Printing Embedded Circuits

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Abstract

Automated manufacturing technologies such as freeform fabrication can greatly reduce the cost and complexity of infrastructure required to manufacture unique devices or invent new technologies. Multi-material freeform fabrication processes under development have the potential to automatically build complete functional devices including electronics. Making this technology available to creative individuals will revolutionize art and invention, but requires extensive simplification and cost reduction of what is still a laboratory technology. The combination of a Fab@Home Model 1 personal fabrication system and commercially available materials allows the demonstration of simple and inexpensive freeform fabrication of functional embedded electrical circuits, and useful devices. Using this approach, we have been able to demonstrate an LED flashlight, functional printed circuit boards in 2-dimensions and 3-dimensions that are actually entirely printed, and a child's toy with embedded circuitry. These results, and the materials and methods involved in producing them will be presented in detail.

Introduction

Artists, inventors, hobbyists, and children use their imaginations to stretch the boundaries of what might be, but are sometimes disappointed with what they can achieve with the resources and technology they can afford. Personal computers, open-source 3D design software tools, and hobby-oriented CNC mills multiply the ability of individuals to realize complex parts, molds, and even circuit boards without requiring enterprise-scale facilities. Unfortunately, milled (or etched) circuit boards are inelegant, planar objects requiring soldering and cabling, and integrating these into more elegant curved devices is difficult at best. Freeform fabrication systems capable of producing electronics and structures together are being developed in laboratories (Medina et al. 2005, Lopes et al., 2006, Malone et al., 2004). Access to this technology would free the creativity of the designer from the unwieldy constraints of the traditional approaches to integration of electronics and structures. Using a Fab@Home Model 1 personal fabrication system, we have been able to deposit conductive silicone traces within silicone and epoxy structures, to drop in multiple electronic components, and then to continue building, resulting in three-dimensional objects with fully-embedded functional electronic circuits, entirely without traditional soldered or crimped wiring interconnections. Using this approach, we have been able to demonstrate a simple flashlight, functional printed circuit boards in two-dimensions and three-dimensions that are entirely printed, and a child's toy with embedded circuitry. These results, and the materials and methods involved in producing them will be presented in detail.

Background

Since its first commercial incarnations in the 1980's, applications of rapid prototyping technology have progressed gradually from building of purely representational and fragile models of objects, to the production of durable end-use parts in a variety of materials, and is an increasingly cost effective way of producing customized or very complex parts. More recently, freeform fabrication is entering the realm of electronics manufacturing, with the accelerating development of "direct write" technologies and printable semiconductors. In laboratories, the mechanical and electronic incarnations of SFF technologies are being integrated into single manufacturing workcells capable of producing three dimensional circuitry - including dropped-in, off-the-shelf electronic devices - integrally with freeform structures,. These experimental systems are typically custom-built for multi-material freeform fabrication (Malone et al., 2004), or commercial RP machines modified to include additional deposition processes and materials (Wicker et al., 2004).

The Fab@Home project (Malone and Lipson, 2007) is an open source kit that allows the user to build his/her own solid freeform fabrication system (or "fabber", Figure 1). The first Fab@Home fabber design is called the Model 1. The Model 1 deposits materials from a robotically controlled syringe (Figure 2) – a process known known as "robocasting". Its hardware and software are designed to allow the user to build objects incorporating multiple materials. Material changes are achieved in hardware by manual exchange of the syringe barrel, and in software by tagging components of model geometry with material properties data, planning paths based upon that data, and prompting the user to change materials at the appropriate times. The material properties data is stored in user-editable text files (".tool" files), and the properties are tuned by the user in a manual calibration process which involves selecting an appropriate syringe tip for the material, and iteratively depositing test paths and tuning the flow rates and delays until satisfactory paths are obtained, and finally recording the height and width of these paths.

