Three-Dimensional Off-Axis Component Placement and Routing for Electronics Integration using Solid Freeform Fabrication

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Abstract

Traditional placement of transistors in chips and components on printed circuit boards has been constrained in two dimensions. Routing of electrical signals in these devices has been extended to two and half dimensions by virtue of additional routing layers which are connected through vertical vias (i.e. four layer printed circuit boards or CMOS chips with seven layers of metal routing); however, truly three-dimensional off-axis component placement and routing have not yet been explored. Solid freeform fabrication provides the means of creating a dielectric substrate suitable for these electronics with sockets for components and channels for interconnect. Direct write dispensing of conductive inks or epoxies into these channels has been reported previously for electronics applications, but was generally confined to two dimensions in a fashion similar to traditional electronics. The current research describes a demonstration prototype in which components are placed off-axis to fulfill application requirements (for a three-dimensional magnetic flux sensor system) and where sections are routed off-axis as well – all of which provides new levels of design freedom for the implementation of electronics systems.

Keywords: rapid prototyping; stereolithography; direct-write; hybrid integrated manufacturing; 3D off-axis component placement; 3D off-axis routing

Introduction

Named after Gordon Moore – a co-founder of Intel – Moore's law describes a trend that electronic devices should continue to reduce in size and cost while simultaneously increase in performance by a factor of two every 24 months (and more recently 18 months). This prediction has held true for the past four decades as semiconductors continue to improve at this remarkable pace. However, semiconductor physics is beginning to introduce roadblocks as the technology reaches nanometer scales. Current CMOS technology includes critical gate lengths at 45 nm with gate oxide dielectric layers at less than 10 atoms in thickness. These small sizes introduce new forms of transistor leakage, and consequently, further dimensional reductions are in doubt as these new leakages cause reductions in battery life and increases in thermal generation of electronic devices. One potential solution is not at the chip or transistor level but rather at the packaging and integration level in which die are now being considered in stacked structures to improve device density without incurring the leakage penalty.

These stacked structures generally rely on die being placed one on top of another with vertical vias between die for power and signal transmission. What has not been considered to date is the possibility of increasing the design space further by providing fully three-dimensional, off-axis placement of die and components as well as three-dimensional off-axis routing. For some electronics applications, which are physically constrained by the exterior shell of the device (i.e., cell phones, mp3 players, implantable bio-medical devices, etc.), this new design freedom could result in dramatic volume reduction. Moreover, other applications – primarily sensors with orthogonal component alignment requirements – would be made possible where previous technologies required two or more separate printed circuit boards to be fabricated and subsequently connected; thus compromising the mechanical integrity of the device.

The fabrication freedom introduced by Solid Freeform Fabrication (SFF) 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 SFF structures. This paper describes a process that provides a novel approach for both off-axis placement and routing of electronics and describes the first prototype demonstration – a three-dimensional magnetic flux sensor.

Previous Work

Interest in integrating electronic systems with SFF techniques has become evident as demonstrated by recent publications. The combination of direct writing (DW) 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) describe improvements to using DW 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 printed and DW circuit connections integrated into SFF structures was described in Palmer *et al.*, (2004) and is the basis for this work. General advancements in dispensing techniques that may be well suited for integration into SFF 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 100 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 SFF 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 SFF-integrated electronics. Moreover, this technology demonstrated the possibility of printing not only the conductive lines but 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 passives. In addition to highly precise conductor deposition, the paper describes the possibility of fabricating batteries, although this work did not include SFF substrates and is limited to two-dimensional deposition.

In the current work, a novel approach of using SFF techniques coupled with DW conductor dispensing to provide three-dimensional off-axis component placement as well as three-dimensional off-axis routing is described. A sensor that would otherwise require two printed circuit boards if built with traditional fabrication was created in one solid substrate to validate the technique and demonstrate the utility of the approach. Fig. 1 illustrates the prototype in CAD and highlights the three magnetic sensors oriented with orthogonal axes. Furthermore, the system required more than simple two-dimensional routing as the complexity of the schematic required crossed wires in at least one plane and a novel technique is introduced to address this by tunneling traces underneath existing traces to avoid routing congestion problems.

