Printing Multi-Functionality: Additive Manufacturing for CubeSats

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I. Introduction

The recent push for disaggregation of satellites is driven by the need for affordability in space assets. Small satellite technology has made advancements that enabled traditional large satellites to reduce their size, while still performing their operational missions. Miniaturization of components is a strong contributor to the overall size reduction, but recent game changing innovations in Additive Manufacturing (AM) allow these miniature devices to be efficiently packaged, and are showing promise to dramatically alter spacecraft size.

Under the leadership of the Keck Center at the University of Texas at El Paso (UTEP) with key support from the team shown above, and funding from two contracts, we were able to pursue new technological methods for embedding components and electronics into 3D printed products. Our research focused on the 3U CubeSat platform, though the results can easily be adapted for larger (and smaller) spacecraft. These two programs, which are still in progress, will result in a key Industry capability that minimizes internal space currently used for spacecraft systems. Meeting that goal will result in even smaller satellites since greater internal space will then be available for sensors and experiments. Increased reliability will also be achieved as more of the process that was accomplished manually, is now achievable (repeatedly) with an automated AM process.

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The following sections describe printing multi-functionality – which allows for fabrication of complex geometries of intricate detail with embedded electronics, sensors, wiring, propulsion, actuation and communication capabilities. This next generation fabrication system is referred to as the Multi^{3D} system. This denotes the use of multi-technologies to produce 3D, multi-material, multi-functional devices with an emphasis on addressing the requirements of aerospace applications. Our goal is to develop advanced materials that are printable, while also investigating key features such as radiation shielding capability, electromagnetic properties, thermal resistance, and general usability for space applications. Key affordable spacecraft enablers such as embedding antennas, solar panels, and wireless communication systems were also evaluated using the most promising materials.

II. Two Program Contributions

The two contributing contracts have strong correlation related to their consistent theme for AM in CubeSats. The common additive manufacturing innovation thread is embedding wiring and electronics into the walls of satellite structures, and applying that process to several different systems that make up satellite core components. The Multi^{3D} System has the ultimate goal of developing an integrated 3D manufacturing system that will automate the process.

A. SmallSat Technology Program (SSTP)

Figure 1. Exterior of LEXR Source

Our SSTP project began in September, 2013. SSTP is a National Aeronautics and Space Administration (NASA) headquarters funded activity to help advance the readiness of new ideas for flight in small spacecraft [1]. The focus of this two year grant is materials research, communications and propulsion design and testing. It is a joint activity between NASA Glenn Research Center (GRC), the Northrop Grumman Corporation, UTEP and the University of New Mexico's (UNM's) COSMIAC Space Center. We proposed to investigate the applicability of 17 different thermoplastic materials to AM and test them for space flight capability through rigorous environmental testing. Based on known orbital requirements, lighter thermoplastic spacecraft could provide benefits not normally achieved from heavier metallic structures. The initial step was to attempt to print the 17 materials and perform initial minor structural testing to assess integrity. Some of the test article "dog bone" shapes were observed to have no structural integrity and were removed from consideration. Other materials were selected and tested for radiation sheilding capability - a feature desired for spacecraft electronics. This testing was accomplished at the Air Force Research Laboratory's (AFRL) Low Energy X-Ray (LEXR) facility (Figure 1) at Kirtland Air Force Base (KAFB) in Albuquerque, NM. The Low Energy X-Ray (LEXR) facility is a unique radiation facility that was established by AFRL in 1992.

When the dosimetry measurement was completed at the LEXR facilty, a comparison was performed to prove the equivalent radiation exposure can be achieved by their Cobalt-60 irradiator. Testing was performed on a P-Channel Metal Oxide Semiconductor (PMOS) Filled Effects Transistor (FET) in both facilities (the LEXR and Cobalt-60). An equivalent dose rate and exposure was performed and the comparison of damage was shown to be equal.

The LEXR facility was used because of the ease of access and direct readings of dosimetry to measure the radiation deposited. A silicon PIN diode measured the deposited dose. The diode was used to measure the radiation without any material at a specific distance. This fixed distance measured the irradiation at a point in space and set the basis for a non-sample level. The AM samples were placed in front of the diode, at that fixed distance, and the attenuated irradiation was measured. The chosen samples had different radiation shielding elements added to them during the printing process and different attenuation factors were observed. This will benefit embedded components within 3D printed articles by increasing radiation shielding for sensitive space components.

