# Freeform Fabrication of Complete Devices: Compact Manufacturing for Human and Robotic Exploration

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**[Abstract] Solid Freeform Fabrication (SFF) refers to a to a family of manufacturing processes, sometimes also referred to as Rapid Prototyping (RP), Additive Manufacturing, or Layered Manufacturing, which can produce almost arbitrarily shaped structures directly from computer-aided design (CAD) data, by computer-controlled deposition or solidification of material. These technologies have traditionally been developed and employed for the production of passive mechanical parts of a single material. Advances in this technology and in materials science make it feasible to develop a single, compact SFF system – including a small set of materials - which can automatically produce complete, active, functional electromechanical devices. In the long term, such systems may evolve into low-waste, extremely flexible, compact factories to enable space exploration, and will offer access to a set of electromechanical device designs in which geometry and performance can be continuously varied to achieve optimal and/or otherwise unrealizable products. One of the major challenges associated with the exploration and development of space is the high cost of production and delivery of equipment and supplies to the location being explored. The high cost of launch systems is the most obvious contributor, in part because within the current paradigm of exploration, the mass of productive materiel applied to the site of exploration is roughly the same as the mass of materiel launched from earth. As a result of this paradigm, the extreme cost of developing the equipment to be deployed – including tools, instrumentation, exploration robotics, etc. – has been difficult to reduce. Each object to be delivered must withstand the rigors of launch and possibly also entry, descent and landing, a great deal of effort is required to ensure that the payload does not constitute a hazard to the delivery vehicle, equipment must be designed to operate in largely unknown circumstances, and all of this must be achieved with a minimum of mass. *In Situ* Manufacturing (ISM) capability, such as may be provided by an SFF-based compact factory, will permit massive multiplication of the utility of materiel mass delivered to the site of exploration. Only the factory itself and the raw materials it consumes need to accommodate the launch and delivery constraints. The products of the factory can be tailored to the immediate need and conditions - and need not be over-designed. Recycling of materials and design of the factory to employ *in situ* resources will further leverage delivered mass, with the result that each launch from earth contributes to an exploration and development infrastructure, rather than simply depositing a disposable scientific payload. We are developing an SFF-based compact factory ($1m^3$) capable of autonomous manufacture of complete electromechanical devices. For simplicity, the system uses primarily polymeric and soft materials with low temperature processes. We have already demonstrated with our prototype system: freeform fabrication of thermoplastic and elastomer structures and flexures, freeform fabrication of Pb-Sn and Ag-ink conductive wiring embedded in structural materials, the first freeform fabrication of complete zinc-air batteries, the first freeform fabrication of Ionomeric Polymer-Metal Composite (IPMC) actuators, and the first freeform fabrication of elastomer strain gages. In addition, a collaborative effort has led to the "net shape" fabrication of alginate hydrogel tissue scaffolds directly from computed tomography (CT) data, and the fabrication of living tissue constructs consisting of chondrocyte cells in alginate hydrogel. Current work is focused on using the system to produce transistors based on organic semiconductors, and on improving the yield, quality, and predictability of devices produced**

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**by the system. The next phase of research will focus on achieving higher-level integration of functionality, and automating the design of products to exploit the novel manufacturing capability of the system.**

## I. Introduction

The traditional paradigm for the human and robotic exploration of space is firmly located "here." Scientists and engineers collaborate to identify a mission, develop hardware and personnel for this mission, and then to deliver these from Earth to (and possibly retrieve them from) the destination being explored. The scope and duration of the mission is limited by the amount and durability of resources that can be delivered "there," which are in turn limited by development and delivery costs. Although data returned from each mission are used to inform the design and development of resources for subsequent missions to the same destination, each mission must endure the twin costs of delivery and design to tolerate the delivery (launch, entry, descent, landing) process, and the deployed resources are *discarded* at the conclusion of the mission. Given the high costs involved, the use of resources during a mission is highly optimized, hence improving the productivity of a mission requires improving the durability and increasing the capability of resources, and/or delivering more resources – both extremely expensive propositions when everything is done "here."

