CubeSat Fabrication through Additive Manufacturing and Micro-Dispensing

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Abstract

Fabricating entire systems with both electrical and mechanical content through on-demand 3D printing is the future for high value manufacturing. In this new paradigm, conformal and complex shapes with a diversity of materials in spatial gradients can be built layer-by-layer using hybrid Additive Manufacturing (AM). A design can be conceived in Computer Aided Design (CAD) and printed on-demand. This new integrated approach enables the fabrication of sophisticated electronics in mechanical structures by avoiding the restrictions of traditional fabrication techniques, which result in stiff, two dimensional printed circuit boards (PCB) fabricated using many disparate and wasteful processes. The integration of Additive Manufacturing (AM) combined with Direct Print (DP) micro-dispensing and robotic pick-and-place for component placement can 1) provide the capability to print-on-demand fabrication, 2) enable the use of micron-resolution cavities for press fitting electronic components and 3) integrate 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 and 3D packaging. 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: a volumetrically-efficient sensor and microcontroller subsystem scheduled to launch in a CubeSat designed with the CubeFlow methodology.

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

Introduction

Over the years, electronics have evolved into a 2 ½ dimensional paradigm with the use of high performance yet physically-confining Printed Circuit Boards (PCB) as a central technology. Components have been reduced drastically to minimum physical limitations through changes in micro packaging techniques; however, the platform upon which such components are integrated has become a bottleneck for further reductions in the overall system volume and weight. Furthermore, although contemporary electronic sub-systems have continued to improve in size, the form of the systems are restricted to generally flat, non-conformal structures which are often inconvenient in terms of design constraints for the larger system. PCBs are limited in ability to optimize the space needed within the overall device. In an alternative approach, AM technologies with the capability of providing volumetric optimization through structural and conformal surface fabrication have recently been explored in terms of fabricating electronic systems – referred to as 3D Structural

Electronics. AM, robotic pick-and-place and Direct Print (DP) integrated together eliminate the need of 2D PCBs through production of 3D substrates which are built to conform to almost any surface and space within the constraints of required internal components. Due to the nature of AM processes, devices are built with high spatial resolution which in turn allows for the building of devices in virtually any shape or form. This provides a novel solution for space hardware, as such technologies have the capability to fabricate devices which conform to any surface or fill any arbitrary volume within the spacecraft such as the cone of a rocket or other curved surfaces and allow for miniaturization and further volumetric optimization of devices like satellites. Given the potential transformational advantages brought to bear by AM technologies, qualification of the associated materials and fabricated structures is critical. The purpose of the following paper is to describe an innovative technique for the fabrication of structural and conformal integrated electronics.

Previous Work

The use of Additive Manufacturing in conjunction with Direct Print was unveiled by Palmer [10] and further researched in Medina [5] and Lopes [4], research focused on the integration of a dispensing system within a Stereolithography machine using three-dimensional linear stages. Proof of concept devices were fabricated for each paper, demonstrating a temperature sensor composed of a 555-timer circuit integrated with nine other components.

Navarette [6] discussed enhancements to integration techniques by introducing channels into the substrate in which the conductive material could be placed; allowing for significant advantages such as delineation of electrical lines and reduction of line pitch and width, while virtually eliminating the possibility of electrical shorts between lines. Including channels into the substrate also gave way to line spacing being under the control of Stereolithography fabrication such as the laser beam width, rather than the dispensing process. Proof of concept devices fabricated by Navarette included a camouflaged rock emphasizing AM abilities to create intricate designed and detailed devices of arbitrary form. The demonstration included a PIC processor, GPS, and radio frequency (RF) functionality through antenna conductors. Three generations of a magnetometer were discussed as well which included a microprocessor, LEDs, DC connector and three magnetic Hall Effect sensors placed on orthogonal surfaces. Each generation began to further make use of available facets, taking full advantage of multiple dimension design using planar faces, which in turn allowed for the reduction of volume in successive generations. The approach of such devices began to further make use of multi-dimensional design; however, this design was restricted to planar faces and had not yet introduced conformal surfaces.