The six materials that exhibit the greatest ability to shield total dose radiation will be embedded with electronics to emulate an Atmel RF meshed network for environmental testing. This meshed network emulates a network of intra-satellite communications. The panels will be joined together allowing them to fit into a standard 1U CubeSat form factor as shown in Figure 2. This configuration allows the system to be placed into a Cal Poly 1U PPOD dispenser for vibrational testing. Upon completion of the vibrational testing, the satellite will be exposed to thermal vacuum testing for outgassing.

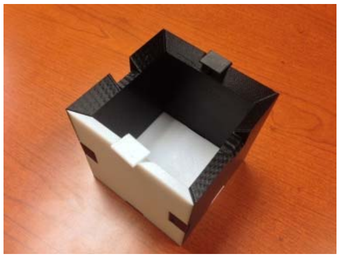

Figure 2. Representative 1U printed structure

B. America Makes

The America Makes program began in March, 2014. The focus of this grant is equipment design and development, which will ultimately address satellite communications research, thermal management and embedded conductive wire testing. This is a joint activity between the Keck Center at UTEP, Northrop Grumman Corporation, NASA Glenn Research Center and UNM's COSMIAC Center. Key enabling technologies were investigated and are described below.

1. Equipment Design and Development

The next generation of manufacturing technology for space hardware will require complete spatial control of material and functionality as structures are created layer by layer—providing fully customizable, high-value, multifunctional products for aerospace industries. Using the America Makes grant, contemporary AM is being integrated seamlessly by the team with a suite of comprehensive manufacturing technologies, including (1) extrusion of a wide variety of robust thermoplastics/metals, (2) micromachining, (3) laser ablation, (4) embedding of wires and fine-pitch meshes submerged within the thermoplastics, along with (5) robotic component placement. Collectively, the integrated technologies will fabricate *multi-material* structures through the integration of multiple integrated manufacturing systems (*multi-technology*) to provide *multifunctional* products. The systems will be able to print a layer with one material, print a complex circuit board, print another layer with a different material, print an antenna then finalize with another material – all with the same machine (Figure 3) A functioning prototype of the proposed system has been created at UTEP as depicted in Figure 4**Error! Reference source not found.** and includes several sub-processes with a conveyance system to translate a device-under-construction between manufacturing stages. The prototype is capable of embedding wires and components within a multi-material substrate to provide mechanical, electronic, thermal and electromagnetic functionality. Although this technology is well suited for fabricating satellite hardware where the harsh conditions of space provide a testament to the robustness of the resulting structures, the proposed Multi^{3D} Manufacturing System can also be used to fabricate any 3D structural electronics including those intended for use in consumer, biomedical, aerospace, or defense markets.

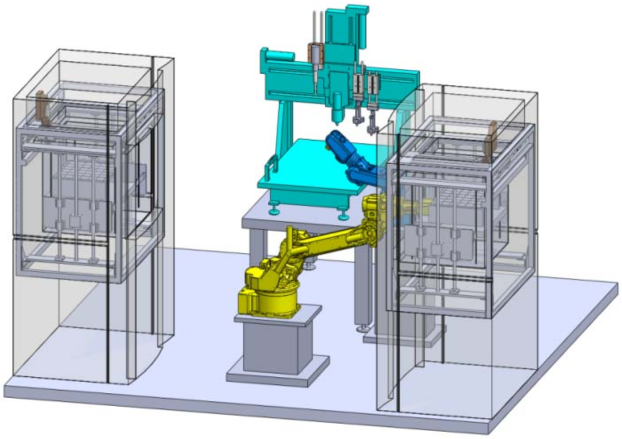

Figure 3. Preliminary version of hybrid fabrication system with integrated complementary manufacturing technologies.

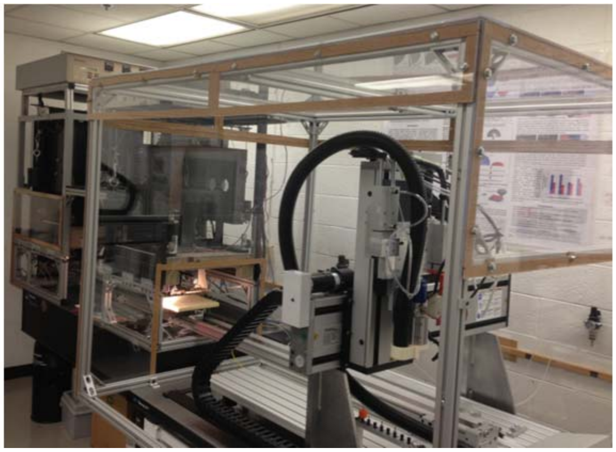

Figure 4. Conceptual design of the multi-function robotic system for America Makes.

