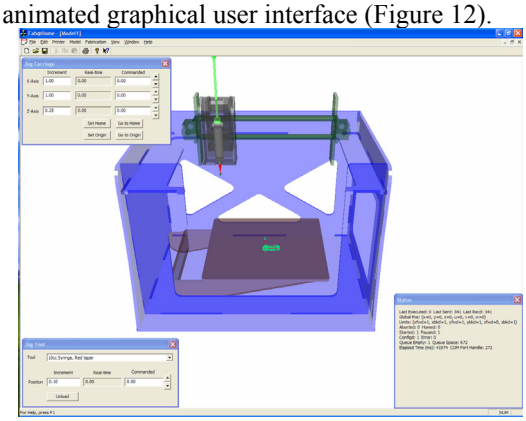
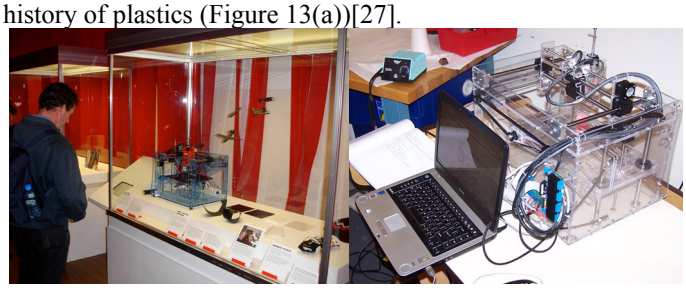


Figure 12. A screenshot from the PC application displaying a model ready for fabrication and dialog boxes for positioning and real-time status information

To promote collaborative development of the technology, we have developed a user-editable "wiki" website [24] to

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publish the designs and documentation, have set up discussion forums using a free online service, and have shared the source code for the project via a free service which facilitates open-source software development. Through these media, participants in Fab@Home have begun to exchange their ideas for applications and their improvements to the hardware and software with us and each other. Kits and fully assembled machines can be purchased from two vendors in the United States [25, 26], and to date, approximately 100 Model 1 systems have been purchased or assembled worldwide. The Science Museum of London, UK, has added a Model 1 to their permanent collection and displayed it in an exhibition on the history of plastics (Figure 13(a))[27].



(a) (b)

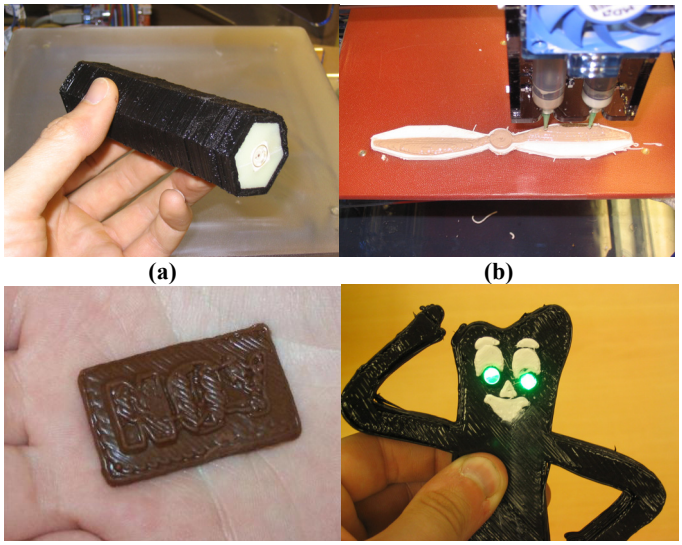
Figure 13. (a) A Model 1 on display in the Science Museum, London; (b) a Model 1 built by students of Prof. Mark Ganter at the University of Washington for use in a course on Computer Aided Technology.

At the University of Washington, students of Prof. Mark Ganter have constructed two Model 1 (Figure 13(b)), Fab@Home machines for use in a course on Computer-Aided Technology [28]. A number of machines have been assembled at universities worldwide for a variety of student and faculty research projects [29].

As shown in Figure 14, a variety of materials can be used with the Model 1, to create tall (800 layers, ~11.5cm tall), functional, and multi-material objects, including fabbed objects with conventionally manufactured parts embedded.

In the 15 months since October 2006 (when the website was first made publicly accessible), the project website has had more than 9.8 million requests for pages from more than 480,000 distinct visitors in more than 150 countries [30]. Users have begun to make contributions to the Fab@Home wiki, the Google Group, and the SourceForge project in the form of new deposition process ideas, bug reports, questions, feature requests, alternative vendors, group purchasing arrangements, and more.

The growth of the Fab@Home Project has been accelerated enormously by media coverage and an award. Newsweek International [31], Newsweek Russia [32], Popular Mechanics [33], Popular Science [34], The Guardian [35], and The New York Times [36] have published brief articles or mention of Fab@Home, and Discovery Channel Canada's DailyPlanet science news show [37] and the Wall Street Journal Online [38] have covered the project in video format. Popular Mechanics magazine awarded Fab@Home a "Breakthrough Award" for innovation in 2007 [39]. Each instance of media coverage results in a large surge of visits to our website, and many inquiries about the capabilities of the Model 1, and many new orders for Model 1 kits.



(a) (b)

(c) (d)

Figure 14. Objects built with a Fab@Home Model 1: (a) A working flashlight – only the LED and batteries are not printed; (b) an epoxy propeller for a model airplane; (c) a personalized chocolate bar; (d) a silicone toy with fabbed embedded circuitry which allows the LED eyes to light when the chest is squeezed

We are continuing development of the software and hardware of the Model 1 to provide performance and usability enhancements in anticipation of an onslaught of questions and complaints as the first wave of Model 1 users finish assembling and start using their machines. This will be a critical test of the survival of Fab@Home, and we must ensure that we do not discourage these brave early adopters.

5. CONCLUSIONS

Manufacturing automation increases the power of humans to shape matter into complicated and useful forms, allowing ideas expressed in design software on a computer to be physically realized with little or no human contact with the raw materials. The compact factories, or "fabbers", we describe here have the potential to greatly increase this power, by compressing much of the technological manufacturing capacity of our civilization into a tool which can be wielded by a single individual.

Solid freeform fabrication technology is currently the most promising approach to realizing fabbers. We believe that the advancement of fabbing technology is being constrained by the high cost and proprietary nature of commercially available SFF systems. High costs limit experimentation and market scale, which in turn limit the development of new applications which would increase demand and reduce system and product prices. We have been attacking this problem in two ways: by demonstrating that SFF is not just for mechanical parts anymore – it is capable of producing complete devices with

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combined mechanical, electrical, biological, and presumably even other functionalities, and by involving the general public in the development of fabbing technology, via the Fab@Home open-source, personal desktop fabricator kit. Our future work will continue to include the promotion of fabbing technology through the Fab@Home project in the hope of expanding public interest, decreasing the cost of fabber systems, and driving innovation in fabbing.

6. ACKNOWLEDGMENTS

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