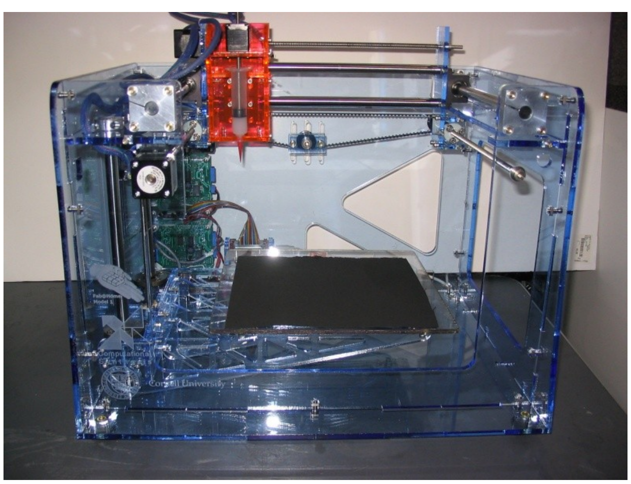

Figure 1 – Fab@Home personal fabrication device.

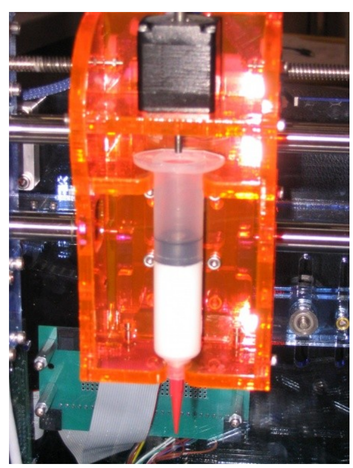

Figure 2 – A closer look at the deposition tool: a simple syringe/plunger system.

Experimental

Making the printing of circuits accessible to individuals requires finding a conductive material which can reliably form high conductivity, robust traces without being prohibitively expensive or difficult to obtain, hazardous, or difficult to use. These concerns suggest retail circuit repair materials as a starting point.

First, we tested a silver conductive ink (Circuit Writer Silver Ink, Caig Laboratories, Inc.), but its viscosity proved too low for well-controlled syringe dispensing, and the highly voltatile solvents in the material make it very prone to solidifying in the syringe needle. As a result, the ink does not deposit uniformly, either coming in spurts or flowing excessively, making 3D traces impossible. Next, we tried SS-26F (Silicone Solutions), a 1-part, silver-filled RTV silicone, available in small quantities directly from the manufacturer. This material is self-supporting, and holds its shape very well, and is ideal for use with the Fab@Home system. After tuning tool file parameters, we achieved reliable dispensing through a 1.27mm ID syringe needle. It bonds very well to the typical Fab@Home structural materials – 2-part epoxies, and silicone RTV. There are two caveats associated with SS-26F: it is fairly expensive, and it shrinks while curing and does not form good electrical contact from uncured to cured material. Thus traces that must be connected should be added in episodes separated by less than 10 minutes, to prevent one from curing prior to the addition of the next, or connection overlaps must be designed to be very generous.

We evaluated the electrical resistivity of the SS26F conductive silicone material using a four point resistance probe apparatus, shown in Figure 4. We used the Model 1 to deposit multiple linear traces in a single session (Figure 3) from a single batch of material. The cross section of each tested trace was measured using digital calipers.

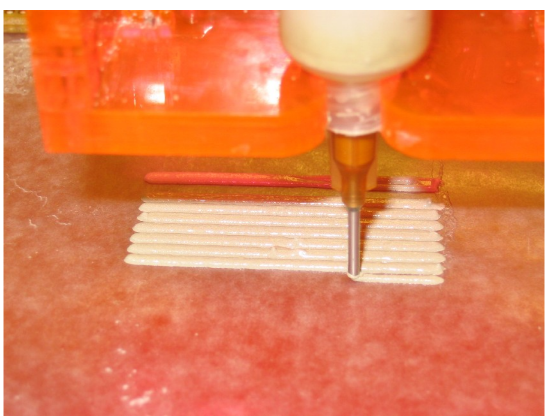

Figure 3 – Printing conductive silicone traces.

