Structural Electronics through Additive Manufacturing and Micro-Dispensing

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Abstract

Implementing electronics systems that are conformal with curved and complex surfaces is difficult if not impossible with traditional fabrication techniques, which require stiff, two dimensional printed circuit boards (PCB). Flexible copper based fabrication is currently available commercially providing conformance, but not simultaneously stiffness. Consequently, these systems are susceptible to reliability problems if bent or stretched repeatedly. The integration of Additive Manufacturing (AM) combined with Direct Print (DP) micro-dispensing can provide shapes of arbitrary and complex form which incorporate 1) miniature cavities for insetting electronic components and 2) conductive traces for electrical interconnect between components. The fabrication freedom introduced by AM techniques such as stereolithography (SL), ultrasonic consolidation (UC), and fused deposition modeling (FDM) have only recently been explored in the context of electronics integration. Advanced dispensing processes have been integrated into these systems allowing for the introduction of conductive inks to serve as electrical interconnect within intricately-detailed dielectric structures. This paper describes a process that provides a novel approach for the fabrication of stiff conformal structures with integrated electronics and describes several prototype demonstrations: a body conformal helmet insert for detection of Traumatic Brain Injury (TBI), a 3D magnetic flux sensor with LED indicators for magnitude and direction and a floating sensor capable of detecting impurities in water while maintaining orientation through density gradients.

Keywords: Additive Manufacturing; stereolithography; direct-print; hybrid manufacturing; Structural Electronics, three-dimensional electronics

Introduction

The capability of designing and fabricating electronic systems, which are both conformal and can easily be customized at the unit-level, will provide a breakthrough in the fabrication of advanced electronic devices that cannot be realized in traditional two-dimensional format. Furthermore, mechanical systems that require integrated electronics in structural components would stand to benefit as well (e.g. sensors and microprocessor systems embedded in the nose cone of an unmanned aerial vehicle). Numerous applications that require embedded electronic devices can be developed and fully customized into a specific or arbitrary three-dimensional shape.

Human anatomy requires medical devices to have non-orthogonal, curved surfaces that may be either flexible or stiff depending on the application (e.g. bandages need to be flexible and stretchable while prosthesis require stiffness). As body shapes vary from person to person, the capability of customizing shapes of bio-medical devices is particularly important, as the strategy of one-size-fits-all is not well suited for these applications. This paper describes a proposed hybrid Additive Manufacturing and Micro-dispensing system capable of providing 3D, unit-level-customized electronics.

Previous Work

Though reports in literature are sparse, a growing number of researchers have shown interest in the capability of fabricating three-dimensional and conformal electronics using Additive Manufacturing (AM) – previously referred to as Rapid Prototyping. The combination of Direct Printing (DP) of conductive inks onto Solid Freeform Fabrications (SFF) structures was introduced by Palmer [1] and expanded in Medina [2] and Lopes [3] in which simple circuits were implemented to demonstrate functionality by integrating a dispensing system into an SL machine using three-dimensional linear stages with a dispensing head. This approach included a demonstration of a simple prototype temperature sensor with nine components including a 555-timer chip. Periard [4] demonstrated a similar circuit as well as several clever electro-mechanical applications all created by an open-source fabrication system. Navarrete [5] describes improvements to using DP on AM substrates by introducing channels into the substrate for the conductive material in order to provide delineation of the electrical lines and allow for the reduction of line pitch, width and spacing while reducing the possibility of line-to-line shorting. Line spacing was thus controlled by the precision of the SL fabrication constraints (e.g. laser beam size) rather than the dispensing process. Furthermore, the demonstration of this technique included not only digital electronics (e.g. PIC processor and GPS chip set) but also included radio frequency (RF) functionality (e.g. antenna conductors). The electronics were implemented in a shape of a camouflaged rock to highlight the possibility of creating intricately detailed and arbitrary-formed devices made possible by AM. All of the reported circuits to date required only the use of a single plane of routing (e.g. no crossing conductors) although the concept of multiple planes with vertical interconnects was clearly the next step.

