Multi-Material 3D Printing

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Abstract

Digital manufacturing has garnered significant exposure recently with many announcements of new 3D printers, improved capabilities to print different materials, and the White House's announcement of the creation of a Digital Manufacturing Institute. These recent developments in digital manufacturing are primarily focused on techniques that create individual parts for subsequent assembly, with the most sophisticated printers allowing combinations of several similar structural materials. The most interesting application of 3D printing today is to create unique mechanical structures that cannot be obtained by other means. 3D printing is also used as a prototyping technique, the final object being manufactured by conventional means.

In order to expand 3D printing and making it more versatile, new processes are needed that are able to deposit a broader range of materials (plastics of different characteristics, as well as metals), along with embedded electronic circuits consisting of both printed and conventional components. Such printed objects go beyond conventional mechanical features by embedding optical and electrical functionalities, such as sensor; all in complex structures that are difficult to produce with existing manufacturing methods. Coupled with user-friendly design software it becomes possible to analyze complex designs in order to determine structural properties as well as model electrical and mechanical operation, explore materials compatibility and diagnose other aspects of the design which may cause fabrication problems. We have demonstrated a printed wireless sensor as an example of a complex functional object. The circuit senses pressure and temperature embedded into a shoe insert and comprises inductor and antenna structures for communication. In our presentation we will describe our progress in printing integrated multi-material objects, including a collection of our latest demonstrators.

Introduction

Over the past decade, and we have demonstrated a variety of new technologies relevant to digital manufacturing – these include materials, printing processes as well as printed thin-film electronic circuits and devices [1-9]. In this paper we describe our progress in printing multi-material three-dimensional objects with embedded electronic and/or mechanical functionality [10]. Our research-scale printing platform, as displayed in Figure 1, includes ink jet, various forms of extrusion deposition, aerosol jet, as well as a UV curing lamp and a halogen thermal lamp for cross-linking and annealing of deposited materials. This printer builds up the object in a layer-by-layer fashion. The objects to be printed are designed in solid modelling and VLSI CAD software. The fabrication workflow is created by software that analyzes the object design and subsequently, for each slice of the design, assigns the fabrication methods and materials deposition parameters, as well as inter-layer treatment steps.

3D printing of multiple materials faces many of the same challenges as solution printed electronics. Both approaches require deposition of a variety of materials with wide-ranging properties, different post-deposition treatments and causing compatibility issues. Some of the key parameters to successful printing include ink rheology and surface energy, adhesion, compatibility of solvents, dimensional stability, and processing conditions. Additional requirements for optimizing electrical performance further complicate the printing task. In particular, the design has to take into account the specific features and failure modes of the printing process [4]. Figure 2 illustrates an inkjet printed circuit comprising a five layer structure of materials.

In moving from printing planar electronics to 3D integrated objects, one can expect the number of materials and processing challenges to multiply. It is crucial to explore and create compatible material sets that provide adequate functionality and process tolerance, to offer product designers a solid base for product invention.

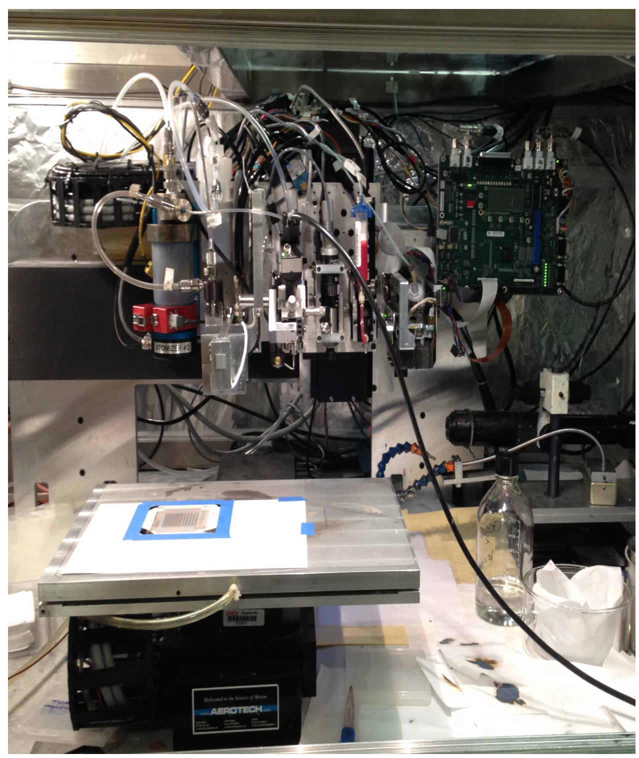

Figure 1 - Currently implemented multi-material 3D printer with ink jet print head, 2 extruder devices, an aerosol print head, UV LED curing lamp and heat lamp.