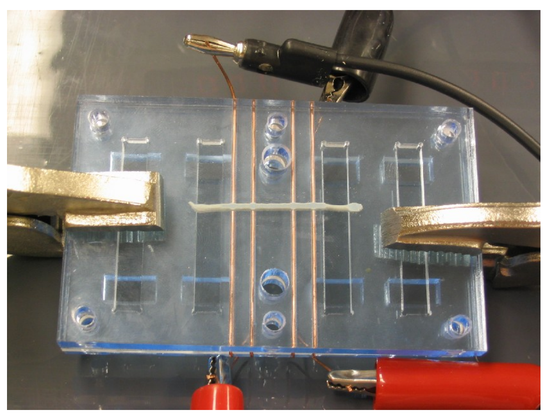

Figure 4 – Four point probe.

The structural materials employed in the present work are materials commonly used with the Fab@Home Model 1: GE Silicone II household silicone RTV sealant, and 3M DP460NS non-sagging 2-part epoxy.

We selected a 2-dimensional and 3-dimensional version of a 555-timer based LED flasher circuit, a hand-held LED flashlight, and a child's cartoon character-inspired toy as demonstrations of complete functional circuits and useful objects that can be made with this simple, inexpensive approach to integrating structure and electronics.

All models were designed using SolidWorks 2006 (SolidWorks, Inc.), exported as STL files, and imported to the Fab@Home application, where material properties, path planning, and fabrication were executed.

Results and Discussion

We find a resistivity of approximately 5.0 x 10^{-6} Ω m for the SS-26F material, with a standard deviation of 8.9 x 10^{-7} Ω m. This is roughly two orders of magnitude higher than the resistivity of pure metals, such as silver (1.59 x 10^{-8} Ω m) and copper (1.724 x 10^{-8} Ω m). Our typical deposited conductive trace has cross-sectional dimensions (post-cure) of 1.2mm X 0.8mm, thus a resistance of 0.192 Ω/m. This makes them approximately equivalent to 40AWG (0.078mm OD) copper wire, which is certainly sufficient for the production of low power circuits and for embedding electrical wiring within a variety of freeform fabricated objects.

Simple Planar Circuit

The most straightforward application for this technique is creating simple planar circuits, embedded in a freeform fabricated substrate - in this case, GE Silicone II. For this first demonstration, an LED flasher circuit utilizing a TS555 low power CMOS timer was produced, the circuit diagram for which is shown below, in Figure 5. The solid model used in producing this circuit is shown in figure 6.

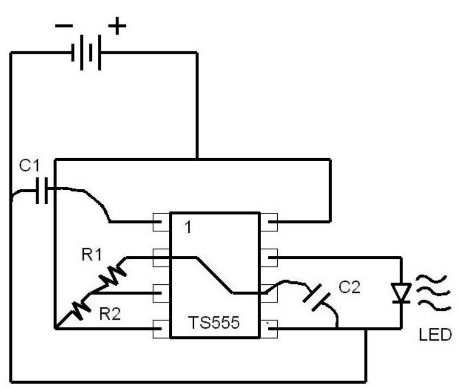

Figure 5 – Circuit diagram for TS555 timer. C1 = 0.01uF, C2 = 1 uF, R1 = 1kΩ, R2 = 31kΩ

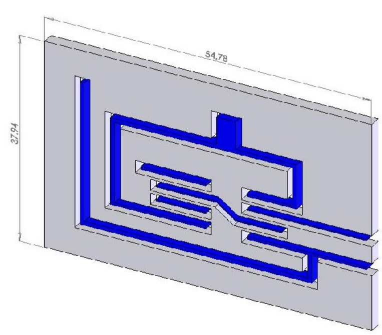

Figure 6 – Solidworks model of 2-D 555-based LED flasher circuit (blue). Dimensions in mm.

The fabrication sequence was designed to minimize the chance of internal shorting between traces. The substrate silicone (shown as gray in figure 6) was desposited first to form channels to guarantee the isolation of the conductive silicone traces from each other especially in the region where the timer will be mounted. The conductive silicone was then deposited into the channels, and a protective layer of silicone was deposited over the top to contain the entire assembly.

Figures 7 & 8 show the final product, without the components inserted, and fully populated with power applied via a watch battery, respectively. The light flashes at a frequency of roughly 0.5 hertz, dictated by the values of the resistors used (videos available at the Fab@Home website). One advantage of the conductive silicone is that the components can be inserted anywhere along its length, simply by pushing the leads through the cured traces. Both the traces and the base are flexible, making this circuit quite robust when it comes to bending.