Advancements in routing of DP electrical interconnect integrated into AM structures was described in Palmer [6] and is considered seminal for the work described in this report. General advancements in dispensing techniques that may be well suited for integration into AM structures was described in Church [7] in which conductive lines were drawn onto glass substrates in order to create wireless sensor systems. The described proprietary pumping system provided precise lines with widths as small as 25 microns while drawing at speeds as high as 250 mm per second. This technology is capable of more than planar processing and can dispense conductive or dielectric materials onto three-dimensional conformal structures (e.g. drawing an antenna conductor onto a soldier's helmet). The integration of this advanced printing technology with the AM fabrication is the subject of on-going collaborative work and will provide for promising improvements to routing density and speed of fabrication of next generation AM-integrated electronics. Moreover, this technology demonstrated the possibility of printing not only the conductive interconnect but also passive electrical components such as capacitors, inductors and resistors, and consequently may provide for further miniaturization and automation capability. Arnold [8] described a technique referred to as Laser Induced Forward Transfer (LIFT) that allows for the deposition of very thin lines in a variety of materials including copper. A timing circuit similar to the ones described previously was demonstrated with bare silicon die and unpackaged surface mount passive devices. In addition to highly precise conductor deposition, the paper describes the possibility of fabricating batteries. This work did not include ALM substrates and is limited to two-dimensional deposition.

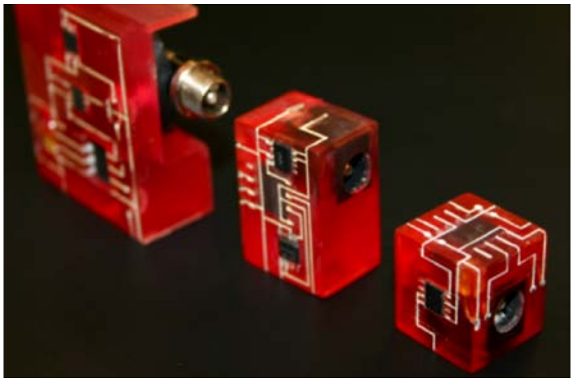


Fig. 1 –Three generations of a three-axis magnetic flux sensor system are shown from first generation (back) to third generation (front).

Fig. 1 illustrates three of the four generations of a three-dimensional off-axis placement and routing of a magnetometer system, which included a microprocessor, LEDs, a DC connector and three orthogonally placed magnetic Hall Effect sensors [9]. Not only did these generations of the magnetic sensor systems become successively smaller but they improved on the utilization of all available facets, taking full advantage of design in multiple dimensions. They were, however fabricated with completely flat orthogonal surfaces. A fourth generation magnetic flux system, introduced an additional Hall Effect sensor, a new method of multi-surface interconnections, placement of electronics on curved surfaces, surface-mount packaged electronic devices, and an alternate means of generating three dimensional sensing, capable only through utilization of multiple dimensions. All these attributes can easily be seen in Fig. 2.

Conformal Electronics Design Methodology and Fabrication

In the current work, a novel approach of using ALM techniques coupled with conductor dispensing to provide dielectric substrates that are conformal, stiff and three-dimensional is described for multiple devices. A similar sensor fabricated with traditional flexible PCB techniques would have compromised reliability and also result in bunching to conform to the interior of a helmet. Furthermore, the helmet

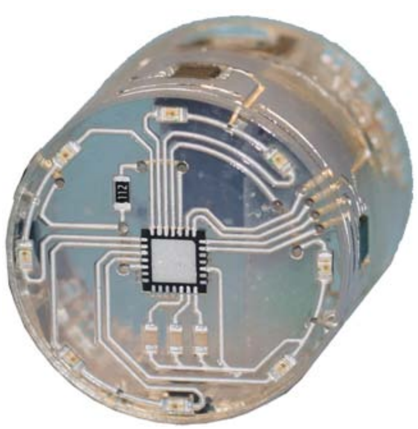


Fig. 2 – This fourth-generation three-axis magnetometer utilized many new design methods and capabilities.

system includes wireless capability with an ink-based antenna. The 3-dimensional design freedom could provide for enhanced RF capability as the antenna design is not limited to just a 2-dimensional or a conformal curved surface. In this report, the antenna was applied directly to the helmet insert surface.