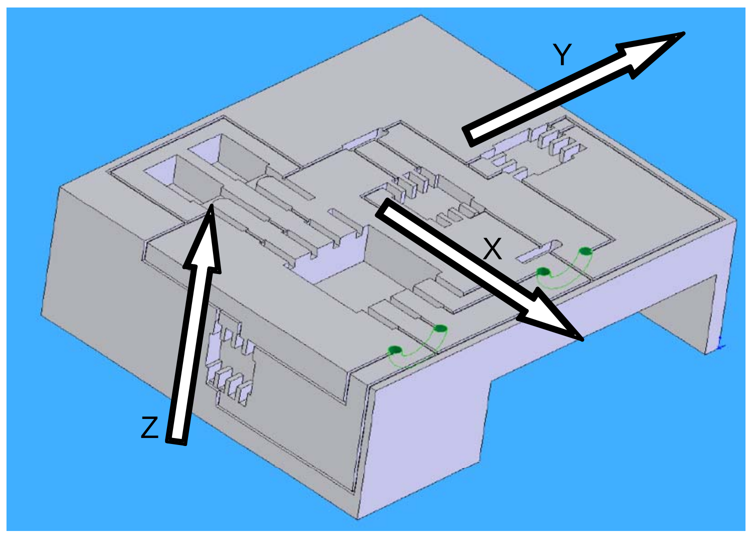

Figure 1 – Three-axis magnetic flux sensor system

Three Dimensional Off-Axis Component Placement and Routing

The motivation for off-axis component placement and routing begins with the need for miniaturization as demanded by the on-going revolution of hand-held battery-operated devices that are proliferating throughout our world. By providing the design freedom of placing components at arbitrary angles, electronics can more readily conform within the exterior of the application thus providing for smaller form factors. Furthermore, some sensor applications require orthogonal placement such as magnetic flux meters or accelerometers and consequently a new generation of sensor systems can now be fabricated within a single substrate. In addition, routing with full three-dimensional freedom not only supports off-axis placement but also

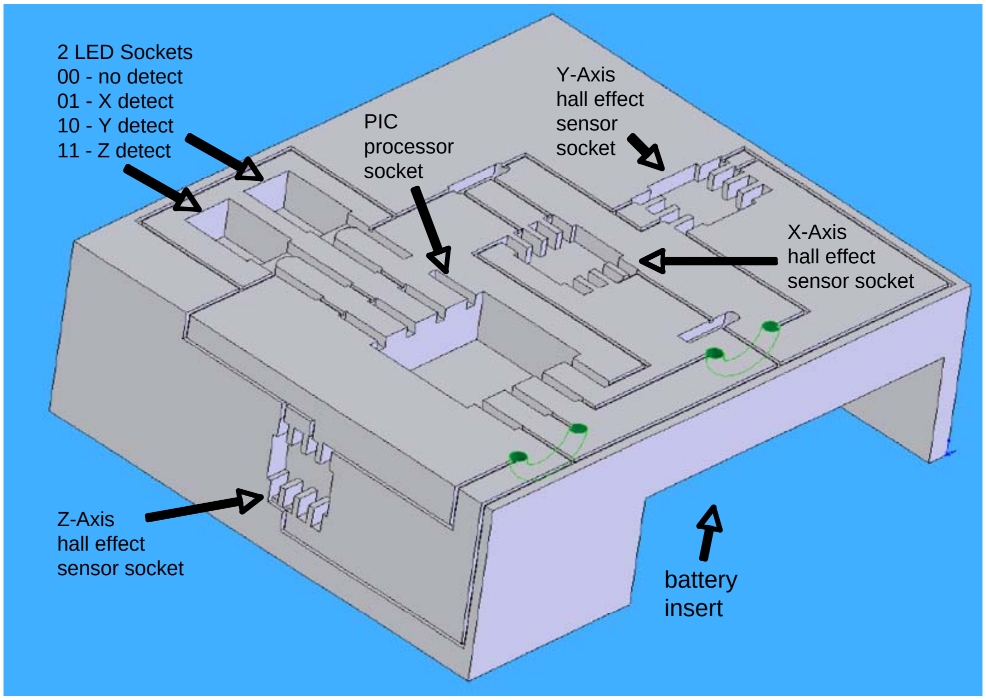

Figure 2 – Component placement in 3D sensor

provides for the possibility of significantly more complex routing as well as interesting antenna designs. Routing three-dimensionally in a solid substrate also may provide for reverse-engineering resistance or anti-tamper capability in critical proprietary designs resulting from the routing becoming sufficiently complex and embedded.

Component placement within the context of SFF electronics integration in the proposed approach includes creating component sockets within the substrate. The design freedom that SFF provides allows for the ease of creating designs with sockets in any orientation as illustrated in Fig. 2. In this example, an 8-pin DIP package socket is introduced for a PIC processor. Two magnetic sensors with 8-pin TSSOP packages are also placed on the same plane but orthogonally to one another. Two discrete light emitting diodes (LEDs) are included as output. A third off-axis magnetic sensor socket is drawn into the side of the substrate to provide for final axis of magnetic field sensing. The components can be held in place by a variety of methods including applying non-conductive epoxy prior to device insertion, press fit or by continuing the SFF build after component insertion to fully embed the component within the substrate. In this paper, devices were held in place sufficiently well using a press fit approach and subsequently secured by the cured conductive inks that attached to the pins. Generally speaking, continuing the SFF build process to fully encapsulate the components is our intended method, but for the purposes of this project, we left the components exposed to illustrate the process.