Since the financial pressure to maximize the productivity of missions is not likely to abate, we believe that shifting ever more of the exploration infrastructure to "there" will continue to be the most effective way to make gains in productivity. We propose that the most significant step in this direction is to eliminate the transportation of hardware from "here" to "there" by *establishing manufacturing capability "there!"* The ability to manufacture parts and complete devices remotely would mean that only raw materials and exotic components need be transported to sustain an ongoing mission – reducing the volume and complexity of cargo. Coupled with recycling capabilities and eventually *In Situ* Resource Utilization (ISRU), this may even lead to information being the only resource needed – the latest technologies on Earth could be uploaded and deployed in minutes.

This logic is not new, but as we will argue below, new technological advances are finally making such a proposal feasible in terms of cost, size, and complexity. Advances in Solid Freeform Fabrication (SFF) technologies made by ourselves and others will result in the development of compact factories, no larger than satellites are today, capable of manufacturing almost any desired component or complex device, given raw materials, energy, and information as inputs. We will detail our work on SFF of complete functional devices and our efforts to accelerate the development of SFF technology through the creation of an open-source, inexpensive, personal SFF system kit, which we call Fab@Home.

## II. Background

Solid freeform fabrication (SFF) is the name given to a class of manufacturing methods 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 mean that SFF processes are subject to very different constraints than traditional material removal-based manufacturing. Nearly arbitrary part geometries are achievable, no tooling is required, mating parts and fully assembled mechanisms can be fabricated in a single step, and multiple materials can be combined, allowing functionally graded material properties. New features, parts, and even assembled components can be "grown" directly on already completed objects, suggesting the possibility of using SFF for the *repair and physical adaptation of hardware!*

SFF has traditionally focused on printing passive mechanical parts in a single material, and the emphasis of research has been on improving the quality, resolution, and surface finish of parts, and on broadening the range of useable materials.

A more recent focus in SFF-related R&D is producing functional mechanical structures and microstructures, multimaterial structures, and structures with embedded exogenous devices. As an example, stereolithography, which employs a computer-controlled laser to polymerize photosensitive resin, has been used in a laboratory apparatus at the Laser Zentrum Hannover, Germany, to create micromechanical systems such as a free-spinning impeller and free-turning meshed gears both with diameters under 1mm[1], and has also been adapted to the production of multiple material objects[2]. As another example, the Ultrasonic Consolidation (UC)[‡] process combines ultrasonic welding of aluminum tapes to build up material, with CNC machining to precisely shape and remove material in a single system. The UC process operates at or near ambient temperatures, and achieves significant plastic flow of the aluminum tapes during ultrasonic welding, such that other materials and devices can be *embedded into solid aluminum*. At Utah State University, Prof. Brent Stucker has used UC to produce aluminum plates with embedded electronic devices, including USB networked sensors, and to produce silicon-carbide fiber reinforced aluminum plates[3].

Despite these exciting developments, the general public is still largely ignorant of SFF technology, funding for SFF research is minimal and commercial manufacturers of SFF systems are not flourishing. These are issues that must be addressed if SFF technology is going to have a significant impact on space exploration and development.

## III. SFF of Complete Functional Devices

In prior work, we have described the multimaterial SFF research platform which we have developed[4]. At that time, we also demonstrated that this system can produce simple single-material structures using a variety of materials – a capability only now being explored more extensively by the research community[2,3,5]. However, the primary goal of our project has been, from the start, to explore the capability of SFF to produce complete *functional* devices – with a target demonstration of the freeform fabrication of a complete mobile robot. Pursuant to this goal, we demonstrated the first ever freeform fabrication of complete zinc-air batteries[4], and have since been expanding the range of functional devices that can be produced, while working on improving the performance of those that can already be produced. Our research platform has not been designed specifically with space applications in mind, that is compactness, low mass, or low power consumption, yet all of the work described here was achieved with a system that is semiautonomous, occupies about 1.5 m$^3$, has a mass of about 1000 kg (800 kg for the granite base), and uses roughly 500W.