The design of the accelerometer system, a helmet insert, multi-axis magnetic flux sensors, a floating hydrocarbon sensor and a self-orienting dice with blinking dots began with modeling of the geometry in the three-dimensional CAD software SolidWorks®.

For the helmet insert, a silicone mold was made from inside of a helmet, measurements were taken, and a three-dimensional model of the basic shape, shown in Fig. 3(a) was created for SolidWorks® by laser scanning. An extruded circular plate was then created with some reference art included for later features. Using the *deform* feature in SolidWorks®, this plate was shaped to match the helmet form. Fig. 3(b) and (c) show the plate before and after deformation. Holes were cut into this deformed shape to correspond to the mounting holes on the target helmet. These holes also served as the general boundaries for the design. Using arcs to define the outer perimeter of the insert, excess material was cut from the model. Fillets were used at the mounting holes to ensure mechanical integrity and give a purposeful appearance. The overall contour of the insert shown in Fig. 4(d) was produced using stereolithography to ensure proper fit and alignment in the target helmet.

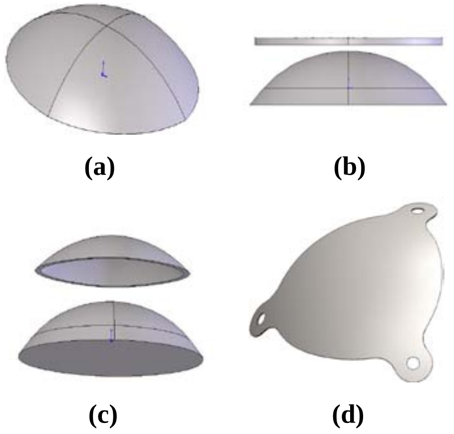


Fig. 3 – The deformation process for designing the helmet insert (a) – (c) and final cut (d).

Although the magnetic sensor system, the floating sensor and the rolling dice were not customized to fit in a predefined mold, their shape was defined and restricted to forms acceptable by the respective application. The magnetometer not only required orthogonally positioned Hall Effect sensors in order to properly determine magnetic flux in three directions, but also needed to function on a curved surface. This was solved by using a cylinder shape and having four sensors placed 90 degrees apart around the cylindrical surface (see Fig. 2). The shape necessary for the floating water purity sensor to float and self-orient itself was a sphere with varying density gradients. It was determined that the method required to allow this capability was a build-place-resume process also completed using stereolithography. In effect, the bottom half of the floating sensor was designed to be a solid half-sphere and contained the circuit on the top layer of the semi-sphere. The sphere shell of the same dimension was then used to cover the circuit and lower half of the floater. For the rolling dice, various requirements made this design extremely complicated. The system needed to have the capability of containing a replaceable battery, exposed interconnections and circuit components on all six facets of the exterior, all capable of handling repeated mechanical impacts. To comply with all the requirements, the dice was designed to be on two press fit pieces, similar to the floating sensor.

Once the overall form for each device was established, the electrical design could begin. For the helmet insert the two primary integrated circuits chosen for use in the design (an accelerometer and a microcontroller with integrated transmitter) were designed with 26 mil fine pitch leads and required precise geometry for effective implementation in SL. As such, the circuit was designed in small sections and projected onto the surface of the dielectric, thus minimizing the distortion of the circuit, since the *wrap* feature in SolidWorks® cannot yet be used to place the circuit on multi-curved surfaces. Also necessary, for each device, were precisely defined

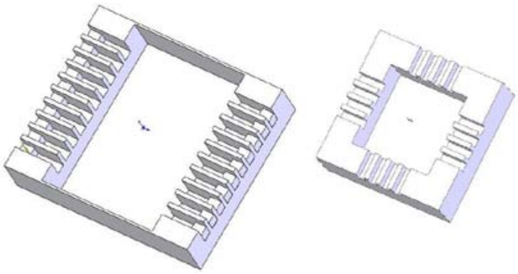


Fig. 4 – Reusable component models help prevent duplicate design work.

extruded cavities for several discrete components such as capacitors, resistors, inductors, resonating crystals, interconnecting pins, and LEDs. The channels and thru-holes in this design provide a consistent path for the dispensing of conductive silver ink for interconnections spanning multiple sides of the device.