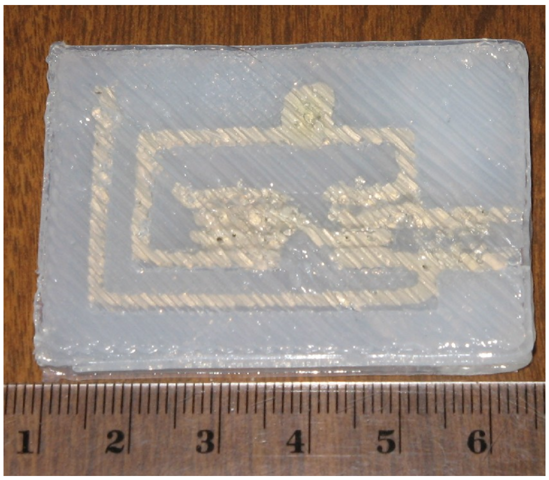

Figure 7 – Two-dimensional printed circuit (dimensions in centimeters).

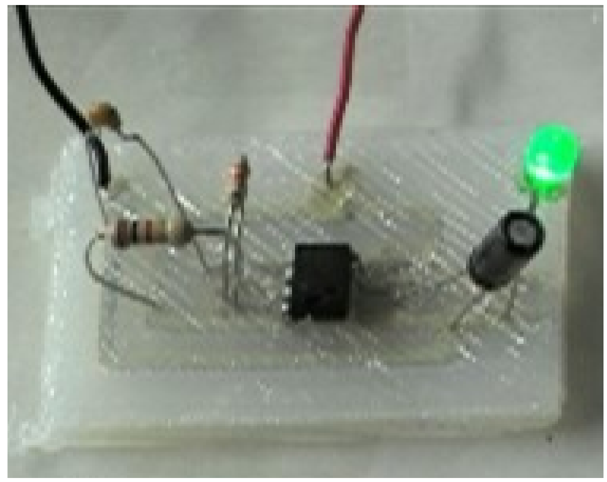

Figure 8 – Completed build, populated and powered up.

Three Dimensional Timer Circuit

From the two-dimensional version, we decided to extend the above technique into three-dimensions by making a version of the same circuit in the form of a cube (figures 9 & 10). The 2D circuit is roughly 40mm x 65 mm x 5mm, a total volume of 13,000 mm^3; by extending the circuit into 3D, it occupies a volume 15mm on a side, or 3,375mm^3. While this may not be a completely fair comparison, as there is a great deal of "wasted" space in the 2D circuit, it still shows some of the value in opening up an additional dimension.

For this present demonstration, the components were not embedded within the substrate – it is essentially a 3D solderless breadboard of the circuit (figure 11). As seen in figure 12, the circuit functions when powered.

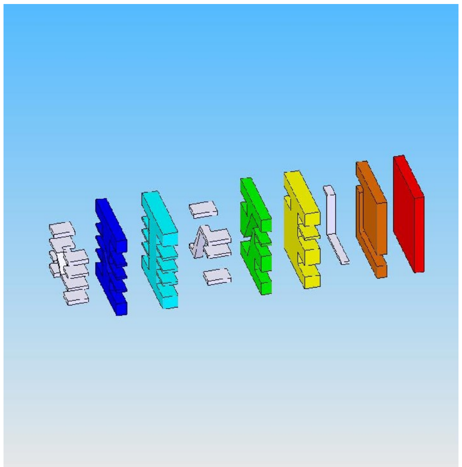

Figure 9 – Cube timer circuit, broken into layers. The traces are shown in white. The order of building progresses from right to left.

Figure 10 – Cube timer circuit.

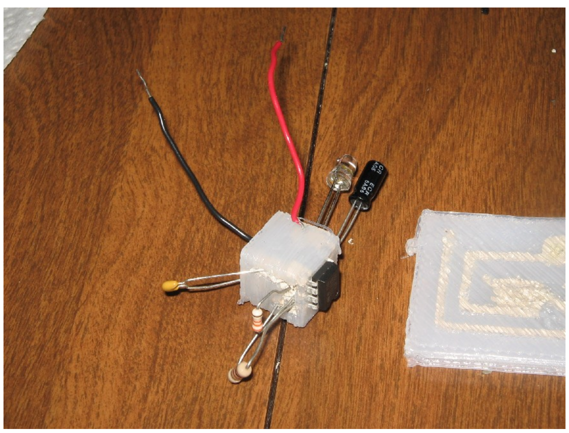

Figure 11 – Fully populated cube circuit.