Olivas [8] discussed a fourth generation magnetic flux sensor system which introduced a new method of multi-surface interconnections and placement of electronics. The magnetometer was made of a cylindrical structural substrate with the circuit constructed along the non-uniform, conformal exterior surface. The device made use of surface-mount packaged electronic devices, including single axis Hall Effect sensors whose placement along the conformal surface allowed for an alternate means of generating three dimensional sensing; capable only through utilization of multiple dimensions. The use of a microprocessor and indication LEDs allowed for the tracking of magnetic fields along the three axes, as well as intensity. Such an application would be difficult to implement on traditional 2D PCBs and would require a connector or mechanical piece to extend to at least the sensor in an orthogonal orientation.

Figure 1. Magnetometer.

A 555-timer circuit similar to that discussed previously was demonstrated in Periard [11], where the use of channels ensured isolation of conductive silicone traces within the substrate. Demonstrations included the use of fully embedded electronics within a fully functional LED flashlight, as well as, proof of concept for simple electronics embedded with a children’s toy; all devices discussed were created through the open-source fabrication system Fab@Home, a Cartesian gantry based personal Solid Freeform Fabrication system. Devices fabricated through Fab@Home were built through layered and orthogonal planar surfaces, but did not make use of conformal surfaces. According to Periard, fabrication was restricted to the horizontal plane as building channels in the vertical plane was unsuccessful.

Palmer [9] discussed advancements in routing of DP electrical interconnect into AM structures; foundational work for integrated AM and DP structural and conformal electronics. In Church [2], further advancements were proposed for the integration of AM and DP. The pumping system described was efficacious of printing lines with precise widths as small as 25 microns and drawing speeds up to 250 mm per second. Such technology was able to break restrictions of planar processing, allowing for the printing of materials onto three-dimensional conformal surfaces. The integration of AM and DP processes, including capabilities of printing conductive and dielectric materials onto three-dimensional conformal structures proves to have the capability to further improve such fabricated devices and provide further improvements to routing density, speed of fabrication and miniaturization. A technique referred to as Laser Induced Forward Transfer (LIFT) was described by Arnold [1], which allowed for highly precise deposition of conductive materials. Here, the fabrication of batteries was discussed and a timing circuit similar to those described above was demonstrated making use of bare silicon die and unpackaged surface mount passive. This work was limited to two-dimensional deposition and did not include AM substrates.

The successful implementation of devices fabricated through AM and DP is shown through various projects including a gaming dice with accelerometer. A die was also fabricated through Stereolithography which contained a corresponding number of LEDs along each face. A microcontroller and accelerometer were among the embedded components who together tracked which side lay face up and lit the corresponding LEDs in an attention-grabbing sequence.

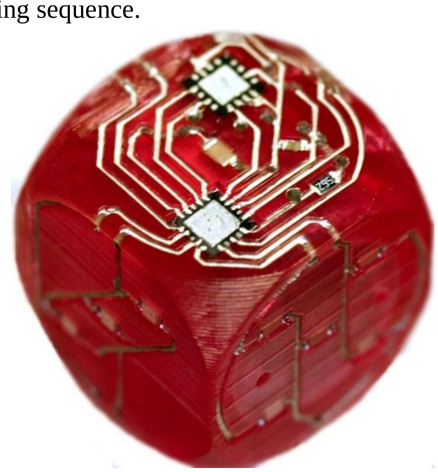


Figure 2. Die.

The CubeSat project is a widely known collaboration within the academic community to participate in space research through picosatellites and shared launches. Kief [12] describes a CubeSat proof of concept satellite, constructed from off the shelf parts and traditional fabrication techniques. Various modules of the CubeSat are responsible for different tasks including a Control and Data Handling and Electrical Power System. Two payloads to be included within the CubeSat are discussed. The first payload is a Dosimeter to measure radiation experienced in the South Atlantic Anomaly. The second payload is an Inertial Measurement Unit fabricated through AM processes. The paper also mentions the advantages of incorporating the AM and DP fabrication techniques to CubeSat including low power requirements and low cost for fabrication, as well as volumetric optimization.

