Electronics Integration in Conformal Substrates Fabricated with Additive Layered Manufacturing

Sylvia Castillo, Dan Muse,
Frank Medina, Eric MacDonald and Ryan Wicker
The University of Texas at El Paso, W.M. Keck Center for 3D Innovation,
El Paso, Texas 79968

A three-dimensional (3D) accelerometer sensor system with microprocessor control was fabricated using a previously developed integrated layered manufacturing system that combines conductive ink dispensing with stereolithography (SL). The electronics are integrated into a conformal substrate that is press-fit into a helmet for the purpose of detecting Traumatic Head Injury (THI) when an excessive acceleration to the head is measured. Applications include monitoring the health of soldiers or athletes. Traditional fabrication of electronics is implemented with a 2 dimensional printed circuit board (PCB), which are not well suited for rugged installations in curved locations such as the interior of a helmet. The advantage of layered manufacturing for the integration of electronics is the ability to fabricate in a conformal substrate - conforming to the curved, complex, and often flexible shapes dictated by the human body.

Keywords: rapid prototyping; stereolithography; direct-print; hybrid manufacturing, conformal electronics, accelerometer, 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 bio-medical engineering devices. 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). 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.

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 cannot be simultaneously stiff. Consequently these systems are susceptible to reliability problems if bent or stretch repeatedly. The integration of additive layered manufacturing with micro-dispensing can provide shapes of arbitrary and complex form including miniature cavities for electronics components and conductive traces for electrical interconnect between components.

The fabrication freedom introduced by Additive Layered Manufacturing (ALM) 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 curable conductive inks and epoxies to serve as electrical interconnect within the ALM dielectric structures. This paper describes a process that provides a novel approach for the fabrication of stiff conformal structures with integrated electronics and describes a prototype demonstration – an accelerometer sensor with a microcontroller and wireless reporting capability. The intent of the demonstration is to act as an insert to the helmet of a soldier or athlete to detect the Traumatic Head Injury and report detection as a concussion can result in the injured person being unaware of the problem.

Previous Work

Though reports in literature are sparse, a growing number of researchers have shown interest in the capability of fabricating 3D and conformal electronics using Additive Layered Manufacturing (ALM). The combination of Direct Printing (DP) of conductive inks onto SFF structures was introduced by Palmer *et al.*, (2004) and expanded in Medina *et al.*, (2005) and Lopes *et al.*, (2006) 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 *et al.*, (2007) demonstrated a similar circuit as well as several clever electro-mechanical applications all created by an open-source fabrication system. Navarrete *et al.*, (2007) describes improvements to using DP on SFF 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 (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 high 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 SFF. 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 the obvious next step.

Advancements in routing of DP electrical interconnect integrated into ALM structures was described in Palmer *et al.*, (2004) and is considered seminal for the work described in this report. General advancements in dispensing techniques that may be well suited for integration into ALM structures was described in Church *et al.,* (2005) 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 our ALM 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 ALM-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 capability. Arnold *et al.,* (2007) 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. 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 illustrates three generations of a 3D 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 (de Nava *et. al*. 2008). The first generation was almost entirely built on one surface of the structure as designing and routing on two dimensions is supported with current electronics CAD programs and is significantly simplified as a result. The top face contained a majority of the circuits and routing. Included on the top face were two of the three hall effect sensors (one for the X direction and the other for Y). The third sensor was placed alone on an alternate side to provide the Z axis. The second and third generations were successively improved and miniaturized as all six faces of the structure were utilized and the microprocessor was embedded in the interior. These final versions included significantly improved volume utilization, but were significantly more difficult to design as CAD software does not exist that provides the design freedom required for a 3D design in terms of placement and routing All though these demonstrations did illustrate the possibility of 3D fabrication with off-axis placement and routing, all surfaces were flat and all angles were at 90 degrees.