To reduce duplicate design work, reusable models were created based on the pin and package geometry for both ICs (Fig. 4). These models were imported into the helmet design, creating an assembly. The benefits from this method were immediate, in that the magnetometer and rolling dice used identical microcontrollers. After the microcontroller cavity was designed for the magnetometer, it was simply placed into the rolling dice substrate without having to be designed again.

To complete the design for the helmet, a rectangular loop antenna along with a battery cavity and ground plane (under-side of design) were extruded. The channel for the conformal antenna was projected from a plane tangential to a point on the curved surface, thus keeping the antenna within the contour of the design. The battery cavity was designed to hold a standard 3-volt lithium coin cell housing and is connected to the insert's electronics through vias from the bottom of the insert. The ultimate goal was to use lithium polymer technology, which will allow the battery to not only be rechargeable, but also be formed to match the contour of the insert, or any shape restrictions. The ground plane for this helmet insert is an elliptical area cut directly beneath the circuit on the bottom of the design and serves a dual purpose: a convenient ground connection to various points of the circuit (via through holes on the substrate); and improves the radio frequency performance of the circuit by providing a quick path to ground for any stray radiation from the antenna.

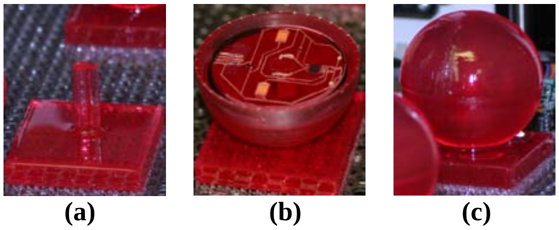
The floating sensor was developed in two parts as well. The bottom half was first built onto a platform with a key (Fig. 5(a)) that allowed for registration when the time came to build the second half of the device. The circuit was then completed (explained later in this text) and tested for functionality prior to finishing the build. The completed bottom half of the floating sensor was placed back on the key (Fig. 5(b)) permitting precise positioning for the top half of the sphere within the manufacturing system for continued processing.

The rolling dice required a solid interconnection in order for the two sides to be able to work as one unit. Ten square-shaped cuts were extruded seven millimeters deep into each side of the top half of the rolling dice. These cuts allow for interconnection pegs to slide permanently into each cut for connection to the other half of the dice.

The completed models for the various designs are shown in Fig. 6. Each was produced using stereolithography. At the completion of the stereolithography process, each dielectric substrate (the magnetometer, floating sensor and dice halves) were rigorously cleaned and post-cured in a UV oven. The ICs and discrete components were then inserted into their designated cavities. Conductive silver ink was then dispensed throughout the substrate to create the circuit interconnections. The completed devices were placed into a convection oven for final ink curing. However, prolonged exposure to higher-than-ambient temperatures was discovered to somewhat discolor the final parts. Therefore, a vast majority of the inking process was completed prior to any such curing in the convection ovens, minimizing discolor or shape distortion.

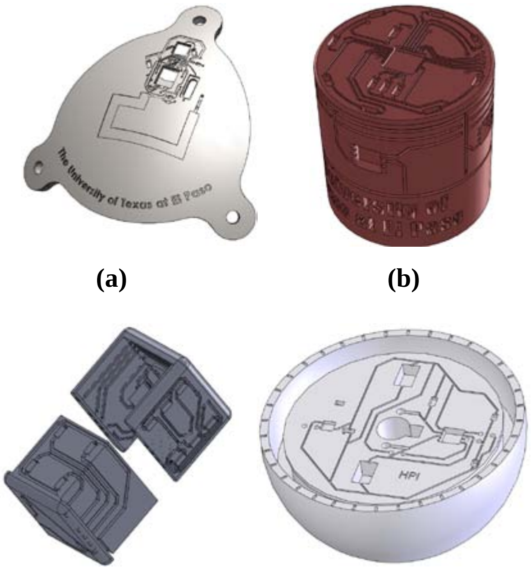
System Demonstrations

The demonstrations included the conformal structure that fit tightly to the interior of a soldier's helmet and has three bolt holes corresponding to holes in the helmet. Fig. 7 illustrates the completed insert. A wireless-capable RF PIC microcontroller was included that only requires an external loop antenna (seen in the figure as the thick trace) and matching circuit to be included externally. The chip



(a) (b) (c)

Fig. 5 – A platform and registration key (a) were necessary to allow precise placement of the bottom half of the sensor (b). This made it possible for the resume process to complete (c) with little to no offset.