3D Structural Electronics Design and Fabrication

3D structural electronics are designed through a multi-step process, which begins with the design and physical implementation of the electronic circuit to be implemented. Traditional electronics CAD programs (e.g. Cadence) are optimized for PCB technology with multiple flat planes of interconnect tied together through inter-layer vias. In some cases, such technology can be used to support the process of designing structural electronics; however, given the departure from traditional electronics, much of the implementation details were crafted by hand. The interconnect is captured in .dxf file, which contains a description of the electrical interconnect. This file is then used to program the routing for the circuitry and micro-dispensed with conductive ink.

A 3D rendering of the device can be created in mechanical CAD (e.g. SolidWorks), where the .dxf file can be imported and adjusted to conform to the shape of the device. Here the user is given full creative control over the formation of the circuitry along the surfaces of the device, as well as connections within the device and placement of components to be embedded within the surface. Cavities for embedded components are constructed based on the dimension specifications of the component datasheet. For small packages of microcontrollers cavities are created with fins which isolate each individual pin eliminating the possibility of shorts along small packages. Channels are also created in order to fully isolate electrical connections preventing shorting. Once the device is fully realized in mechanical CAD, the remaining file can be converted to a .STL file, a file native to the AM processes which is a tessellated representation of the three-dimensional surface geometry.

Finally, a post-processing program (e.g. 3D Lightyear by Stratasys) is required to show the 3D rendering of the device and formulate position and orientation for building. The program then slices the files into multiple 2D cross sections of the device, which in turn become individual layers during the AM building process and also includes component insertion and micro-dispensing information.

The purpose of the devices described within this paper is meant to prove strength and durability for participation in space flight. With the goal to participate in a CubeSat launch, UTEP has chosen to perform further research into the capabilities of the fabrication materials needed for the AM and DP processes. Various types of polymers and thermoplastics are accessible for use in AM processes; here, the primary focus is on materials used in the Fused Deposition Modeling process as these materials are much more functional than the photo-curable polymers used in Stereolithography, although Stereolithography materials are included for comparison. For the purposes of this paper, five materials have been chosen to undergo outgas testing; each being strong, durable thermoplastics. Information on these materials is taken from Fischer [14]. Acrylonitrile butadiene styrene, or ABS, is among the most widely used thermoplastics, especially for FDM processes. ABS-M30 is up to 70% stronger than the standard ABS in areas including tensile, impact and flexural strength. Layer bonding for ABS-M30 material is also significantly stronger. Polycarbonate, or PC, is the most widely used industrial thermoplastic, which is most likely due to inherent durability, high tensile strength, mechanical properties and heat resistance. PC-ABS is a combination of PC and ABS and encapsulates the best properties from each material, allowing for the highest impact strength, significant mechanical properties and heat resistance. The last material studied here is ULTEM, which is an FST (flame, smoke, toxicity) certified thermoplastic with high heat and chemical resistance, as well as, the highest tensile and flexural strength of the thermoplastics. Of the aforementioned materials, ULTEM offers the lowest precision on layer thickness at 0.25mm, while the others all offer up to 0.18mm thickness. However, such small sacrifice in precision comes with great advantages in having one of the best ratings with regards to mechanical stability and strength.

Figure 3. Thermoplastics used in FDM fabrication.