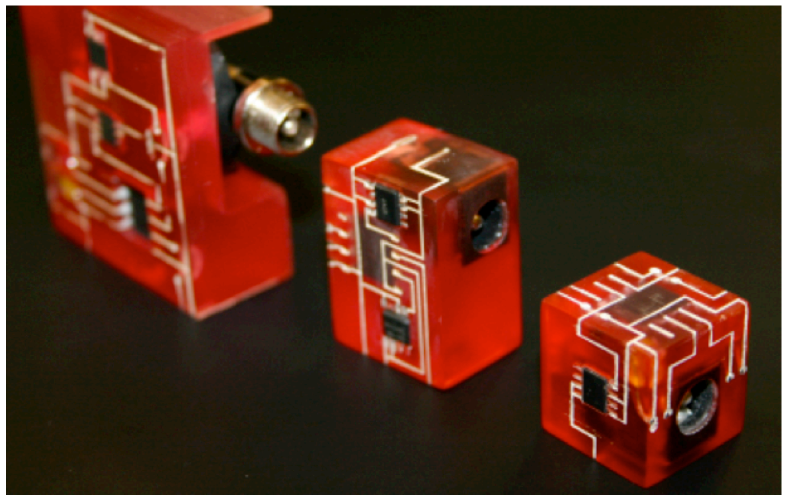
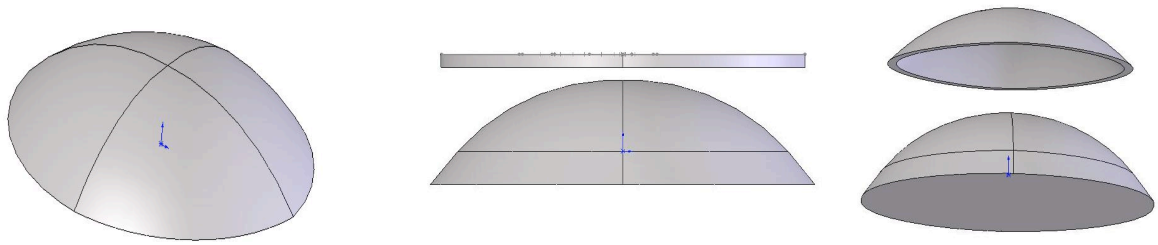


Figure 1 – Three Generations of a Three-Axis Magnetic Flux Sensor System

In the current work, a novel approach of using ALM techniques coupled with conductor dispensing to provide a dielectric substrate that is conformal, stiff and three-dimensional is described. A similar sensor fabricated with traditional flexible PCB techniques would have compromised reliability and also result in bunching to conform to the interior of the helmet. Furthermore, the system includes wireless capability with a ink-based antenna. The 3D design freedom could provide for enhanced RF capability as the antenna design is not limited to just a 2D or conformal curved surface, however in this report, the Antenna was applied directly to the helmet insert surface.

Conformal Electronics Design Methodology and Fabrication

The design of the Accelerometer System Helmet Insert began with modeling of the geometry inside the target helmet. A silicone mold was made from inside of the helmet, measurements were taken, and a 3D model of the basic shape, shown in Fig. 2(a), was created in SolidWorks. 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. Figure 2(b) and (c) show the plate before and after deformation. Holes were cut into this deformed

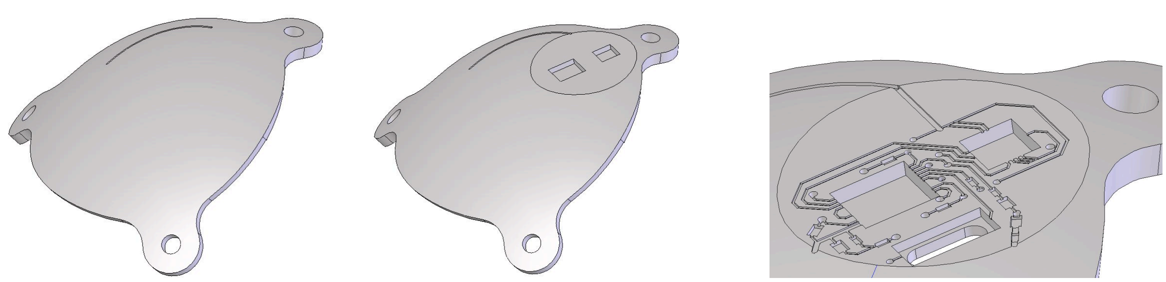


(a) (b) (c)

Figure 2 – Deformation Process

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. 3(a) was produced in stereo lithography to ensure proper fit and alignment in the target helmet.

