Multi-functional 3D Printed and Embedded Sensors for Satellite Qualification Structures

Corey Shemelya*, Luis Banuelos-Chacon†, Adrian Melendez*, Craig Kief‡, David Espalin*, Ryan Wicker*, Gijs Krijnen*, and Eric MacDonald†

Email: emac@utep.edu

*The W.M. Keck Center for 3D Innovation, The University of Texas at El Paso, El Paso, TX, 79902, United States
†COSMIAC, The University of New Mexico, Albuquerque, NM, 87131, United States.
‡MESA+ Research Institute, University of Twente, Enschede, The Netherlands.

Abstract—Three dimensional (3D) printing has recently gained attention in a variety of industries ranging from aerospace to biomedical. However, in order to create truly functional 3D printed structures, electronic functionality must be integrated into building sequence. This work explores the integration of both printed sensors (copper capacitive touch sensors) and embedded COTS sensors (surface mount accelerometers) in order to fabricate a space-flight qualification test coupon in the shape of a 1U CubeSat (10 x 10 x 10 cm) as required for stress testing. The 3D printed electronics were fabricated by an enhanced MultiME3DP 3D Printing system, allowing the direct integration of 3D printed dielectric structures with electronics components fabricated together using a single non-assembly build sequence. Both sensors and structures successfully demonstrated electronic functionality after full encapsulation, and show promise for integration in space based cube satellites.

I. INTRODUCTION

Enhanced three dimensional (3D) printing is enabling the next generation of geometrically-complex electronics may enable the fabrication of printed circuit boards in custom and arbitrary forms. Until recently, traditional 3D printing produced parts which have been purely structural in nature – with generally one or two different printed materials. This research leverages a decade of exploration in integrating electronics functionality into 3D printed devices (MultiME3DP Manufacturing) by interrupting the fabrication, selectively submerging copper wire, foils, and electronic components into the extrusion-based printed structure and subsequently continuing fabrication. Material extrusion 3D printing (ME3DP) employs high performance dielectric thermoplastics in a layer-by-layer manner and is well suited for stop-and-go manufacturing [1-4]. While 3D printing is credited with providing Complexity for Free, MultiME3DP Manufacturing provides Electronics for Free [4] – integrating components and interconnect to improve volumetric efficiency, enable patient-specific prosthetics, design-and-print satellites, wearable computing, and the next generation of remotely manufactured electronics – all of which require both printed and embedded COTS sensors.

Capacitive sensing integrated with 3D printing has been in development for many years; however, research in directly printing these sensors while embedding the associated support electronics in a single printing sequence is limited [5-8]. Furthermore, embedding COTS sensors such as accelerometer chips in 3D printed structures has been reported in Ref. [4], but without a comprehensive performance verification. However, verification becomes especially important with 3D printed sensors as performance may be compromised due to: the high-temperature build chamber, encapsulation of the sensors within the structure, and joining of the electrical interconnects (in this case welding by laser of embedded wires to package pins).

This work examines one application of 3D printed electronics, micro-satellites (CubeSats [9]) and more specifically the various test coupons required for the associated space qualification testing. Three versions of a test coupon were designed and fabricated. Each version includes six plates containing embedded electronics. The six plates can be snapped together to form a robust 1U CubeSat structure. Due to the unique assembly design which utilizes 3D printed snap fittings, these CubeSat test coupons are referred to as SnapSats when fully assembled and will undergo space-qualification testing including thermal vacuum testing and vibration. However, the performance of the printed and embedded sensors must be characterized both before and after qualification in order to identify performance shifts brought on by the harsh simulated conditions. Specifically, this work examines the performance of each sensor before space qualification in order to create a baseline performance metric.

In addition to sensor qualification, this work also demonstrates the robustness of the MultiME3DP Manufacturing System and the appropriateness of the technology for manufacturing space components. This paper discusses the design, fabrication and characterization of three versions of the SnapSat – each with different sensors - some directly printed and others embedded. Additionally, the work will describe a theoretical framework for advanced 3D printed normal and shear capacitive force sensors that will provide additional sensing capabilities for space, biomedical and...
robotic applications. An initial proof of concept for these sensors is included.