### A. Batteries

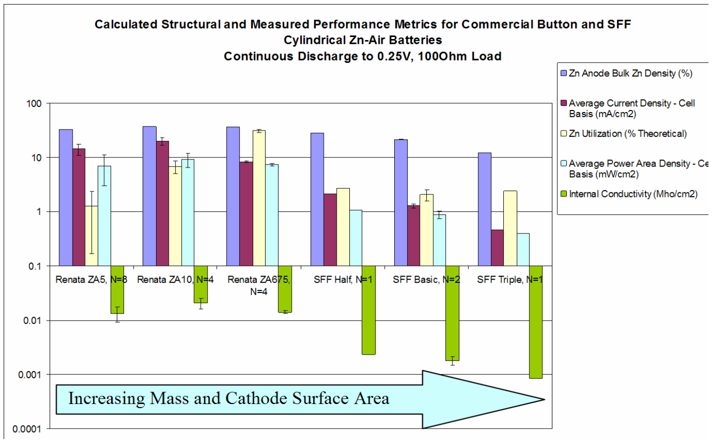

**Figure 1. Structure and performance comparison between several sizes of commercially manufactured Zn-air batteries and solid freeform fabricated (SFF) Zn-air batteries. Error bars are provided for cases in which multiple batteries were tested - N indicates the sample size.**

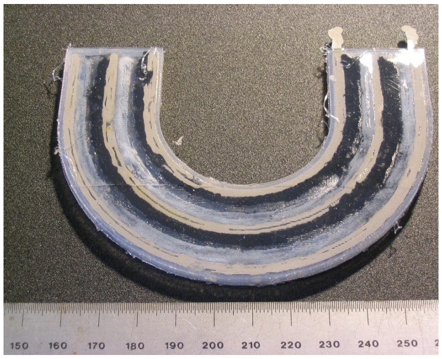

**Figure 2. We have produced a 2-cell, flexible freeform fabricated Zn-air battery as a demonstration of the design freedom possible using SFF to produce complete functional devices.**

Through an extensive set of formulation and manual cell fabrication and testing experiments[6] we have achieved an enhanced set of SFF-compatible active battery materials which are vast improvements over our first set of materials[4] both in consistent and stable rheology which allows reliable deposition, and in electrochemical activity – as demonstrated by service lifetimes measured in days, rather than seconds, and reliable power output of several milliwatts. Using these materials and our freeform fabrication system, we have produced several cylindrical batteries with a range of active surface areas. These have been tested under fairly demanding continuous discharge

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[‡] Solidica Incorporated, http://www.solidica.com

conditions along with several sizes of commercially produced Zn-air button batteries. The data (Figure 1) has been analyzed in light of the insights which can be derived from the numerical model of Mao and White[7].

While the performance achieved by our freeform fabricated batteries is roughly 10% of the commercially produced batteries, the analysis has indicated likely causes for this – especially electrolyte solvent loss, high internal (possibly contact) resistance, and poor catalyst activity. We are continuing the work of testing these hypothesized explanations, and believe that significant performance gains will follow shortly. Along with the performance gains, there is still the need to enhance the mechanical robustness of these devices, although the need for this can be somewhat mitigated when applications favor embedding batteries within larger freeform fabricated structures. We have produced and tested a flexible, two-cell battery (Figure 2) with an unusual shape that shows the type of geometric and functional customization that freeform fabrication brings to the manufacture of batteries.

More recently, we have also begun applying our experience with Zn-air primary cells toward achieving SFF of lithium polymer secondary cells. While this work is in a very preliminary stage, we have already developed a set of SFF-amenable materials, demonstrated that cells made with these materials can store charge and can survive multiple charge-discharge cycles.

### B. Ionomeric Polymer-Metal Composite Actuators

An Ionomeric Polymer-Metal Composite (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 DuPont Inc., Flemion from Asahi Glass, Japan). Nafion is a modified PTFE (Teflon) with perfluorinated sulfonate anion side branches. The standard approach to IPMC fabrication[8] involves purchasing a solid extruded membrane, and replacing the proton by another cation (e.g. $Li^+$) to improve actuation properties.