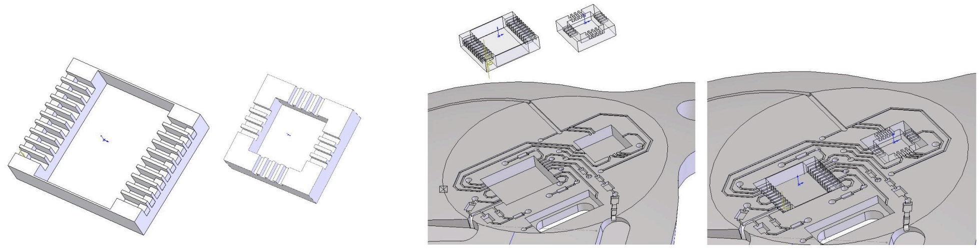
Once the overall form of the insert was confirmed, the electrical design could begin. The two primary integrated circuits used in the design (an accelerometer and a microcontroller with integrated transmitter) use 26mil fine pitch leads and require precise geometry for effective implementation in SLA. As such, a small portion of the insert required a flat surface from which to develop the circuit geometry. Figure 3(b) shows an elliptical area which was cut in the top of the design to provide the flat surface. Also shown are the two cavities where the ICs will be placed. Using SolidWorks tools such as construction lines, offset entities, and extruded cuts, the circuit interconnections were created on the flat surface as shown in Fig. 3(c). The channels and thru-holes provide a consistent path for the dispensing of conductive silver ink. Also shown in Fig. 3(c) are extruded cavities for several discrete components such as capacitors, resistors, a crystal and LED.



(a) (b) (c)

Figure 3 – Overall Shape and circuit development

To reduce duplicate design work, reusable models were created based on the pin and package geometry for both ICs (Fig. 4(a)). These models were imported into the design, creating an assembly. Figure 4(b) and (c) shows these components before and after insertion into the design.



(a) **(b)** **(c)**

Figure 4 – Reusable component models

To complete the design, a rectangular loop antenna along with a battery cavity and ground plane (under-side of design) were extruded. The antenna, though not conformal, was extruded from a plane tangential to a point on the curved surface, thus keeping the antenna within the contour of the design. A flat antenna surface was used to maintain a symmetrical radiation pattern giving optimum antenna performance. The battery cavity was designed to hold a standard Lithium coin cell housing and is connected to the insert's electronics by way of a channel on the top surface of the design and an extruded guide on the bottom surface. Ultimately, our goal is to use lithium polymer technology, which will allow our battery to not only be rechargeable, but also be formed to match the contour of the insert. A more ambitious goal is to utilize Direct Print technology to print a conformal battery system onto the insert. The ground plane is the elliptical area cut directly beneath the circuit on the bottom of the design as shown in Fig. 5. Its purpose is two-fold: to provide convenient ground connection to several points of the circuit (through holes to the surface); and to improve the radio frequency performance of the circuit by providing a quick path to ground for any stray radiation from the antenna.

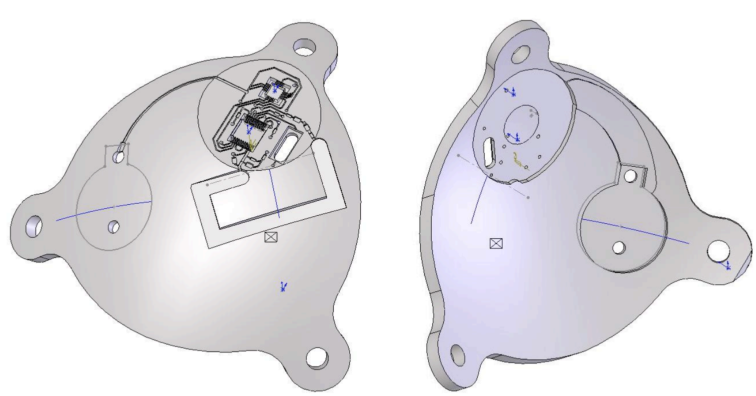


Figure 5 – Completed Model

The completed model shown in Fig. 5 was produced using stereo lithography. After the insert was rigorously cleaned, the ICs and discrete components were inserted into their designated cavities. Conductive silver ink was then dispensed throughout the design to create the circuit interconnections. After the conductive silver had cured in a convection oven, the antenna and ground plane were coated with the silver ink and again the insert was placed into a convection oven for final curing.

Helmet Insert Accelerometer System Demonstration

The demonstration included a conformal structure that fits tightly to the interior of a soldier's helmet and has three bolt holes that correspond to holes in the helmet. Fig. 6 illustrates the insert. A wireless-capable RF PIC microcontroller was included that only requires an external loop antenna (seen in the figure as a thick trace with three sides) and matching circuit to be included externally. The chip 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 microcontroller was programmed in assembly and included non-volatile memory in order to store the program with no additional configuration chips required.