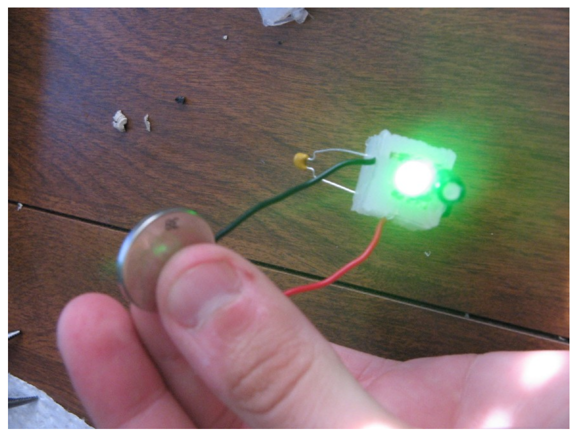

Figure 12 – Applying power with a 3V watch battery activates the circuit.

Flashlight

This technique can easily be extended to produce useful products with fully embedded components, As one example, we've had success in producing a fully functional flashlight, complete with a fully printed push-button tactile switch and fully printed wiring, an embedded LED, and flap opening for access to a battery compartment for 2 AA batteries. The CAD model is shown in figure 13, below.

First, a DP460NS epoxy front plate was deposited by the Model 1, and an LED was dropped into a socket designed into the front plate. SS26F contacts were deposited from the LED anode upward to link to the forward (+) end of the battery compartment, and radially outward from the cathode to join a trench running along the exterior of the body. A double-walled silicone tube was then fabricated atop the front-plate and the space between the walls filled (by manual pouring) with epoxy to form a rigid, silicone covered body with hollow battery compartment. The battery compartment was filled with water to serve as a support material for the end cap and tactile switch. The partially attached end cap was achieved by applying a release agent (dish detergent) to 2/3 of circumference of the end of the flashlight body to prevent the deposited silicone of the end cap from bonding except at the top 1/3 of the circumference – once cured, the portion treated with release agent can be separated, created a flap which can be opened to access the battery compartment. The end cap has a perforated end and a channel to accommodate the fully printed tactile switch. An SS26F switch terminal was deposited into the channel and into the perforation (prevented from dripping by the water in the battery compartment), and then covered over by a finishing layer of silicone. By carefully designing the gap between the end cap and the expected position of the battery negative terminal, the switch will not normally contact the battery terminal. The end cap is flexible enough that gentle pressure applied to its center by a finger will close the circuit and light the LED. Once the body and end cap were completed, the water was drained from the battery compartment, the flashlight laid on its side, and conductive silicone printed in the trench (figure 14) to connect the LED cathode contact to the tactile switch contact. This is the most expedient method of completing the necessary circuit. Figures 15 & 16 show the completed flashlight and it in operation, respectively.

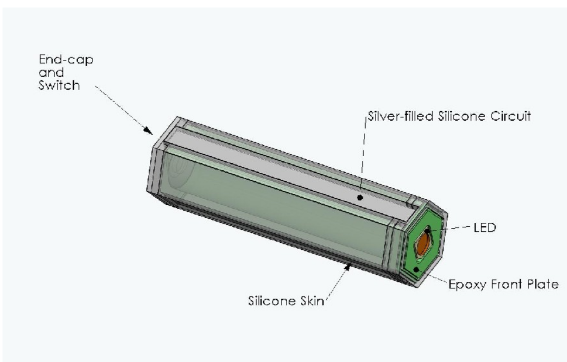

Figure 13 – Solidworks model of flashlight.