2. *Thermal Management*

Thermal management of spacecraft is traditionally accomplished by means of heatpipes or crycoolers. 3D printing offers the potential for innovative active thermal management solutions for space applications. One of the key attributes of 3D printing is that realization of geometric complexity is free (i.e., the cost to fabricate is the same regardless of complexity) and therefore can be used to optimize the functionality of the part. For example, 3T RPD and Within Labs designed a heat exchanger and fabricated it using direct metal laser sintering (DMLS) [2]. The geometry is a significant departure from the traditional heat exchanger with an organic external appearance and internal turbulent producing stators to improve cooling.

For space applications, the vacuum prevents use of convection, so the only way to remove heat is through radiation. Without thermal management, the solar-exposed portion of a space vehicle would reach temperatures up to 250° F (121° C), while thermometers on the dark side would plunge to –250° F (–157° C) [3]. On platforms such as the space shuttle and the International Space Station, heat rejection uses radiator panels deployed from the vehicle and oriented away from direct solar radiation. Radiation behavior is governed by the Stefan-Boltzmann Law. The amount of energy that can be radiated from a body is directly proportional to the area of the radiating surface. The Stefan-Boltzmann Law also informs us that low-temperature heat rejection requires an even larger radiating surface than at higher temperatures [4].

Finding surface area on a small satellite such as a 3U CubeSat for thermal radiation is a challenge since a radiator panel competes for space with solar arrays and RF antennas. As noted above for larger platforms, deployable panels are one approach. However, one can take advantage of 3D printing to fabricate surface topologies into the radiating panel to increase the surface area of the panel. Further, the addition of heat pipes embedded into the vehicle structure can be accomplished just as the RF antennas and other devices shown in this paper were. Of course fluid options are limited by the material properties of thermoplastics, much more so than traditional metallic systems.

Our Multi^{3D} printing and fabrication system will use Fused Deposition Modeling (FDM) to print the CubeSat structures using polymers such as Polycarbonate (PC) and ULTEM 9085, which are good thermal insulators. For our application, we desire materials that are thermally conductive but also electrically insulating. Our teammates at Youngstown State University and rp+m are supporting the team with 3D printing manufacturing as well as materials and process development. They have developed processes involving loading FDM-capable polymers with other materials to make composites that achieve the desired thermal, electrical, and mechanical properties. Although early in the project, the thermal management approaches for our 3U CubeSat are on track with several candidate materials under development and test.

3. *Embedded Wiring*

The team has printed wiring into 3D structures using conductive inks as well as embedding the actual wiring, and laser welding to electronic components for connectivity as depicted in Figure 5. The use of 3D printing to make unique electronics in complex geometric forms has been demonstrated in the past using conductive inks as interconnect [5-13]. Although inks are improving, limits to curing temperatures have resulted in relatively poor performance in terms of conductivity and current carrying capacity, which is required for high-frequency and high-power applications. Testing for space reliability has also shown lower quality results for inks as compared with actual wires. This is especially true if there is any requirement for flexibility in the printed item such as our cubesat structure. Recent advances in the thermal embedding of wires within thermoplastic substrates have provided printed-circuit-board-like routing densities and performance with final connections to electrical components enabled by laser welding. Moreover, embedded fine-pitch wire meshes can serve as either ground planes or patch

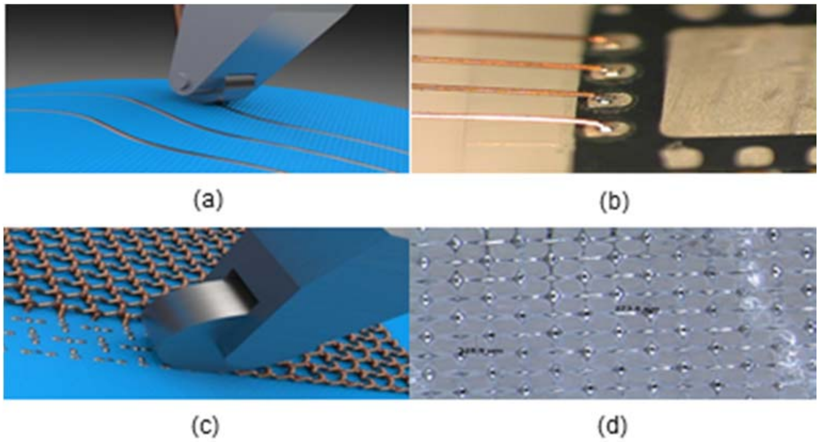

Figure 5. (a) CAD depiction of wire embedding. (b) Laser-welded component. (c) CAD depiction of embedded mesh. (d) Picture of surface after mesh embedding manufacturing technologies.

antennas. By introducing meshes within the polymer, novel attachment points can be created between polymer and metal components within larger systems to robustly join subsystems of disparate materials (e.g., welding polymers to metal structures). The uncharacterized portion of the work under this grant is the performance of embedding wiring in a printed structural wall. The funded research will look at the performance impact of that same wiring after it is embedded in a series of printed materials.