Demonstrations

The UTEP satellite project has garnered attention from the CubeSat community through provision of cost effective participation in space research and potential to lead to print-on demand satellite fabrication capability. The small satellites are 10 cm cubes the subsystems of which communicate amongst each other through the CubeFlow SPA-1 protocol. A Control and Data Handling Module was created in order to show proof of concept for AM and Direct Print processes. The design of the module was created in part to show the conformal ability of the AM process; as well as to highlight the ability to fabricate structures to fit into any arbitrary available volume in an application in which any available real estate is premium. Due to the restrictive power limitations on space missions, the module includes a Texas Instruments MSP430F2619 low-power microprocessor, which controlled output to LEDs, as well as clocked by two external oscillators. This process began with the simple circuitry whose purpose was only to prove AM and DP fabrication is able to survive space flight. The circuit contained three LEDs which would light in sequence given from the TI MSP430 microprocessor. The form factor of CubeSat allows for multiple facets, each performing several different tasks, to connect to a single Control and Data Handling module. The facets communicate through I2C to the Control and Data Handling module whose primary purpose is to receive and relay data. The proof of concept circuit included four channels which connected to the I2C lines of the chip as well as power and ground. These connections made it possible for four facets to receive power from and communicate to the Control and Data Handling Module. Each of the channels was sent to one of the four sides of the module. Here, jumper connections were created to allow facets to connect to the channel lines. The circuit layout was then superimposed on the top surface of the Cubesat Module. To allow connections to be made securely, the module was recessed at each of the four sides creating a solid space for the facet to sink in and connect.

Figure 4. CubeSat Control & Data Handling Module Proof of Concept.

Secondly, in collaboration with COSMIAC, UTEP has built a device including a SPA-1 ready Atmel Chip AT90USB1287 capable of communicating through I2C to an external data module, set to launch in 2012. The AT90USBKEY demo board was used for the development of this device, in order to show proof of concept for AM devices participating in space missions. The circuit included the Atmel AT90 microprocessor as well as an external oscillator, and included connections to the I2C channel needed for communication. The device was built as a single straight substrate including embedded components as well as a serpentine line to test the behavior of ink within the vacuum. The final form factor of the device has not yet been determined as the final available volume within the CubeSat remains in flux.

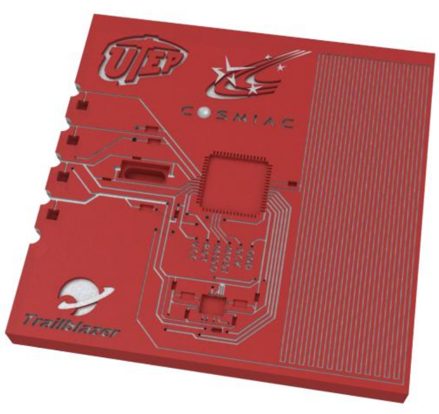
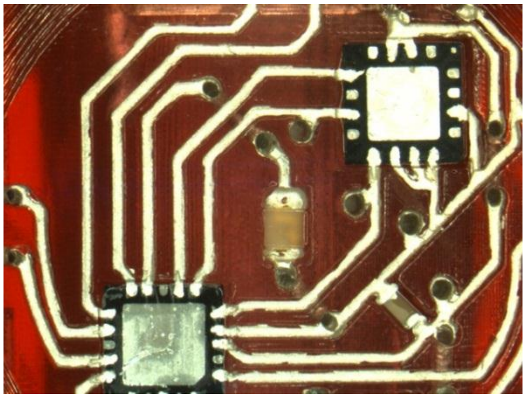


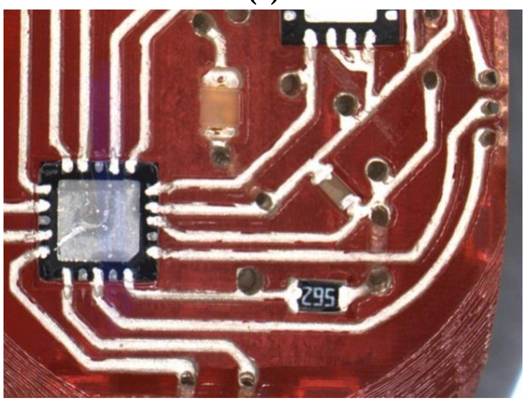
Figure 5. CubeSat Facet AT90USBKEY Proof of Concept.