The software begins by configuring the analog to digital converter and then initiates an endless loop, which repeatedly measures, digitizes, and stores each analog voltage. A 72 bit digital word is then formed consisting of the transmitter serial number (used for device identification at the receiver), function codes, and the three acceleration values 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.

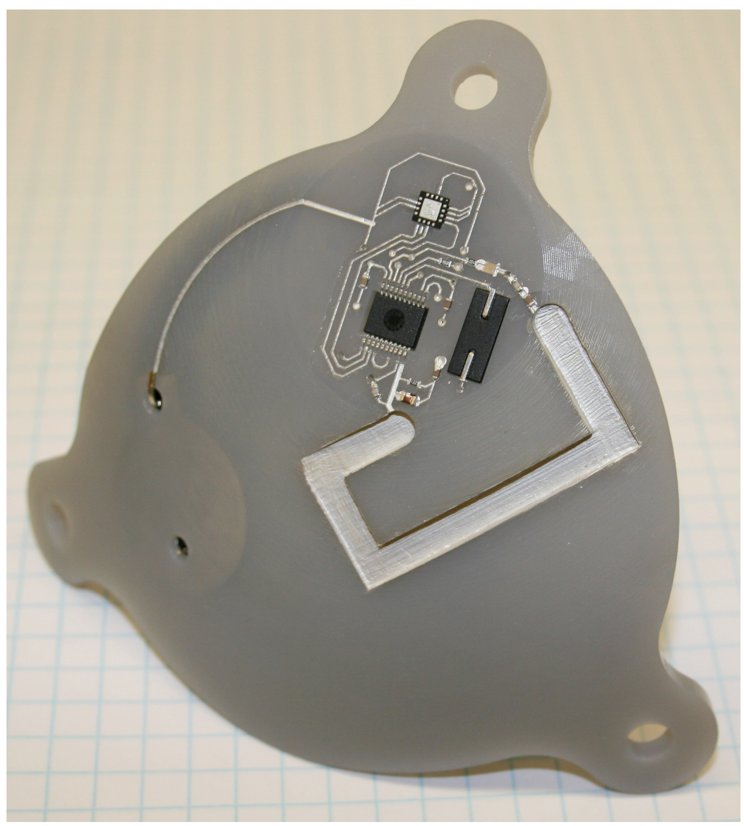


Figure 6 – Accelerometer System Helmet Insert

The microcontroller for the 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.

Conclusion

This paper has described a novel approach for providing a conformal dielectric substrate, which includes embedded electronics functional with a sensor, microprocessor 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. A three-dimensional off-axis magnetic flux sensor was demonstrated to illustrate the utility of this proposed capability.

Future Work

Further work is required to automate many of the steps in this proposed design process which will convert the output of more traditional electronics printed circuit board CAD. We have had preliminary success making these 2D outputs conformal by using the deformation tool provided by SolidWorks (a simple example is illustrated in Fig. 7) and employing a library of chip and passive sockets that hold chips with press fit and physically separate the pins with 75 micron isolation walls - thus avoiding shorts when dispensing ink to the individual pins and avoiding ink seepage under chip.

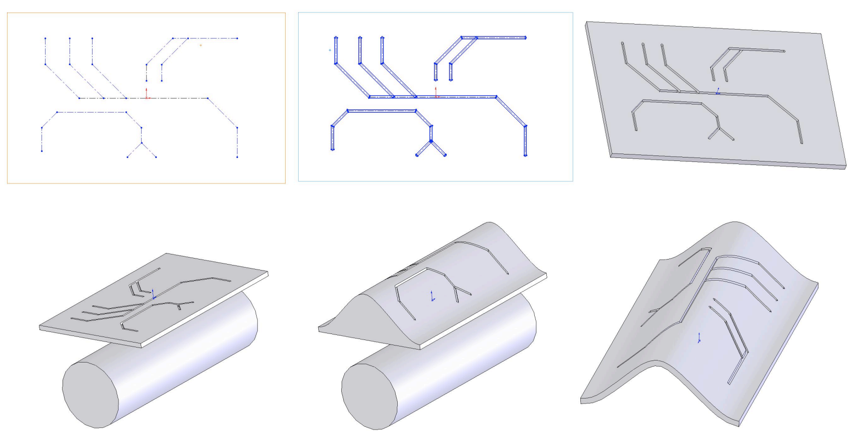


Figure 7 – Conformal Approach

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