Using Additive Manufacturing to Print a CubeSat Propulsion System

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Small satellites, such as CubeSats, are increasingly being called upon to perform missions traditionally ascribed to larger satellite systems. However, the market of components and hardware for small satellites, particularly CubeSats, still falls short of providing the necessary capabilities required by ever increasing mission demands. One way to overcome this shortfall is to develop the ability to customize every build. By utilizing fabrication methods such as additive manufacturing, mission specific capabilities can be built into a system, or into the structure, that commercial off-the-shelf components may not be able to provide. A partnership between the University of Texas at El Paso, COSMIAC at the University of New Mexico, Northrop Gruman, and the NASA Glenn Research Center is looking into using additive manufacturing techniques to build a complete CubeSat, under the Small Spacecraft Technology Program. The W. M. Keck Center at the University of Texas at El Paso has previously demonstrated the ability to embed electronics and wires into the addtively manufactured structures. Using this technique, features such as antennas and propulsion systems can be included into the CubeSat structural body. Of interest to this paper, the team is investigating the ability to take a commercial micro pulsed plasma thruster and embed it into the printing process. Tests demonstrating the dielectric strength of the printed material and proof-of-concept demonstration of the printed thruster will be shown.

Nomenclature

AM   = Additive manufacturing
AWG = American wire gage
CAD = Computer aided design

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CNC	=	Computer Numerical Control
DLMS	=	Direct laser metal sintering manufacturing
FDM	=	Fused deposition modeling
GRC	=	NASA Glenn Research Center
LEO	=	Low Earth orbit
PC	=	Polycarbonate
PTFE	=	Polytetrafluoroethylene
SLA	=	Stereolithography manufacturing
SLS	=	Selective laser sintering manufacturing
SSTP	=	Small Spacecraft Technology Program
STMD	=	Space Technology Mission Directorate
UTEP	=	University of Texas at El Paso
1U	=	A 1-unit CubeSat. Multiples indicate number of units (e.g. 6U would be a 6-unit CubeSat)
μPPT	=	Micro pulsed plasma thruster

I. Introduction

SMALL satellites, such as CubeSats, are increasingly being utilized to perform missions traditionally ascribed to larger satellite systems. NASA defines small satellites as spacecraft with masses under 180 kg, and can be further distinguished into mini- (>100 kg), micro- (10–100 kg), nano- (1–10 kg), and picosatellites (0.1–1 kg).[1] The Space Technology Mission Directorate (STMD) Small Spacecraft Technology Program oversees a suite of programs and missions devoted to these class of satellites.

CubeSats are a special class of nanosatellite. One cubesat unit (1U) has dimensions of 10 cm x 10 cm x 11 cm. CubeSats have been built in various combinations of the 1U form up to 6U sizes, with some examples shown in Figure 1. Universities, governments and commercial business are increasingly turning to CubeSats as ready-to-build systems that provide inexpensive and relatively quick access to space for research and development (R&D) and, now, operational missions such as earth observations, deep space and asteroid intercepts.[2] However, the market of components and hardware for small satellites, particularly CubeSats, still falls short of providing the necessary capabilities required by ever increasing mission demands. Typically many CubeSat components are commercially available as off-the-shelf standard components provided by a limited number of suppliers.

One way to overcome this shortfall is to develop the ability to customize every build. By utilizing fabrication methods such as additive manufacturing, mission specific capabilities can be easily built into a system that commercial off-the-shelf components may not be able to provide, or not able to provide in an optimized manner. While some efforts have already looked into using AM to fabricate components of CubeSat systesms,[3-5] to date none have looked into fabricating the complete, integrated system. As part of the Small Satellite Technology Program in NASA's STMD, NASA Glenn Research Center (GRC), the University of Texas at El Paso W. M. Keck Center (UTEP), Northrop Gruman Corporation (NGC), and the University of New Mexico (UNM) COSMIAC Center have teamed together to examine how additive manufacturing might be used to print a complete, functional CubeSat.[6]

II. Use of Additive Manufacturing

A. Background on Additive Manufacturing

Additive manufacturing (AM), or 3-dimensional (3-D) printing, is a manufacturing technique where material is progressively added, layer by layer, to fabricate geometrically complex structures. Historically, additive manufacturing techniques were initially used as a method for rapid prototyping, since builds could be rapidly produced with near-net shape features but lacked sufficient structural strength or ideal surface finishes. However, recent advances in fabrication techniques have provided much more promising material properties and finishes from AM fabricated parts. Initially developed for plastics and polymers, the field has developed to include a wide range of materials, including metals and ceramics. Various techniques, including materials extrusion, stereolithography, selective laser sintering (SLS), or direct laser metal sintering (DLMS), are currently used to create the individual layers and build parts.