(a) (b)

(c) (d)

Fig. 6 – Completed models of the helmet insert (a), magnetometer (b), rolling dice (c) and floating sensor (d).

includes an internal clock, two general purpose outputs and three analog to digital converter input pins as required for reading the accelerometer – providing an analog voltage proportional to the acceleration of the insert for all three dimensions. A single 3V power pin and ground were also included and a ground plane was painted behind the circuit to improve RF performance. The microcontrollers for the magnetometer and the rolling dice were programmed in C while the microcontroller for the helmet insert was coded in assembly. Each included non-volatile memory in order to store the program with no additional configuration chips required.

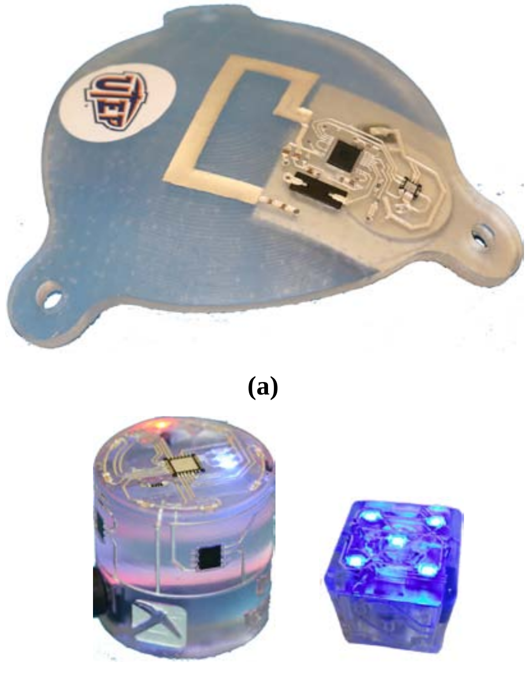
The software for each begins by configuring the analog to digital converter and then initiates an endless loop, which repeatedly measures, digitizes, and stores each analog voltage received from the accelerometer (helmet insert and dice), or the magnetic Hall Effect sensors (magnetometer). In the case of the magnetometer and rolling dice, each loop used various algorithms to effectively display the respective outputs. In the case of the magnetometer, the LEDs around the circumference of the top surface illuminate indicating the direction of the magnetic source. Depending on the intensity of the magnetic field, one, two or three of the magnitude LEDs will light. Regarding the dice, each LED on the top surface illuminate only after the microcontroller recognizes that movement has ceased and orientation has been determined.

For the helmet sensor, a 72 bit digital word is formed consisting of the transmitter serial number (used for device identification at the receiver), function codes, and the three acceleration values (voltages), which correspond to the three axes. The transmitter then uses Amplitude Shift Keying (ASK) to modulate a 315MHz carrier signal and transmit the 72 bit word along with framing pulses for synchronization.

The microcontroller for the helmet insert receiver was also programmed in assembly language. The basic operation of the receiver program is to validate incoming transmissions by timing the framing pulses, verifying function codes in the transmission, and reading acceleration values from the 72 bit word received. The receiver can be configured via software to constantly output the acceleration values to a binary LED display, output acceleration values to the display only if they exceed a programmed threshold, or output the values to an RS232 serial port for use by an external application.