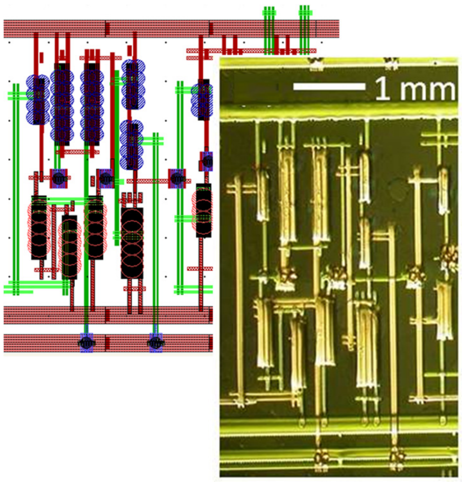

Figure 2 – Inkjet printed shift register circuit: layout of the multilayer structure and final printed device.

3D printing mechanical components

There has been strong interest in additive manufacturing attracting academic, corporate and government entities [11]. For the most part, the field has focused on the introduction of new processes for creating unique mechanical parts, the continuous improvement in materials properties as well as methods of model building. Interest in new materials is particularly strong for fused deposition techniques.

3D printing offers the capability to print prototype-quality, mechanically functional objects created with a few similar materials. Despite showing different mechanical or visual properties, the materials generally are limited due to their mechanical strength and are difficult to combine with other functional materials. As of today, the field focused on the prototyping and mold casting markets to provide tailored materials compatible with a particular forming tool. An interesting next step in digital manufacturing is to advance the multi material/multi deposition method technologies that offer greater design freedom and manufacturing capability, to go beyond designing for structural appearance to designing for functionality. The integration of different techniques and a broad set of materials has the ability to fundamentally change the way 3D printing is being used.

To progress towards the vision of a multi-functional printer, we have developed fabricator design, materials processing, CAD software specifically designed for multi-material additive fabrication, and design analysis tools that correct errors and provide assurance that the production and functionality of the design can be successfully achieved.

Electronics in 3D printing

Introducing electronics into 3D printing is a particulalry exciting challenge. Figure 1 shows deposition and processing components of our current research system. With the combination of ink jet, aerosol jet and extrusion print heads, we have deposited material ranging from 1 to several 10,000 cps with a wide range of solvents, particle loading and binder materials. With extrusion, we have largely focused on epoxies, acrylates and urethanes, which are UV or thermally cured in between layer depositions. We have also extruded conductive silver paste to form hybrid sensor circuits. Figure 3 shows a 3D printed shoe insole with embedded pressure and temperature sensing circuitry, with wireless communications chip for data transmission. This shoe insole was produced to demonstrate the feasibility of fabricating an electronically functional object through 3D printing.

For inkjet deposition, we have used a Xerox print head consisting of 880 ejectors that are spaced at 84.6 µm and is capable of ejecting at 43 kHz at temperatures up to 150 °C. This print head is ideal for 3D printing due to its ability to rapidly deposit significant amount of materials and print thermal phase-change inks that solidify upon landing on cool surfaces. This allows for rapid deposition of materials in the vertical direction without spreading horizontally. We have recently demonstrated two example applications using the thermal phase change inks: 1) printing 3D textural features for the blind and visually impaired using proprietary UV gel inks and 2) MEMS structures patterned with a sacrificial structural support material. High-aspect ratio pillars printed from this phase-change support material is shown in

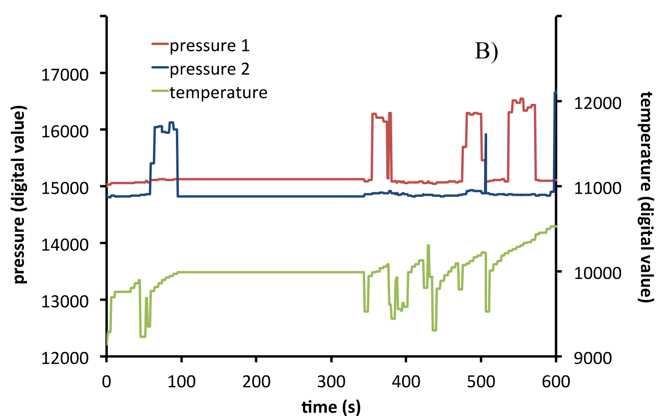

Figure 3 – A) Printed wireless pressure and temperature sensor within a shoe's insole. B) Pressure and temperature data obtained through wireless communication from the printed insole.

Figure 4. The pillars in this photo are ~150 µm high and ~30 µm in diameter consisting of 25 ~30 pL drops. Figure 5 shows silver paste ink which was applied over an 80 µm printed block of the support material. The support material was removed to leave the remaining cantilevered conductor. This material and process holds promise for the formation of printed complex meta-material structures which require small embedded features.

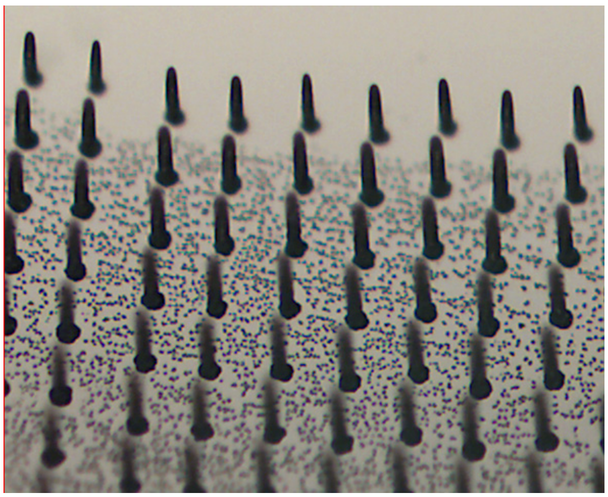

Figure 4 – Inkjet printed pillars made from a phase-change sacrificial material. The structures are ~30um in diameters and ~150um in height.