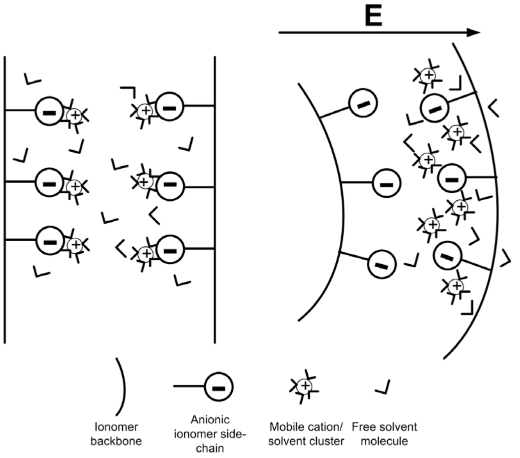


**Figure 3. Possible IPMC actuation mechanism: pressure differential from electric field driven ion and solvent motion (adapted from Ref. 9, Figure 8).**

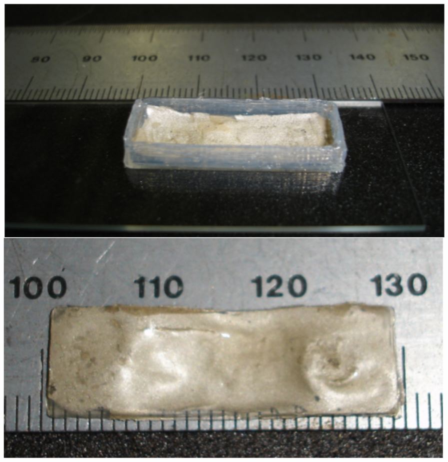


**Figure 4. (top) A freeform fabricated IPMC in its freeform fabricated silicone well; (bottom) closeup of freeform fabricated IPMC**

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[10]. 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 electroded film is soaked in water or another polar solvent to solvate the mobile ions. 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 3), a change in electrostatic forces between the anionic side groups, and reorientation of the (polar) solvent molecules[9,10].

**Table I. Comparison of performance of IPMC's produced by SFF to those produced by other means**

| Type | Dimensions | Test Conditions | Force (mN) | Est. Shear Stress (MPa) | Est. Shear Stress/Power (MPa/W)* | Service Life (cycles) |
|---|---|---|---|---|---|---|
| Freeform fabricated 5-layer $Li^+$ Nafion IPMC | 16mm by 9mm by 0.8mm | 1.5V, 0.1Hz square | 1.89 | 5.2E-03 | 2.2E-01 | 3222 |
| Freeform fabricated 3-layer $Li^+$ Nafion IPMC | 16mm by 9mm by 0.5mm | 1.5V, 0.1Hz square | 0.916 | 6.2E-03 | 3.2E-01 | 1384 |
| Freeform fabricated 5-layer $H^+$ Nafion IPMC | 20mm by 9mm by 1mm | 1.5V, 0.1Hz square | 0.678 | 1.5E-03 | 1.6E-01 | 513 |
| Recast $Li^+$ Nafion IPMC, standard Pt/Au[11] | 15mm by 5mm by 2mm | 2V, 0.5 Hz square | 60 | 4.5E-02 | 9.0E-01 | |
| Standard $Li^+$ Nafion IPMC, standard Pt/Au[9] | 20mm by 5mm by 0.2mm | 1V, 0.5Hz square | 16 | 1.6 | 6.4E+01 | |
| Stretched $Li^+$ Nafion IPMC, standard Pt/Au[8] | 10mm by 5mm by 0.2mm | 1.5V, 0.5Hz square | 60 | 3.0 | 8.0E+01 | |

In a recent effort[12], we have developed new material formulations and manufacturing processes which have allowed us to produce the first ever completely freeform fabricated IPMC actuators (Figure 4). 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 (Table I). We have also developed 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 hours and 3000 cycles. The output stress measured for our freeform fabricated devices is substantially inferior to that produced by IPMC devices produced in the standard manner, but this difference seems to be largely correlated with the use of Nafion materials cast from liquid dispersions, suggesting that some microstructural difference between extruded (as used in the literature) and cast Nafion (as in our SFF experiments) 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.