Future Work

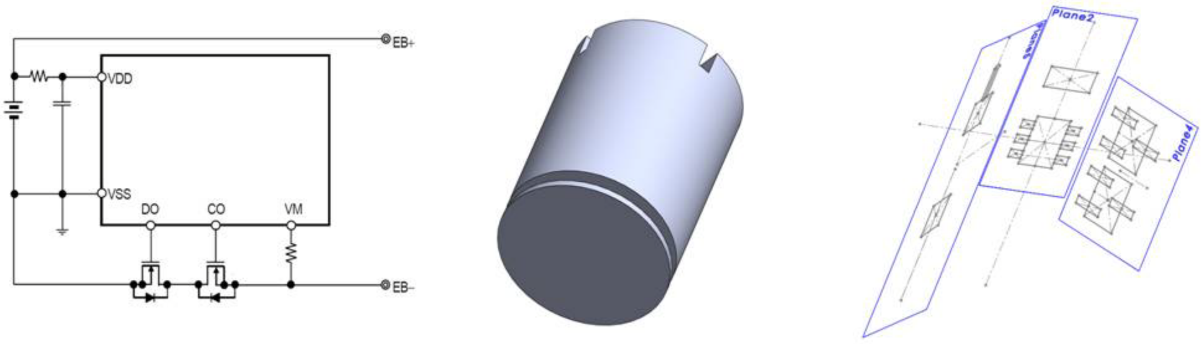
Several improvements are necessary to automate the steps in this proposed design process by converting the output of more traditional electronics PCB CAD. One of these improvements is the ability to project a circuit design onto a multi-curved surface. The capability does not yet exist in the currently implemented CAD software that does not distort the soon-to-be three-dimensional shape of our circuit. Inclusion of this feature will greatly reduce



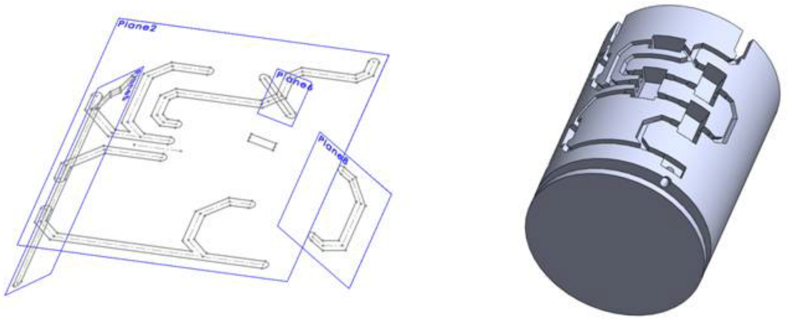
(a)

(b) (c)

Fig. 7 – Completed helmet insert (a), magnetometer (b) and rolling dice (c).



(a) Schematic design **(b) Predefined Shape** **(c) Component Sketches**



(d) Interconnect Sketches **(e) Final Design**

Fig. 8 – The steps of the conformal electronics design methodology are shown above.

the amount of time spent between circuit design and three-dimensional circuit conversion. This work demonstrated success converting two-dimensional circuits to conformal and three-dimensional shapes by using the deformation tool provided by SolidWorks® (a simple example is illustrated in Fig. 8). Also demonstrated was the use of employing a library of chip and passive sockets (SolidWorks® cavities) that physically hold chips with press fit and physically separate the pins with 100 micron isolation walls, helping to prevent short circuits when dispensing ink to the individual pins. Additionally, these pin isolation walls avoided ink seepage under the chip. This chip and passives socket library can be re-used in numerous future projects. Not only does the library of chip and passives sockets save time for future designs, but coupled with the design of rechargeable devices, we can develop a standard shape for a rechargeable battery and cavity making it possible to insert the battery into any substrate required moving forward. This will allow for faster design-to-production time and more final products capable of remote use and charge without proximity to a wall outlet.

Finally, the customized integration of the stereolithography with micro-dispensing requires further automation. The work described in this paper also included the manual insertion of all components as this can be automated in the future with pick-and-place robotic technology. For the current research efforts, this was deemed out of scope.

Conclusion

This paper has described a novel approach for providing conformal, application defined dielectric substrates, which include combinations of embedded electronics functional with sensors, microprocessors and antenna. This novel capability is well suited for bio-medical devices that need to be conformal to the human body and can be customized on a unit level to form fit an individual's anatomy, or potential military applications such as nosecones for missiles, or helmet sensors for soldiers. Various three-dimensional sensors were successfully demonstrated to illustrate the utility of this proposed capability.

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