II. DESIGN AND FABRICATION

In order to facilitate space qualification of the Multi3D Manufacturing system, three versions of SnapSat were designed in SolidWorks®. The CAD models were then fabricated and underwent a characterization process. The SnapSat pieces presented in this work were characterized before stress to provide insight into the impact of the embedding process on sensor performance, and to determine the feasibility of using each sensor in CubeSATS or other space vehicle applications.

One advantage of 3D printed electronics is the capability of rapidly iterating through a design for optimization. In the case of the SnapSat, three versions were designed, fabricated, and tested. All of these versions integrate a low power embedded microcontroller (MSP430) for collecting sensor data, and multiple LEDs to visually demonstrate sensor outputs. SnapSat Version 1 is shown in Fig. 1a during fabrication, and this version included an embedded accelerometer (Analog ADXL335) which demonstrates the potential of COTS integration in 3D printed structures. SnapSat Version 2 added wireless communication by including a chip-scale Bluetooth printed circuit board to communicate the accelerometer output (Fig. 1b). SnapSat Version 3 contained a printed capacitive touch sensor (32 gauge copper wire and 100 mesh size copper) controlled by an embedded MSP430. As shown in Fig. 2 both during and after fabrication the embedded LEDs indicate the structure is functioning. All versions contained a lithium ion battery, charging circuit, and microUSB connector for programming the microcontroller and battery charging.

The fabrication of the SnapSat involved a multi-step fabrication process using the Multi3D Manufacturing system and extruding polycarbonate (PC) as the build material. First, a 5.0 mm base structure was fabricated with a Stratasys Fortus 400mc, which was interrupted to allow for insertion of components (shown in Fig. 1a). Subsequently, wires (32 gauge copper wire) were embedded (thermally at 280°C) and components laser welded (532nm wavelength) and the electronics were tested for functionality (Fig. 1b). Although, the work presented here included manual insertion of components and wires, a funded effort is underway to automate the entire process.

After insertion, the ME3DP process was continued and an additional 5.0 mm of material was printed directly on the embedded circuit to create a sealed and robust system. To maintain 3D printing accuracy during these interrupts, a registration procedure was developed in which the pieces were replaced reliably into the same position within the build chamber using a keyed substrate. This process allows fabrication to be resumed without a noticeable change to the external surface finish. The final interrupt allowed insertion of the “snaps” so that the six plates of the SnapSat can be assembled together to create the 10 cm cube required for standard CubeSat stress testing fixtures. As a final step, a rechargeable battery was inserted into a printed cavity after printing and a chemically welded capping plate was used to seal the cavity. The battery in this work must be embedded after the ME3DP process as the build envelope (145°C) maintains temperature beyond those recommended for the commercial battery. The microcontroller was programmed in a similar manner as described in Ref. [5] and Ref. [6]. One completed plate and one full SnapSat are shown in Fig. 3.

All sensor outputs were managed by the MSP430 microcontroller, using the method described in [5-6]. The output of the accelerometer was analyzed by comparing the output of the analog-to-digital converter of the accelerometer

fig. 1. fabricated cubesat “snapsat” versions demonstrating multiple points in fabrication. (a) pre-wire embedding, (b) after thermal wire embedding.

fig. 2. fabricated cubesat “snapsat” versions demonstrating multiple points in fabrication. (a) pre-wire embedding, (b) with wires
to that of the predefined acceleration of gravity. The MSP430 was then programed to associate that acceleration with a tilt angle and turn on or off specific LEDs. While the output methods used here do not represent absolute values, the resulting analysis provides the basis to describe the future highly accurate and customizable sensors discussed in the next section.

III. RESULTS

The embedded COTS accelerometer and the printed capacitive sensors were characterized using the standard output of the MSP430 micro-controller through a back channel serial port. The output was normalized to external measurements in order to obtain initial sensor data for calibration. Subsequently, the MSP430 was used for pre-digital filtering to provide noise elimination on the raw sensor output in order to allow LED activation reliably within certain pre-calibrated thresholds (i.e. a specific tilt angle at a given rotational speed for the accelerometer or a specific capacitance for the capacitive sensor).

