Combining 3D printing and printable electronics

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Abstract
A platform that enables the integration of conductive traces and printed three dimensional mechanical structures has been developed. We discuss the development of the platform and address issues that arise when combining 3D printing and printable electronics. We demonstrate a rapid prototyped three dimensional conductive trace and propose future applications for the platform.

Keywords
3d printing, printed electronics, rapid prototyping

ACM Classification Keywords
H.5.2 Information interfaces and presentation (e.g., HCI): User Interfaces - Prototyping.

Introduction
The goal of this project is to explore the combination of two emerging technologies: 3D printing and printable electronics. Desktop 3D printers that allow users to print a wide range of mechanical structures are becoming more affordable and accessible. At the same time researchers have demonstrated printable electronic devices, such as transistors, solar cells, and light emitting diodes. Advances in materials and fabrication techniques will continue to increase the performance and affordability of both technologies. These two technologies have been largely independent, but combining them would enable exciting new possibilities that extend the "personal factory" concept to functional objects.

Related Work
One of the most accessible and wide spread 3D printing technologies is fused deposition modeling (FDM), which builds objects layer by layer by extruding thermoplastic materials. One approach to printing conductive traces, arguably the most fundamental building block of all electronics, with these systems is to replace the non-conductive thermoplastic with an extrudable conductive material. There are currently no commercially available materials with the necessary properties, but researchers have demonstrated thermoplastics doped with conductive material that are attractive candidates [1]. A more common approach has been to add additional hardware. Some examples include a heated syringe that dispenses a dispense a low melting point solder [2], a device that lays down solid core wire [3], and a pneumatic syringe that dispenses conductive slurries and paste [4]. The major limitation of all these approaches is they are generally limited to printing only in the XY plane.

Fabrication Platform
We propose a new approach that uses a spray deposition system based on a commercial airbrush and room temperature air drying conductive inks. Spray deposition allows for easy conformal deposition of materials on non-planar, non-uniform surfaces [5]. The platform consists of an off the shelf 3DTouch triple head 3D printer (BitsfromBytes) and a single action gravity feed airbrush (Iwata). The airbrush is mounted vertically parallel to the extruder heads and is triggered by a servo motor that depresses the trigger. The electronics for the third extruder have been removed and additional hardware has been added to turn on the airbrush when a command to turn on extruder 3 is issued. This modification allowed us to repurpose the system without modifying the firmware. The important process parameters for deposition are air pressure, spray time, and the distance between the nozzle and the surface. Proper adjustment of these parameters is essential to ensure uniform coverage in the XY plane and good sidewall coverage in the XZ and YZ planes.

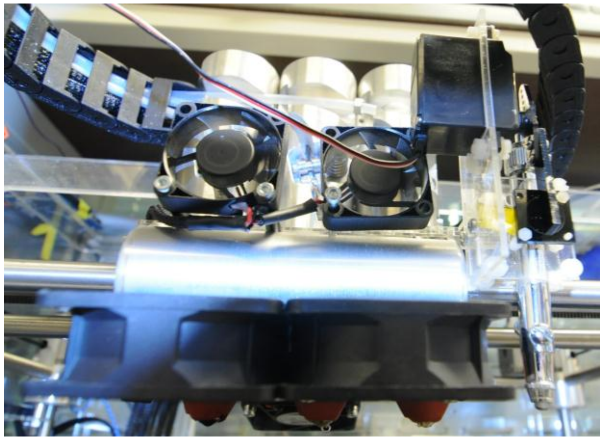

figure 1. extruder heads and airbrush

Conductive Materials

The ideal conductive material would be low cost, nontoxic, and widely available, and its viscosity and curing conditions should be compatible with the deposition system used. The conductive film produced should also have high conductivity, high uniformity, and good surface adhesion. After a thorough search, two candidate materials, CuPro-Cote copper paint and Electrodag 915 silver paint, were selected. The copper paint is water-based, lower cost, lower conductivity and designed for large area applications, such as EMF shielding. The silver ink is solvent based, higher conductivity, and designed for small area applications, such as scanning electron microscope sample preparation. Important properties of the materials are shown in table 3. Preliminary test showed good uniformity and agreement with stated resistivity.

The conductivity of the deposited trace, the ultimate performance metric, depends on the material, the deposition system, deposition process parameters, and the substrate. Previous research has extensively characterized materials, deposition techniques, and conventional substrates for printed electronics, but extruded thermoplastic substrates have not been characterized. Due to the nature of the printing process the surface will be have periodic non-uniformities. Horizontal, vertical, and angled surfaces will have different characteristics that depend strongly on the extrusion process.

Material	Conductivity (Ω/Sq@25um)	Price ($/mL)	Coverage (cm^2/mL)
CuPro-Cote (Cu)	1	0.10	137
Electrodag 915 (Ag)	0.015	15	187

table 2. Conductive ink properties

Masking Materials

The three most common materials used in FDM systems are acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and polyvinyl alcohol (PVA). PVA is soluble in water and sodium hydroxide (KOH) solution, PLA is soluble in KOH solution but insoluble water, and ABS is insoluble in both water and KOH solution. PLA and PVA are commonly used as support material for ABS structures, but they can also be used as a sacrificial mask material to pattern the conductive traces. The conductive traces, when dried, are not affected by immersion in water or KOH solution. If the minimum trace width achievable by airbrush deposition is not sufficient, then a sacrificial PLA or PVA mask can be printed before deposition. In this case the minimum trace width is constrained by the minimum feature size of the extruded PLA or PVA mask.

