Hybrid printing of photopolymers and electromechanical assemblies
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Abstract:
Performance of electronic systems 3D-printed from raw materials falls short of conventionally-fabricated systems due to material limitations. 3D-printed transistors are low-power, have relatively poor transconductance specifications and low on-off ratios, while 3D printed conductors typically exhibit volume conductivity specifications that are an order of magnitude less favorable than their base-materials. Here we present an alternative approach that embeds electrical functionality by placing standardized prefabricated electrical components within a 3D printed structure while it is being built. The process is facilitated by restricting the components to a fixed repertoire of modular functionalities, and using a module design that is readily manipulated by automated assembly equipment and assembled on a regular lattice. This approach leverages the strengths of traditional semiconductor manufacturing technology while enabling scalable on-demand additive manufacturing of functional, integrated electromechanical systems with performance that is on par with conventional processes.

Keywords: Hybrid Printing, 3D printing, Printed Electronics, Electromechanical Systems

1. Introduction
Despite a great deal of effort, and some recent progress, there is no current manufacturing technique that can simultaneously create high-quality electrical interconnects, computational circuits or actuators together with mechanical elements in an integrated system; post-process assembly steps are always required. This is a very active area of research; a great deal of effort has been devoted to a class of techniques known as Direct-Write electronics (DW), or the similar Direct Print (DP) technique [1, 2]. Researchers have demonstrated Inkjet printers capable of fabricating transistors [3, 4, 5, 6], and have used a combination of Inkjet or DP and Fused Deposition Modeling (FDM) or Stereolithography (SL) to create electrical circuits within a 3D printed part [7]. One interesting alternative approach uses conventional semiconductor fabrication facilities to create very small semiconductor devices that are subsequently blended with an ink binder [8]. We have recently demonstrated rudimentary electromagnetic actuators fabricated in one process via FDM and DP [9], based on earlier work [10].

Enormous challenges in developing materials and deposition methods for co-fabrication of components with mechanical and electrical functionality in 3D printed parts must be overcome. Synthesizing electrically conductive materials with volume resistivity similar to bulk metals that can be extruded or deposited in a low-temperature environment (so that is it process-compatible with other materials in the assembly) remains an elusive challenge. The current state of the art, available from various vendors, employs powdered metal inks that are solvent-borne and achieve volume resistivity that is 4x to 10x larger than bulk metal in the case of silver, and
10x to 50x for copper. These materials require a post-process sintering step, typically by heating to between 80 and 150 degrees C in order to achieve the stated resistivity, which can be difficult to integrate with other heat-sensitive components within the assembly. Local heating applied via laser has been used to sidestep these challenges [7], and is available from at least one commercial vendor (PulseForge tools from Novacentrix, Austin, TX), though integration remains a challenge. The active devices (transistors) that have been fabricated thus far have lower carrier mobility and lower on-off ratios than similar devices fabricated in silicon [11, 5]. The challenges faced can be thought of in the following way: these methods rely on effectively “refining” diverse and potentially incompatible raw materials at the print site, going in a single step from “ink” to finished product in a printer that should also be small, relatively simple and low-cost - a set of requirements that is currently impossible to satisfy, and that will likely prove challenging for the foreseeable future.

Previous work has demonstrated one approach to solving these challenges: embed pre-produced sub-modules with specific electromechanical functionality and fabricate electrical circuits within the printed part’s shell to interconnect these modules [12, 13, 14, 15, 16, 7]. The alternative that we propose is to forego the external printed part (the interconnect shell) entirely. Instead, the printed part is built by combining multiple sub-modules, each of which has specific electromechanical functionality, and that share a common electromechanical interconnect scheme. When assembled these sub-modules combine to form a Digital Material (DM), i.e. an object composed of elementary discrete parts that reversibly interconnect in a finite number of ways in a regular geometric pattern [17, 18, 19].

In this work we extend and improve upon existing 3D printing methods by combining ideas from the field of Digital Materials with conventional analog additive manufacturing in order to circumvent the limitations of current electronics printing technologies. This "Hybrid Printing" approach embeds pre-produced components into additive manufactured assemblies as they are being fabricated by using high speed pick and place equipment, parallel pick and place techniques, or other similar methods. The digital materials are placed and interconnected in layers as the assembly is constructed, allowing electromechanical functionality to be embedded. Though previous work [12, 13, 16, 7, 15, 20] has shown embedded discrete components, our approach introduces a practical, scalable approach that allows high-volume, general purpose electronic functionality to be embedded directly within a printed assembly.

2. Module Description

The electronic modules employed in this work consist of different commercially available electronic components soldered to mechanically uniform carrier boards, fabricated using conventional printed circuit fabrication techniques. The modules accommodate different device packages, providing a common electromechanical interface for the electrical interconnects between modules, as well as a uniform contact strategy for automated manipulation via pick-n-place equipment. This common electromechanical interface is critical because the modules that we employ do not connect to a common printed circuit board, as they would in a conventional circuit design. Instead, each module connects directly with its nearest neighbors (if the neighbors are present in the design), and the circuit is constructed in a 2.5D
stacked layout as successive layers of modules are placed while the assembly is constructed. These modules are not fully space-filling, by design, allowing room between them for the conventional additive manufacturing material that forms the bulk of the assembly; photopolymers deposited via inkjet techniques using an Objet Connex 500 are employed in the examples that we show later.