III. Communications Research

Communications research has been a critical part of the activities for both the SSTP and America Makes programs. This research can be broken down into: satellite RF communications, intrasatellite communications and phased array communications.

Satellite RF Communications

The project investigated antenna designs that can be printed directly into the walls of a spacecraft for space-to-ground links. Fabricating antennas can characterize a specific facet where additive manufacturing may improve space-to-ground smallsat communications with regards to performance, customizability, and/or cost. These include embedded wires, embedded electronics devices, non-planar conformal printing, and the use of the novel materials detailed in previous sections. The first of these antenna concepts to have been fabricated and tested is a planar 2-arm Archimedean spiral at S-band, as shown in Fig 6. Spiral designs have the advantage of being wide-band, as well as low-profile so as to not to occupy a significant volume of the satellite or require deployment mechanisms. They are also beneficial when circular polarization is desired as they are inherently right-hand or left-hand circularly polarized according to the orientation of the spiral [ref 14, 15]. The spiral was selected as the first iteration design for these characteristics given their value to smallsat applications, and is intended to demonstrate the wire embedding processes as well some beneficial applications of novel materials, specifically thermoplastics with high electric permittivity.

The spiral was designed and simulated in CST Microwave Studio and fabricated by printing a 10cm x 10cm x 0.6cm polycarbonate plate, after which the two arms of the spiral were constructed by embedding wire into the plate. An SMA connector and ground plane were added manually as shown in Fig 7, but are targets for future fabrication or embedding with 3D printing technologies. The design parameters of an Archimedean spiral are the inner and outer circumference (which define the frequency band), the number of turns or flare rate of the spiral, and the feed structure, all of which are easily configurable through the above-described fabrication processes designs or applications. A ground plane was included in the design to shield the rest of the satellite from the antenna's radiation, as well as reflect the radiation so as to increase directivity in the desired direction. A ground plane distance of 0.6cm was chosen to be representative of dimensions that may be available for an embedded antenna within a smallsat system. Traditionally, ground plane or cavity-backed spiral antennas may be loaded with absorber between the spiral and the ground plane to prevent reflections from the ground plane from interfering with the desired radiation pattern, Alternatively, when no absorber is used, the ground plane may be spaced a quarter of a wavelength ($\lambda/4$) from the spiral plane such that the reflections from the ground plane constructively reinforces radiation at a desirable frequency. In polycarbonate ($\varepsilon_r = 2.9$, $\mu_r = 0.87$), the quarter-wavelength distance at 2.1 GHz is 2.25 cm, which would occupy a significant portion of a cubesat. However, as the relative permittivity of the substrate material increases, this distance shrinks. For example, at $\varepsilon_r = 30$, $\lambda/4 = 0.7$ cm. Subsequent iterations of the design are underway to use the newly developed high-permittivity thermoplastics to demonstrate an antenna that is electrically a quarter-wavelength and therefore performs well at the desired frequencies but, through the use of innovative materials, remains physically small enough to embed on a CubeSat.

Figure 6. An S-band planar 2-arm Archimedean spiral printed into a 10cm x 10cm polycarbonate plate.

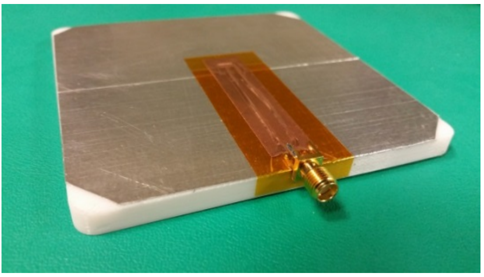

Figure 7. A 10cm x 10cm polycarbonate plate with ground plane and SMA connection added manually.