Proof of Concept Structures

To prove the masking concept we built a structure that consists of a series of simple two-dimensional conductive traces on an ABS substrate. The traces were patterned with a PLA masking layer. The design for this test structure is shown in figure 2. After the structure was printed the conductive material was deposited and allowed to dry. Finally the structure was placed in a KOH bath to remove the PLA. Using this method, the minimum width of dense traces produced by the platform was decreased from 2.5mm to 1mm.

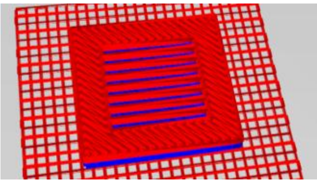

figure 2. masking test structure (ABS: blue, PLA: red)

Another test structure demonstrates the possibility of truly three dimensional traces. The structure is printed in ABS without a mask. The contact pads are 4mm x 4mm and separated by a horizontal distance of 10mm and a vertical distance of 4mm. The conductive material was deposited after the structure was printed. Sidewall coverage was achieved by starting deposition on the bottom contact pad and moving the airbrush along the trace toward the top contact pad. In this case the trace is short enough that the sidewall can be completely covered after printing. Taller traces could be achieved by depositing the conductive material during the print. The finished test structure is shown in figure 3. The resistance between the pads varies between 25Ω and 100Ω depending on the area of the pads contacted. This resistance can be reduced by modifying the printing process of the ABS structure to decrease the surface roughness of the trace.

These two relatively simple test structures, while unimpressive in themselves, prove that it will be possible to print complex structures with embedded three dimensional conductive traces.

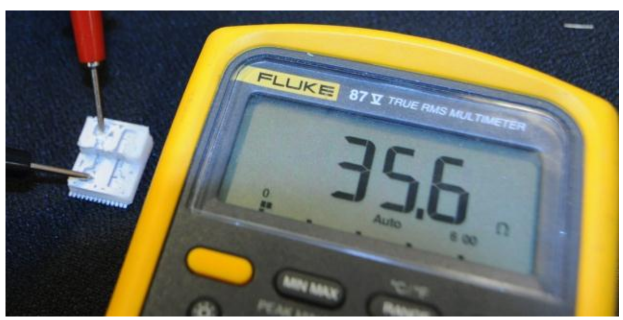

figure 3. a printed 3D dimensional trace

Advanced Prototypes

To explore the capabilities of the system we designed structures that could be eventually printed using this platform. The first prototype is a single sided printed circuit board (PCB). We generated a .DXF file from a printed circuit board layout (EAGLE) and used this file to construct a 3D model in a constructive solid geometry modeler (OpenSCAD). This model, which includes a masking layer, can then be exported as an STL file and 3D printed. An example PCB with the conductive material deposited and mask removed is shown in figure 4.

This technique allows for the simple fabrication of single sided surface mount or through hole PCBs. Components can be attached using conductive epoxy or low temperature solder. Compared to other PCB manufacturing processes, such as milling copper clad sheets, this is a completely additive process. This process could also be expanded to include multilayer PCBs and three dimensional printed circuit boards with arbitrary shapes.

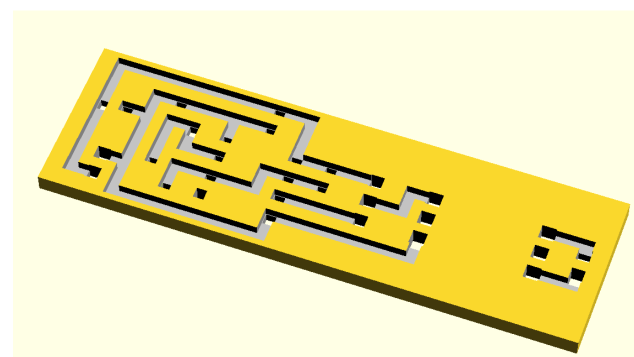

figure 4. printable PCB concept (ABS: yellow, Ag: silver)

Software Toolchain

The process required to go from 3D model to 3D printed object can be quite involved. Typically a model is designed in a 3D CAD program and exported as an .STL file. Bitsfrombytes provides a program called Axon which processes these .STL files and generate a series of commands, called G-codes, to send to the printer. When the G-code is sent to the printer a microcontroller parses the commands and controls the hardware to perform the actions specified by the G-code. Adding additional hardware requires repurposing existing G-codes or implementing additional G-codes by modifying the firmware. Our hardware allows us to treat the airbrush deposition system as a normal extruder loaded with conductive material in the software.

This is a rather complex toolchain and errors can be introduced along the way, even for simple mechanical structures. Current 3D file formats, such as STL, only contain information about geometric structures. Integrating information about functional electronic components is difficult. Printed circuit boards are defined by a schematic netlist, a list of all the components and the connections between them, and a board layout, the physical location of the components and the traces that connect them. As the platform evolves there will be a need for an integrated file format, similar to the proposed RepRap File Format [6].

Conclusions and Future Work

We have demonstrated the ability to combine 3D printed mechanical structures and three dimensional conductive traces. This is the first step toward combining 3D printing and printable electronics, which would fundamentally change the process of rapid prototyping embedded systems. We are currently working to improve the functionality of the hardware, by adding and tilt to the airbrush, testing new materials, such as transparent conductors and electroluminescent materials, and developing new software to design structures that combine electrical and mechanical elements. We welcome feedback from the community on how we can extend this technology and establish useful standards for further development.

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