A basic carrier board that supports various 2-terminal devices is shown in Figure 1 with a resistor soldered in place. This board is 3mm on each side, and is approximately 1mm thick. Vias at the pads in each of the corners provide electrical connectivity between the top and bottom, while the traces on the top side connect the pads to the electrical device. Any 2-terminal device (resistors, capacitors, diodes, inductors) that fits on the carrier module’s pads can be soldered in place without modifying the carrier board, allowing a great deal of flexibility in addressing electrical devices with different package sizes. There is a tradeoff, of course, between the flexibility of using multiple types of different electrical components in a design (for example, using different resistors with different resistance values), and maintaining a small number of unique module types. Because we envision using prefabricated modules in a hybrid 3D printing machine, the complexity of the machine increases with the number of unique module types. In practice, the need for different resistance types could potentially be reduced by combining multiple modules with identical resistances in series and in parallel in order to achieve the desired composite resistance.

![Figure 1 - Resistor module. CAD model (left) and implemented in FR4 circuit board material (right)](image)
In addition to 2-terminal electrical components, other prototypical module types provide programmable logic and state machines (microcontrollers), signal amplification and power control (field effect transistors), and sensing (phototransistors). The precise number of different module types that are required to yield a particular design is unknown, however as illustrated by the previous discussion of resistor modules, it seems likely that a tradeoff exists between the number of different module types and the total number of modules required to implement a particular circuit design. Each module type is intended to be readily mass-produced using conventional printed circuit fabrication techniques, so this may be an acceptable tradeoff.

3. Assembly Fabrication

We envision hybrid printing as a high-volume process that complements existing additive manufacturing techniques that fabricate parts in a layer-by-layer manner. The process is schematically represented in Figure 2. When the model design files are created, voids that correspond to the intended locations of the modules are defined and the print process is paused after the deposition of the last slice of material is deposited (corresponding to the uppermost extent of the module). All the modules corresponding to that particular module layer are inserted into the pre-defined voids in the part, the modules are electrically and mechanically connected to any nearby modules (from lower layers) using fusible alloys (solder) or conductive adhesives (epoxy) and the printer is resumed. This process continues until the part is completed, resulting in a finished piece that incorporates electrical and mechanical functionality via a mold-free process. Because the modules interconnect on a regular lattice, the process is amenable to high-volume pick-n-place equipment. In particular, we are developing parallel manipulators capable of simultaneously moving entire layers of modules. At the current module size of 3mm square, a 10cm² build area could potentially incorporate approximately 490 modules, and this number would grow much larger as the module size decreases. For example, a module size of 100um square, which is readily achievable using silicon micro fabrication techniques, would result in as many as 45,000 modules on each 10cm² layer. Clearly, parallel assembly methods will be important to the success of this fabrication approach.

![Figure 2 - Hybrid printing steps: A - print is paused at the top of the voids for the embedded modules; B - modules (green) are inserted; C - the next layer of the model is printed; D the final embedded module inserted, soldered to the layers below and the print is finished](image)
4. An Example

The first hybrid printed object, shown in Figure 3, is a keychain LED flashlight that incorporates four modules, consisting of three different types: an LED, a momentary switch, and a “pass-through” module that simply connects the pads at each corner electrically. The light is powered by a coin cell battery that is inserted after the part is removed from the printer. The thickness of the coin cell was chosen to match the vertical spacing between the modules, so that when inserted, the coin cell makes electrical contact with the tiles. In this example, an Objet Connex 500 was used in Digital Material mode to deposit two model materials simultaneously. A transparent material (Vero Clear) makes up the bulk of the part, while a dark opaque material (Vero Black) allows lettering and images to be embedded within the assembly. The printer was paused four times during the deposition process to allow modules to be placed at four different layers within the assembly. The modules are completely encapsulated within the photopolymer material, with the exception of the top of momentary switch, and the contact points for the battery.

Figure 3 - A hybrid printed keychain LED flashlight.
5. Conclusion
This work demonstrates a method to fabricate complete, functional electronic devices using a relatively small repertoire of pre-fabricated modules in conjunction with conventional 3D printing processes. In contrast to other recent approaches, which employ direct writing techniques to create conductive traces that traverse a surface and then solder electrical devices of varying shapes and sizes to the traces on that surface, our approach directly embeds electrical modules into the growing assembly. The use of modules with a uniform shape allows our approach to be automated, allowing very large numbers of electrical modules to be embedded simultaneously, while the use of conventional silicon-based electronic components leverages the best of that technology, rather than redeveloping electronic components for 3D printing applications.

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7. Bibliography