Channels within the substrate were used to connect all relevant signals and electrical power. These channels are highlighted in fig. 2 and have dimensions of 12 mil widths and 8 mil depths. These dimensions could be reduced with further optimization of the process but the focus of this work was confined to the novel off-axis placement and routing. At the point in the SFF build in

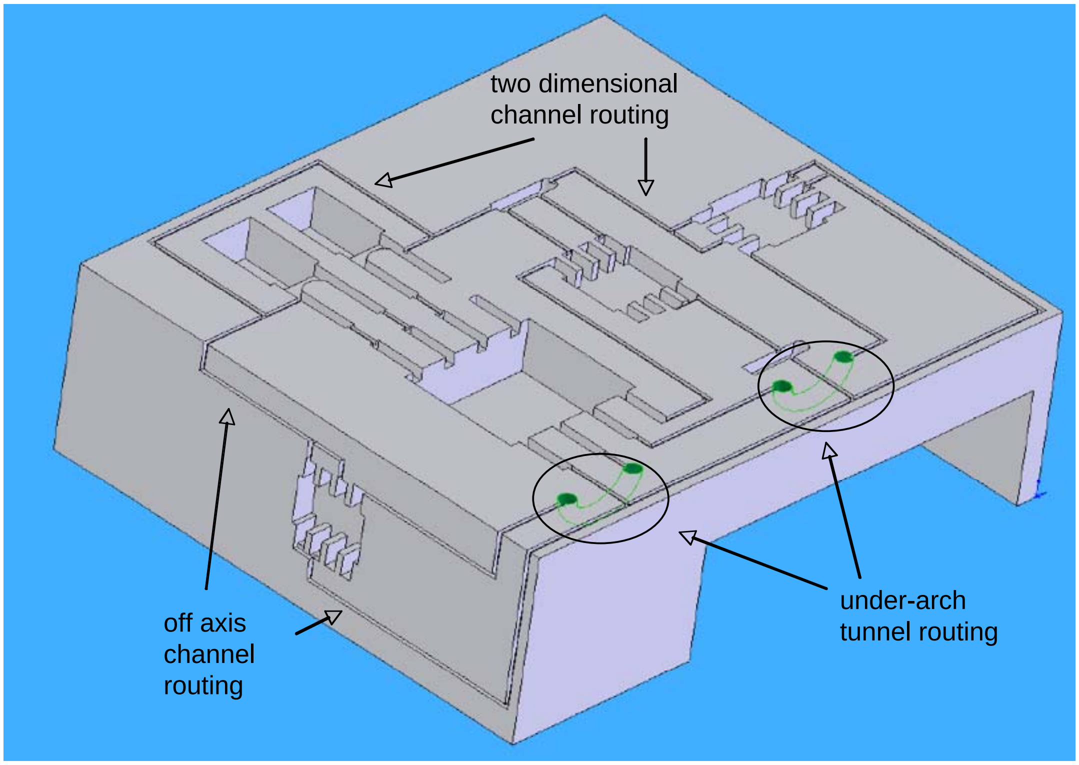

Figure 3 – Off-axis and under-arch tunnel routing

which the channel was completed and yet remained exposed, conductive ink was dispensed within the channel and cured. To provide interconnect to the third sensor, channels were simply created that make the required 90 degree turn at the edge of the top face of the substrate. Dispensing of the inks required that the dispensing system be controlled by three-axis stages with a nozzle at a 45-degree tilt.

To further demonstrate the true three-dimensional capability of routing in SFF, two under-arch tunnels were used to extend the two-dimensional routing and avoid routing congestion. Both tunnels are highlighted in fig. 3 and shown more closely in fig.4 in both CAD and photo format. Where traces were required to cross due to only using one plane of routing in this example, 12 mil circular tunnels were introduced into the substrate to avoid shorting between two independent electrical lines. These tunnels were then pumped with conductive inks and thermally cured to provide continuity within the interconnect. One limitation to this approach is the requirement of being thermally cured. Conversely, the channel interconnects have the option of being cured with UV as the ink remains near the surface of the substrate at the time of dispensing even if further SFF builds continue above the channel subsequently. Vertical interconnects that could be used to tie together signals from more than one parallel plane of routing clearly are possible using a similar tunneling technique. Fig. 4 illustrates a transparent close-up in the CAD drawing as well as a photo in which the tunnel ink can be seen through the polymer substrate.