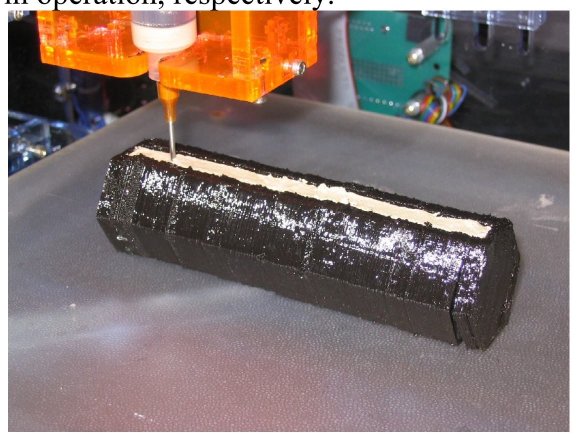

Figure 14– Printing conductive silicone along body to complete circuit.

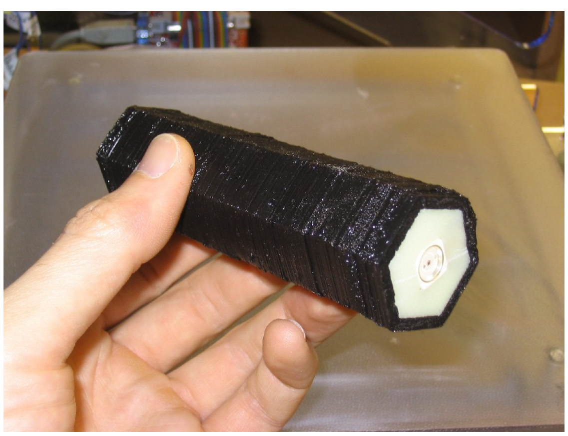

Figure 15 – Completed flashlight.

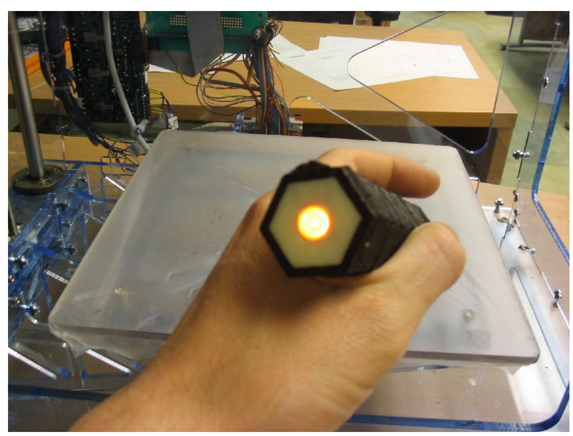

Figure 16 – Flashlight in operation.

Children's Toy

From the flashlight, it is easy to see the possibilities of such a process. One exciting use for this technique is the production of children's toys or action figures. By creating a toy with fully embedded components, one makes a more robust product, and the ease of use of Fab@Home and relative safety of the material means that children can conceivably build their own functional toys. In this case, we created a silicone "Gumby" figure, with green LED eyes that light up when his chest is squeezed. A watch battery is used to power the LEDs, and is fully enclosed inside the object.

Figure 17 shows the CAD model of the object, broken down into layers. Again, channels are laid out to insulate the silicone traces (figure 18), while holes are left to accommodate the LEDs and battery (figure 19). One item of note, a vertical trace is required to make the connection from the top of the battery to the LEDs. By making a layer that holds the battery up from the lower contact, one creates a simple switch that controls whether the eyes are on or off (figure 20).

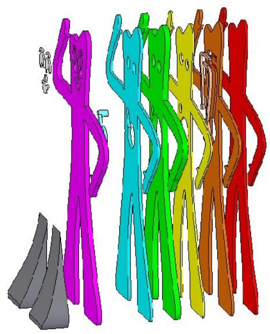

Figure 17 – Solidworks model of Gumby, broken into layers

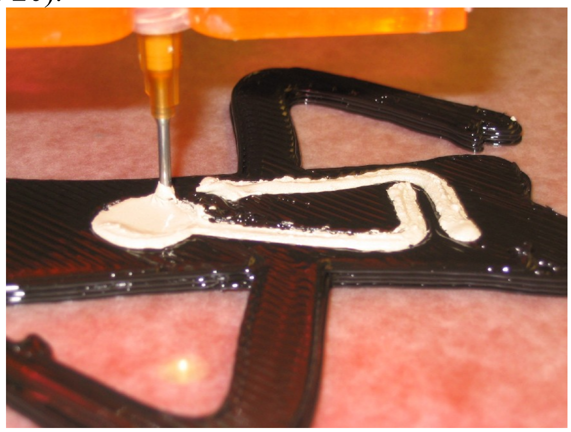

Figure 18 – Printing conductive silicone to provide batter contacts and power to the LEDs.