The first iteration of the spiral was characterized at NASA Glenn Research Center, 8, to measure the return loss, far-field pattern, and co- and cross-polarization patterns. 9 shows the characterization of the co- and cross-pol far-field patterns measured at 4 GHz. Although initial test results agreed with simulations, the frequency independence of the antenna within the designed band was limited due to interfering reflections from the ground plane from the 0.6 cm ground plane spacing and impedance mismatches. However, testing identified several areas where the subsequent iterations will use AM technologies to improve performance. Particularly, interfering reflections from the ground plane will be minimized while maintaining a slim profile through the use of high permittivity thermoplastics, and impedance will be matched by embedded or printable baluns. Future iterations will involve printing the antenna, metal backplane and embedding all circuitry for balancing (as well as the connectors) as part of the total printing process. At least two more iterations of the planar spiral design are ongoing to demonstrate these concepts, after which future demonstrations are planned to include non-planar, conformal designs.

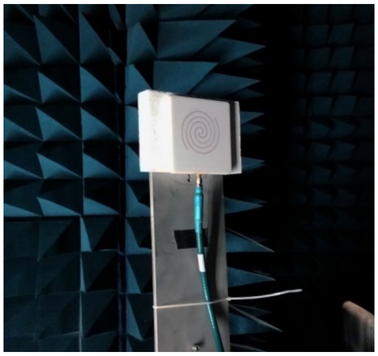

Figure 8. Printed Spiral Pattern Measurement, Far-Field Antenna Range NASA/Glenn Research Center.

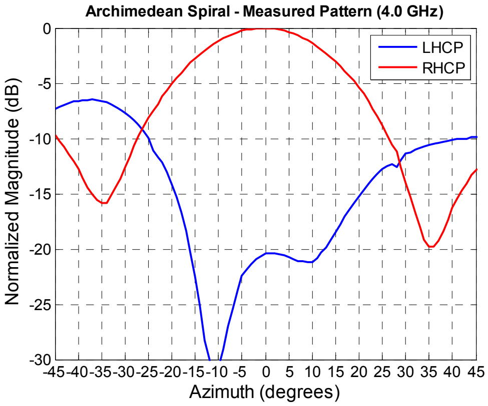

Figure 9. Measured co- and cross-polarization patterns of the spiral at 4GHz.

Intrasatellite Communications

Intrasatellite RF mesh networks are based on the Zigbee automation protocol standard 802.15 [Ref 16, 17]. ZigBee is a low-cost, low-power, wireless mesh network standard which is a possible solution for intrasatellite communications. The low cost allows the technology to be widely deployed in wireless control and monitoring applications and could easily be embedded into 3D structural walls. Low power usage allows longer life with solar panels. Mesh networking provides high reliability and more extensive range. ZigBee chip vendors typically sell integrated radios and microcontrollers with between 60 KB and 256 KB flash memory. Entire wireless networks could be embedded at strategic locations throughout the spacecraft and connectors provided for module integration. ZigBee operates in the industrial, scientific and medical (ISM) radio bands: 868 MHz in Europe, 915 MHz in the USA and Australia and 2.4 GHz in most jurisdictions worldwide. Data transmission rates vary from 20 kilobits/second in the 868 MHz frequency band to 250 kilobits/second in the 2.4 GHz frequency band. The ZigBee network layer natively supports both star and tree typical networks, and generic mesh networks as in Figure 10. Every network must have one coordinator device, tasked with its creation, the control of its parameters and basic maintenance. Within star networks, the coordinator must be the central node. Both trees and meshes allow the use of ZigBee routers to extend communication at the network level.

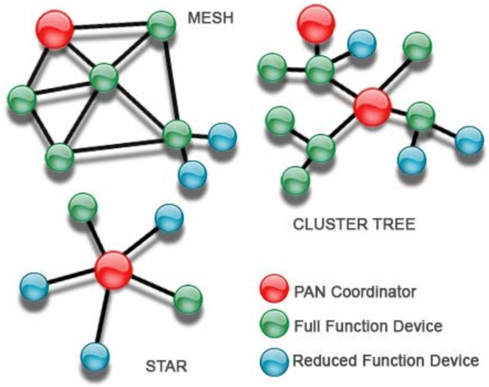

Figure10. Potential ZigBee Networks.

ZigBee builds upon the physical layer and media access control for low-rate WPANs. The IEEE specification goes on to complete the standard by adding four main components: network layer, application layer, ZigBee device objects (ZDOs) and manufacturer-defined application objects which allow for customization and favor total integration. These ZDOs are currently being embedded into our 3D printing process for testing applications. .

Because ZigBee nodes can go from sleep to active mode in 30 ms or less, the latency can be low and devices can be responsive which could be acceptable for many satellite sensor applications.