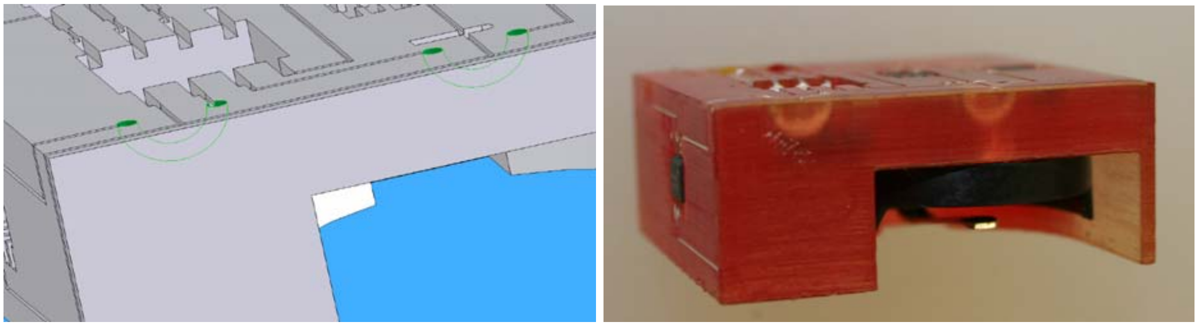

Figure 4 – Close-up of under-arch tunnel (CAD and photo)

Three-Dimensional Magnetic Flux Sensor Demonstration

The demonstration included three orthogonal sensors that were sensed by a PIC microcontroller which included an internal clock, two general purpose outputs and three analog to digital converter input pins as required for reading the three magnetic sensors – each providing an analog voltage proportional to the magnetic flux in the assigned axis. A single 5V power pin and ground were also included. 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 LEDs and analog to digital converter and then initiates an endless loop, which repeatedly measures each analog voltage and establishes if any one of the three voltages exceeds a specific threshold. If more than one value exceeds the threshold, software determines which axis had the highest magnitude and then sets the LEDs accordingly. One or both of the LEDs turn on to communicate which axis measured the greatest flux. The yellow LED only indicates the X-axis; the red LED alone indicates the Y-axis and both LEDs on means that the Z axis was the most significant. A constant verses blinking LED method for all respective axes was implemented to signify the polarity of the sensed magnetic flux. If all flux values were less than the threshold, both LEDs turn off to conserve power. For debugging purposes, a blinking pattern was introduced upon power on reset to establish that the program was running and that the PIC and LEDs were connected correctly with no open connections. To test the design, a magnet was held in different orientations near the system and the LED states were verified for all possible cases.

Fig. 5 shows the system at different stages of fabrication. The first is the fully fabricated SFF substrate without components or routing, but including the sockets for the chips and LEDs. In this example, no further SFF building was required, but nothing would preclude designs from having further layers of substrate containing additional chips and routing by continuing the build. The second photo shows the components inserted into their respective sockets. Finally, the third photo shows the components electrically connected after filling the channels and tunnels with conductive ink and then being cured.

Conclusion

This paper has described a novel approach to providing off-axis component placement and routing in the integration of electronics systems. The advantages of this new capability include improved miniaturization and design freedom for electronics as well as opening the door to

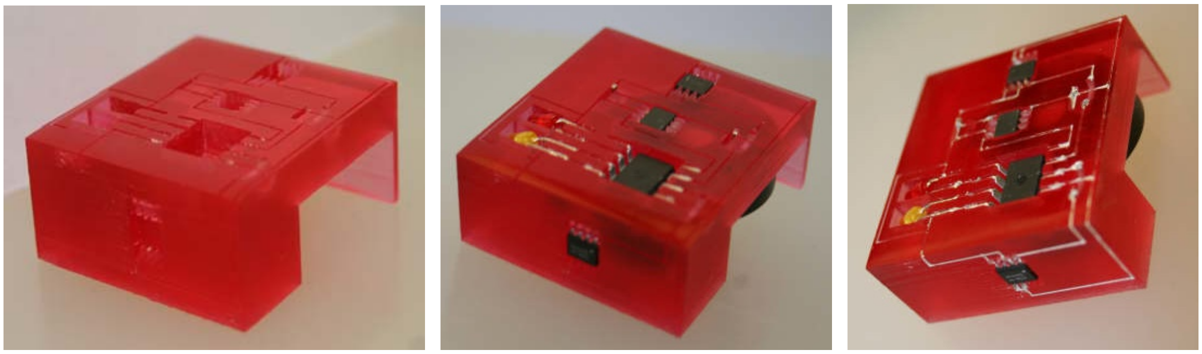

Figure 5 – 3D magnetic flux sensor at different stages of fabrication

sensor systems that require components with orthogonal placement. 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 fabrication technique potentially useful for electronic devices in which three-dimensional component placement provides a substantial benefit. Integration of a more advanced dispensing system (the Smart Pump™ offered by nScrypt, Inc.) is being explored. Incorporation of this more advanced dispensing system will provide for tighter control of dispensing flow (e.g. line uniformity around corners, lines widths, etc.) and significantly improved printing speeds and accuracies.

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