Experimental Results

Before space flight is possible multiple tests must be conducted in order to ensure the safety and proper operation of not only the single device in question, but those within the environment as well. Space qualification testing is an extremely rigorous and thorough testing from every aspect of the mission. Each mission has different specifications, environmental needs, type of space vehicle and overall nature of which thorough validation of operation is necessary. Full space qualification testing includes electrical, structural, mechanical, electromagnetic compatibility, and thermal-vacuum testing. As CubeSat was created purposely to extend involvement to the general public, testing is not as comprehensive. Space qualification testing in this regard requires various tests in areas including structural, mechanical, electrical, electromagnetic compatibility and thermal. Of these tests the first pivotal test to pass in terms of AM and DP is the outgas testing, as this test includes vacuum testing to rate the device's behavior within the vacuum. The vacuum test is of the most critical as effects of outgassing from substrates could potentially harm the environment within the spacecraft, which could potentially alter the surrounding environment and harm other devices. The primary focus is then the outgassing of both the AM substrate materials and the conductive inks within a vacuum. The purpose of this testing was to solidify the compatibility of the materials in space flight and although did not undergo the full space qualification testing environment, were subjected to up to $6x10^{-7}$ torr pressure. This experiment called for an example of each material which included substrates of each of the five FDM materials mentioned earlier; ABS, ABS-M20, PC, PC-ABS and ULTEM. A total of ten substrates, two of each material, built using Fused Deposition Modeling were tested within the vacuum chamber. Mass before and after testing of the materials was recorded. Qualitative results show under the worst case scenario for vacuum, the FDM materials showed less than 1.00% outgassing, making these substrates an excellent choice for space flight as the outgassing is insignificant. As a general standard, the total mass loss screening level for materials is 1.00%, as specified in the Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials [13] used by NASA. Although not required in the case for CubeSat devices, the devices performed beyond the rating of NASA requirements, leading to the potential of these devices to be fabricated for general space missions.



(a)



(b)

Figure 6. Test Circuit (a) Before and (b) After Outgas Testing

A test circuit was created through Stereolithography and sent in order to test outgassing of the ink, Ercon 1660 and validate the construction of the circuit through the AM fabrication. The ink was selected due to characteristic exceptional performance and low resistivity. Although this device happened to be fabricated using Prototherm 12120, the material of the substrate was of little importance. The die was subjected to the same outgas test environment as explained for the FDM substrates. After testing the die was powered on to ensure electrical functionality. The die performed, confirming the integrity of the electrical circuit and showed little to no physical damage.

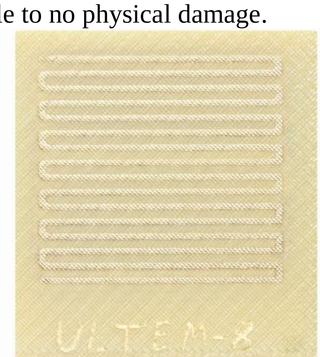


Figure 7. Passive Test Circuit after outgas testing

In addition to the above test circuit, passive test circuits were printed using Ercon 1660 onto the ULTEM FDM material to further validate the compatibility of direct printed silver conductive inks and thermoplastics in space environments. No detrimental effects were found on these samples either physically or electrically.

Future Work

Future work for the CubeSat project includes creating the final form factor of the AT90USBKEY facet, which is to be conformal to the excess area left within the CubeSat. UTEP has previously created conformal structures which have proved the feasibility of the AM and DP fabrication techniques for electronics. The major concern was then the applicability of the materials within space conditions which we found have been satisfactory. From here, the merging of these two aspects is expected to provide a solution to conformal space flight hardware.

Conclusion

The preceding paper has described a novel approach to fabrication of conformal structures with integrated electronics. This fabrication technique has the potential to provide stiff, conformal structures adequate for space flight, shown by the outgas testing of the materials used in fabrication. Two successful prototypes were given as example to the workmanship of AM and DP processes, one of which is scheduled to launch in with the Trailblazer project in June 2012. Samples of the fabrication materials needed were also tested and discussed.

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