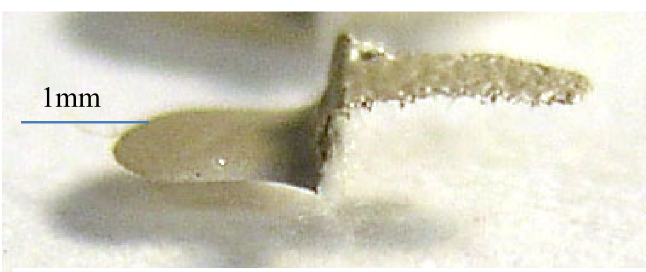

Figure 5 - Silver paste cantilever after removal of inkjet printed support material.

Design Software

In order to print electronics and print mechanical parts simultaneously, one of the key challenges is to develop collision avoidance between the print head and the placed parts. In this situation, the layer-by-layer additive process is not simply a 2D tool path problem anymore, and with the complexities of designing a tool path for every layer and component, this compels a rule based software algorithm approach. We are currently integrating this capability into the ongoing work on Design for Manufacturability (DfM), to provide tools that 1) give automated feedback on tool capability, structural integrity and design flaws, 2) provide for hybrid part placement and definition, and 3) optimize print head tool path with object avoidance and non-planer deposition capabilities dictated by materials, processing requirements, and functionality.

Conclusions

Building on printed electronics prototyping processes, we have developed a printing system capable of seamlessly integrating electronic and mechanical functionalities. This task required the application of a variety of materials with different printing methods, processing needs and material properties. We have deposited materials with a wide span of viscosities to build up complex 3D structures with easily handled thermal phase change support material. We have developed processes based on existing and newly available printable materials.

References

[1] S. E. Ready, A. C. Arias, S. Sambandan, Ink jet printing devices and circuits. Materials Research Society Fall Meeting; 2009 November 30 - December 4; Boston, MA.

[2] S. E. Ready, W. S. Wong, A. C. Arias, R. B. Apte, M. Chabinyc, R. A. Street, A. Salleo, Toolset for printed electronics. International Conference on Digital Fabrication Technologies (DF 2006); 2006 September 17-21; Denver; CO; USA.

[3] T. Ng, D. E. Schwartz, L. L. Lavery, G. L. Whiting, B. Russo, B. Krusor, J. Veres, P. Bröms, L. Herlogsson, N. Alam, O. Hagel, J. Nilsson, C. Karlsson, Scalable printed electronics: a printed decoder addressing ferroelectric nonvolatile memory. Sci. Rep., 2, 585 (2012)

[4] D. E. Schwarz, T. Ng, Comparison of static and dynamic printed organic shift registers. IEEE Elecr. Device L., 34, 271 (2013)

[5] L. L. Lavery, G. L. Whiting, A. C. Arias. All ink-jet printed polyfluorene photosensor for high illuminance detection. Organic Electronics Org. Electron., 11, 682 (2011).

[6] J. H. Daniel, A. C. Arias, T. Ng, S. Garner, Pressure sensors for printed blast dosimeters. IEEE Sensors Conference (2010)

[7] T. Ng, B. Russo, B. S. Krusor, R. Kist, A. C. Arias, Organic inkjet-patterned memory array based on ferroelectric field-effect transistors. Org. Electron., 12, 2012 (2011)

[8] K. S. Kwon, T. N. Ng, Improving electroactive polymer actuator by tuning ionic liquid concentration, Org. Electron., 15, 294 (2014).

[9] A. M .Gaikwad, G. L. Whiting, D. A. Steingart, A. C. Arias, Highly flexible, printed alkaline batteries based on mesh-embedded electrodes. *Adv. Mater. 23*, 3251-3255 (2011).

[10] Ready, S. E.; Endicott, F.; Whiting, G. L.; Ng, T.; Chow, E. M.; Lu, J. 3D printed electronics. NIP29 / Digital Fabrication 2013; 2013 September 30 - October 3; Seattle, WA.

[11] A sampling of 2013-2014 3D printing events:
Inside 3D Printing
RAPID
SOLID
The Complete 3D Printing Conference
3D Printing Live
3D Printing and Robotics
3-D Printing and Additive Manufacturing
IMTS 2014 Conference: Additive manufacturing production
Designers of Things
SVForum 3D Printing SIG

Author Biography

Steve Ready obtained his degree in Physics from the University of California at Santa Cruz. He then joined Xerox Palo Alto Research Center and has since studied the role of hydrogen in amorphous, polycrystalline and crystalline silicon and has contributed to the development of large area amorphous and polycrystalline silicon imaging arrays for optical and x-ray applications. Recently he has designed and developed several high-accuracy inkjet printers for printed organic electronics and documents.