For the capacitive sensor, the instantaneous capacitance measurement readings obtained (oscillator cycles) were first averaged in order to determine a baseline value. The MSP430 was then able to sense a change in capacitance when an object came into contact with the sensing area in a specific pre-defined situation. More information on this process can be obtained in Ref. [5] and Ref. [6]. For this work, the MSP430 was pre-programed to activate only within a certain range of capacitance values and this range was normalized to a firm press on the sensing area from an operator. The resulting capacitance graph is shown in Fig. 4.

The accelerometer sensor was normalized to the acceleration data obtained when the accelerometer chip was oriented at differing angles from the surface normal. When the MSP430 was activated, four embedded LEDs were programmed to turn on at predetermined tilt as illustrated in Fig. 5. These angles corresponded to less than -30° (LED 1 only), -30 to -15 (LED 1 and 2), -15 to 15 (LED 2 and 3), 15 to 30 (LED 3 and 4), and greater than 30 (LED 4 only). It is important to note that the measured accelerations are not mirrored on the +/- X-axis due to a slight tilt in the accelerometer during the embedding process. This distribution demonstrates why post-embedding normalization is important to 3D printed sensing.

IV. ADVANCED SENSORS

The lessons learned from fabricating the previously described prototype sensors have allowed for the theoretical description and initial design experiments of 3D printed, highly-calibrated, capacitive sensor systems. These sensors may prove advantageous as the customization possibilities of additive manufactured systems will enable many new robotic applications in the future. For robotics, the sensing of interaction forces, torques and pressures, and the need for softer materials that stretch are required [9,10]. To this end, initial investigate are underway for embedded sensing using novel commercial flexible elastomer materials such as NinjaFlex. This section will describe the theoretical framework of a potential normal and shear force sensor as well as initial fabricated designs.

In order to create normal and shear force sensor, a multi-wire structure is proposed, such as that in Fig. 5. Using elementary expressions, Ref. [11], for the electrical fields of pairs of oppositely charged wires, it is possible to calculate the capacitance of collections of wire pairs. The results are shown in Fig. 5a and indicate that even for a wire density of only 50%, a capacitance of 85% or more of the fully dense (parallel plate) capacitance can be obtained. This is an important encouraging result for fabrication methods where
both high wire density and continuous metal sheet embedding are challenging. Furthermore, when the datasheet values for 3D printed polymeric materials (i.e. the stiffness, hardness, and elongation) are known, capacitance changes due to the relative motion can be fully described and modeled for two parallel sets of embedded wires.

With a fully characterized sensor model (Fig 5a), a multilayer wire capacitive system was designed within a 3D printed structure (Fig. 5b and 5c). Initial proof of concept structures were fabricated from a variety of materials (Fig. 5d). Materials such as ABS, NinjaFlex, and ULTEM 9085 were used in the fabrication process in order to determine the optimal correct hardness, filling factor, and printing density. Initial results show a softer material such as NinjaFlex may prove to be the most compatible with this sensing system, however, optimization experiments are underway to experimentally demonstrate this conclusion.

V. CONCLUSIONS

This work described the general implementation of a multi-sensor system for use in 3D printed CubeSat applications. Specifically, this work describes the fabrication process and sensor functionality of a SnapSat, which integrates printed as well as embedded COTS sensors. Using this process, embedded communications devices were also included such as micro-USB connectors and Bluetooth. All of the versions were fabricated with internal battery supplies and charging circuits allowing operation away from external power sources.

Using the knowledge obtained from this work, specifically the interactions and embedding process involved with copper wire interconnects, copper wire capacitive sensors, and embedded MSB430 surface mount microcontrollers, a novel 3D printed capacitive force sensor is proposed and investigated. This sensor system can then be integrated into advanced applications such as the SnapSat to allow increased sensing capabilities in remote or harsh environmental sensing applications and in this example to provide a framework for qualifying the process based on flight qualification stress testing that can be characterized before and after stress testing.

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Fig. 6. Fabrication of advanced normal and shear force capacitive sensor system. (a) Total capacitance versus number of wires for a structure of 10mm x 10mm size, a gap of 2mm and a wire diameter of 1mm, (b) CAD rendering of initial wire design, (c) CAD rendering of proposed 3D printed sensing system, and (d) fabricated prototype sensor using NinjaFlex FDM material and a MakerBot2 3D printer.