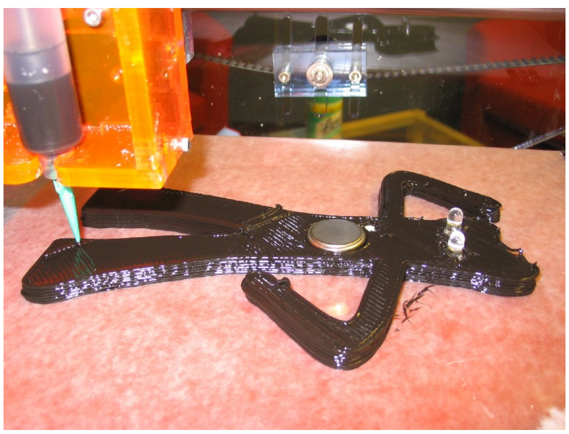

Figure 19 – Holes are left to accommodate the LEDs and the battery.

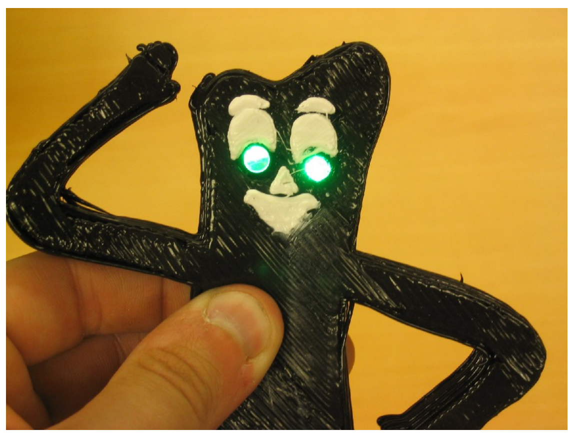

Figure 20 – The toy's eyes light up when the chest is depressed.

The process of printing circuits with the Fab@Home system has been successful. While still in need of some refinement, the technique allows users to produce objects with fully integrated circuitry. Printing vertically with the conductive silicone is difficult, as it cures and shrinks rapidly, making it tough to predict whether a new trace will adequately contact older, cured traces. In the case of two-dimensional circuits, however, the method works quite well. Since good contact can be created simply by pushing the component leads through the traces, the components can be moved around easily, allowing a large amount of customization.

SS26F is a fast-crosslinking formulation of the material, and Silicone Solutions offers SS26 and SS26S, with "normal" and slow cross linking reactions, either of which would probably reduce the connectivity issues. A larger market for this material (e.g. a pooled order by Fab@Home users, or a retailer's order) would help to reduce the cost as well. Other metal fillers than silver might also be satisfactory and help to reduce the price.

Conclusion

Solid freeform fabrication systems are becoming ever more capable of producing complete, finished products, rather than merely prototyping mechanical parts. In particular, laboratory systems are beginning to include the capability of producing electrically conductive traces embedded within freeform structures, and this capability will no doubt eventually trickle out to the commercial RP systems. We fully expect these innovations to have at least as large a positive impact on what kinds of things can be built as has single material SFF. Making this technology accessible to many more creative individuals will multiply this positive impact dramatically by reducing the cost and complexity of infrastructure and specialized technical training required to realize ever more elegant and seamless integrations of form and function. Using an inexpensive Fab@Home Model 1 personal fabrication system and commercially available, benign materials, we have been able to demonstrate desktop manufacturing of an LED flashlight, functional printed circuit boards in two-dimensions and three-dimensions that are entirely printed, and a child's toy with embedded circuitry. These results barely hint at what can be achieved by the tremendous creative energies of the public with the assistance of this technology.

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