### C. Living Tissue Constructs

In a recent collaborative effort[13], we have worked on the development of the processes, materials, and tooling to directly freeform fabricate living, pre-seeded, patient-specific biological tissue implants of spatially heterogeneous compositions – basically to fabricate complete, living, replacement tissues with geometry derived from medical imaging data. The research presented herein attempts to overcome some of the challenges to other modes of creating tissue scaffolds, such as the difficulty of producing spatially heterogeneous implants that require varied seeding densities and/or cell-type distributions. In the proposed approach, living implants are fabricated by the layer-wise deposition of pre-cell-seeded alginate hydrogel. Although alginate hydrogels have been previously used to mold living implants, the properties of the alginate formulations used for molding were not suitable for freeform fabrication. An alginate hydrogel formulation was developed with properties well-suited for freeform fabrication. We demonstrated this technology's capabilities by printing alginate gel implants of multiple materials with various spatial heterogeneities, including, implants with completely embedded material clusters. The process was determined to be both viable (94±5% n=15) and sterile (less than one bacterium per 0.9 µL after 8 days of incubation). Additionally, we demonstrated the fabrication of a meniscus cartilage-shaped structure generated directly

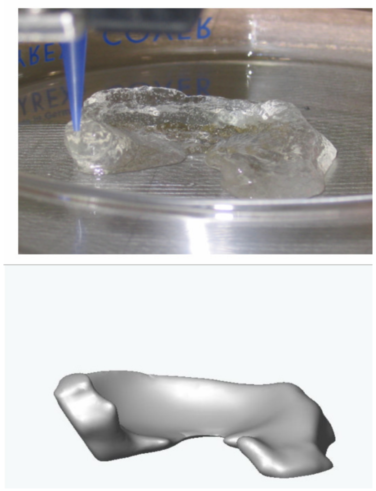
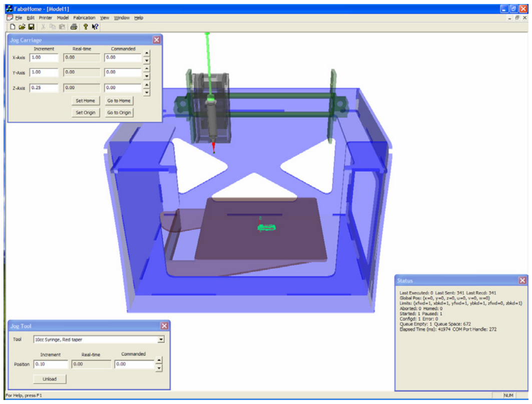


**Figure 5. (top) Alginate hydrogel tissue structure being freeform fabricated; (bottom) target geometry, derived from CT scan data**

from a computed tomography (CT) scan of a sheep meniscus cartilage (Figure 5). The proposed approach may hold advantages over other tissue engineering efforts[14,15]. This technology has the potential to allow replacement tissues and possibly even organs to be manufactured with patient specific cells and geometry, and may be particularly valuable for manned space exploration as a component of an advanced automated medical system.

## IV. Fab@Home: Accelerating the Advancement of SFF Technology



Jog Carriage

| | Increment | Real-time | Commanded |
|---|---|---|---|
| X-Axis | 1.00 | 0.00 | 0.00 |
| Y-Axis | 1.00 | 0.00 | 0.00 |
| Z-Axis | 0.25 | 0.00 | 0.00 |

Jog Tool

Tool: 10cc Syringe, Red taper

| | Increment | Real-time | Commanded |
|---|---|---|---|
| Position | 0.10 | 0.00 | 0.00 |

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Last Executed: 0 Last Sent: 341 Last Recd: 341
Global Pos: (x=0, y=0, z=0, u=0, v=0, w=0)
Limits: (xfwd=1, xbkd=1, yfwd=1, ybkd=1, zfwd=0, zbkd=1)
Aborted: 0 Homed: 0
Started: 1 Paused: 1
Configd: 1 Error: 0
Queue Empty: 1 Queue Space: 672
Elapsed Time (ms): 41974 COM Port Handle: 272
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**Figure 6. A screen-shot of the Fab@Home PC application.**

Future SFF systems that can directly fabricate complex functional artifacts comprising many materials, could transform the way we design, make, deliver and consume products, not only on Earth, but in space and on other planets as well.