Phased Array Communications

Our communications research is also investigating 3D-printed optical phased array systems that can function in space or adverse terrestrial environments. One of the major challenges for 3D printing these type antenna systems is combining different kinds of materials inside the 3D printer. For this application, we need to be able to combine metal electronics and non-metal materials into working RF phased array communications elements. We collaborated with the Optical Sciences Company (tOSC) and the University of Texas at El Paso (UTEP) to explore the possibilities of using 3D printers to generate phased array antennas and related electronics. Our initial focus has been on SATCOM applications, with ubiquitous RF communications systems in a phased array configuration.

This work involves creating advanced machines for 3D printing that will be able to print in one hybrid material, stop in the middle of the process, add electronics, and then continue printing in an entirely different material. The Multi^{3D} System being developed on the America Makes contract has that capability. For our phased array application, candidate materials include Zeonex, Polyimide, Tungsten, SrTi03 and CaTi03. Supporting the phased array design, we have postulated that radiation patterns can be formed by unique shapes with metal backing (solid or mesh). In addition, optical components such as Micro-Electro-Mechanical Systems (MEMS) could be embedded during the printing process. We have demonstrated that by 3D printing antennas and embedding the cabling into the structure, typical wire damage can be averted, which will increase antenna reliability. The work performed in this activity is essential for creating the advanced antennas needed for small-SWAP communication systems. In printing a 3D high-frequency array, it is possible to reduce size while at the same time achieving gains in precision pointing accuracy and nulling interference.

Figure 11 illustrates how these technologies are capable of fabricating intricately detailed substrates in multiple materials. The motivations and resulting benefits for this innovative hybrid technique for integrating electronics include:

1) full design freedom in terms of component placement, material deposition and gradient, interconnect routing and system geometries, and

2) antenna customization in which each fabricated device can be unique in terms of system envelope.

Our AM research will eventually produce nanosatellites that are robust, and will incorporate complex geometries of antenna designs that support the phased array requirement. This will provide satellite developers an affordable, on-demand capabilities for reconnaissance, persistent surveillance, and especially communications.

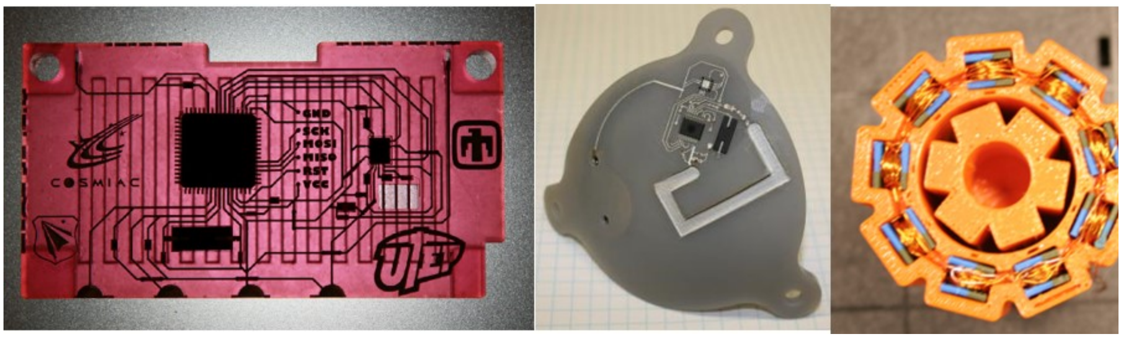

Figure 11. Examples of parts made using Multi-material Additive Manufacturing including: (left) a printed IMU launched in to Low Earth Orbit in 2013 in a UNM CubeSat, (middle) a helmet insert with wireless acceleration detection system both of which were fabricated with stereolithography substrates and conductive ink traces. The final picture (right) is a motor in-process with thermoplastic, magnets and wires.

IV Conclusion

Enabled by two ongoing contracts with NASA/GRC and America Makes, the team has performed advanced applications of additive manufacturing techniques to exploit embedded electronics in spacecraft structures. A series of candidate materials were investigated and assessed for their electrical properties, radiation shielding, thermal properties, and general structural performance in a printed mode. Several are under further investigation to apply embedded electronics which will allow Industry to reduce internal space requirements typically saved for components, antennas, wiring, etc. Thus is important in small satellites like a cubesat where internal space is a premium. The work underway at UTEP, Keck Center to develop a robotic multi functioning machine to automate the process will further advance this new exciting use of Additive Manufacturing in space applications.

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