Unfortunately, SFF technology is trapped in "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 accelerate the spread and development of SFF applications and technology, and escape the paradox, we are developing an open-source, low-cost, personal SFF system kit (Figure 6,Figure 7), which we call "Fab@Home". The current kit design[16] has a parts cost of roughly $2200, requires only basic hobbyist tools and skills to assembly and use, and can be used to deposit almost any room-temperature liquid or paste. This system has nearly the same capabilities as our research platform. We have used it to make multimaterial objects, and it could certainly be used to make any of the functional devices that we have produced with our research platform.

We are also developing a website[§] to foster a user community and to promote the exchange of ideas and improvements of the technology. We have thus far built three complete Fab@Home systems, and two of them have been delivered to users outside of Cornell University – one to a public access computer-aided manufacturing lab in Tshwane (Pretoria), South Africa, and the other to a biological research laboratory at Rockefeller University in New York City, USA. At this laboratory, research is underway which involves the slime mold organism *Dictostylium Discoidium*, which transitions from single-cell independent life to colony organism with coordinated motion in response to scarcity of nutrition. The Fab@Home offers a uniquely simple and customizable platform for executing experiments on the effect of initial spatial distribution of *Dictostylium* cells in the environment and the spatiotemporal evolution of their colony aggregation response to starvation stress. The system has been successfully used to deposit 3D alginate hydrogel structures containing *Dictostylium* cells, and the spatiotemporal data collection is ongoing.

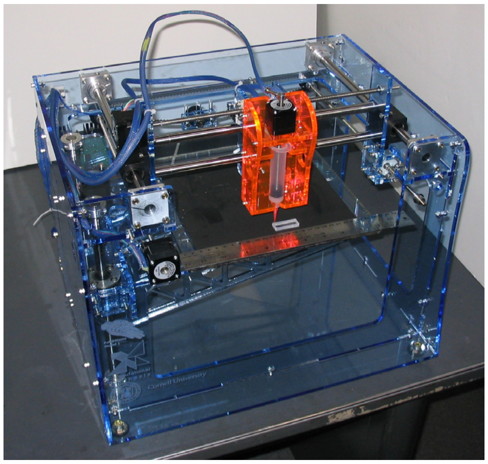

**Figure 7. Fab@Home, an open-source, desktop SFF system which can be built for $2200.**

If the project succeeds, we would expect to see an enormous expansion of public interest in and applications for SFF technology, and a commensurate expansion of commercial and research investment in the technology. The accelerated pace of research should increase the probability of achieving compact "universal" fabrication machines, benefiting terrestrial, space, and planetary manufacturing. In addition, the Fab@Home demonstrates the reduction in cost ($2200), mass (15 kg), and power consumption (40W) that can be attained with SFF systems without sacrificing capabilities – a very promising indicator of the amenability of the technology for spaceflight.

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[§] http://www.fabathome.org

## V. Conclusions

The potential of Solid Freeform Fabrication technology to enable the development of compact "factories" which are able to produce a wide variety of functional parts, devices, even living tissues, has been demonstrated by ourselves and other researchers in the field. We propose that this technology will enable a drastic multiplication of the productivity of resources devoted to the exploration and development of space by making feasible the transfer of the manufacturing aspects of the exploration infrastructure to the destination being explored. Our future work will continue to include the promotion of SFF technology through the Fab@Home project in the hope of expanding public interest, decreasing the cost of SFF systems, and driving innovation in SFF. We are also continuing to develop additional functional devices, including active circuit elements based on organic semiconductor electrochemical transistors.

## Acknowledgments

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