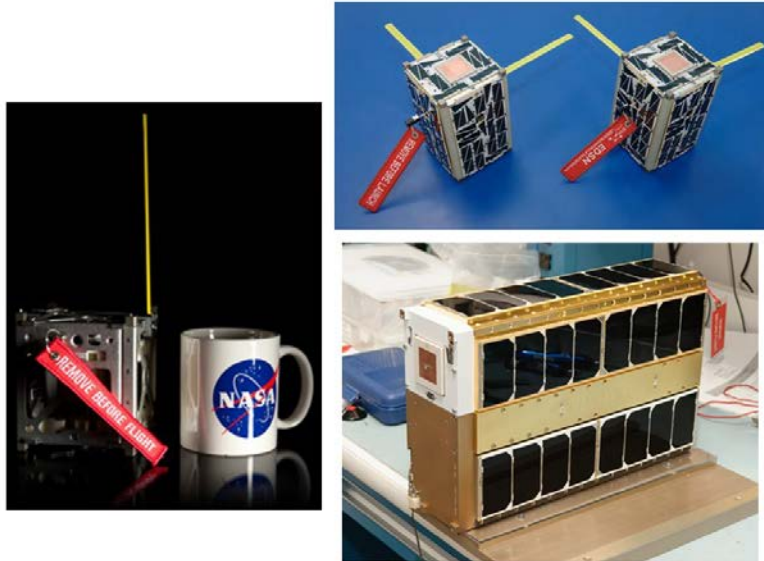American Institute of Aeronautics and Astronautics

Figure 1: Examples of various size CubeSats. Left: 1U "PhoneSat"; Top Right: 1.5U "EDSN Spacecraft"; Bottom Right: 6U "EcAMSat" (All images credit: NASA Ames Research Center)

In the materials extrusion process, a thermoplastic material is heated and extruded by a print-head to deposit a fine thread of material. The print-head follows the programmed path for each layer, laying down material along the path as defined, building the part up layer by layer. The process is further aided by "art-to-part" computer aided design (CAD) software, wherein a designer can design a part using most commercial 3-D modeling software, and then convert the part model to a model comprised of program defined slices, with each slice comprising one layer of the extrusion build. As the patents for the original extrusion process have now expired, low cost desktop systems are proliferating and increasing the participation of the general public in additive manufacturing with a fabrication process that avoids the handling and operational difficulties of powder beds and high-powered laser systems. Additionally, the large selection of compatible polymer and thermoplastic materials, along with the use of additives, provides the designer with sufficient options to address mechanical requirements, including thermal management and structural integrity.

The approach discussed in this paper is based on materials extrusion enhanced with a suite of complementary manufacturing technologies including wire embedding, micromachining and "pick and place" to create multi-functional devices. The W. M. Keck Center at the University of Texas at El Paso (UTEP) has developed the ability to incorporate electrical components and sensors directly into the material extrusion process.[7] Because of the maturity of the process, the wide selection and relatively low cost of available materials, and the ability to further embed wire structures into the materials during fabrication, materials extrusion was identified as the preferred fabrication technique for this work.

B. Embedded Electronics

With the increased interest in 3-D printing, new applications – particularly for space environments – have been identified for 3-D printed structures. Particularly, increased interest in incorporating electromagnetic structures and electronic components into 3-D printed objects has resulted in research to incorporate a variety of wiring, interconnect, sensors, microcontrollers and batteries directly into a 3-D printed structure.[6-14] Traditional 3-D printed electronics have been focused on the micro-dispensing of electrically conductive inks. However, these inks have demonstrated relatively poor current carrying capacity and conductivity when sintered at temperatures under 550°C.[15] When utilizing polymeric 3-D printing platforms, sintering temperatures must be confined to the deflection temperature of the dielectric structure. To improve upon these limitations, this work investigates embedded fully dense copper wires, which do not require heat treatment. These wires provide the bulk conductivity of copper, are commercially available, are cost effective and exhibit higher performance compared to conductive inks. Figure 2 shows embedded electronics in a 3-D printed structure, while Figure 3 shows fully encapsulated components in a materials extrusion printed part.
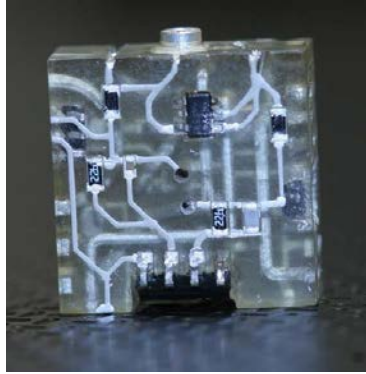
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Figure 2: 3-D printed structure with embedded electronics (from Ref. 13)
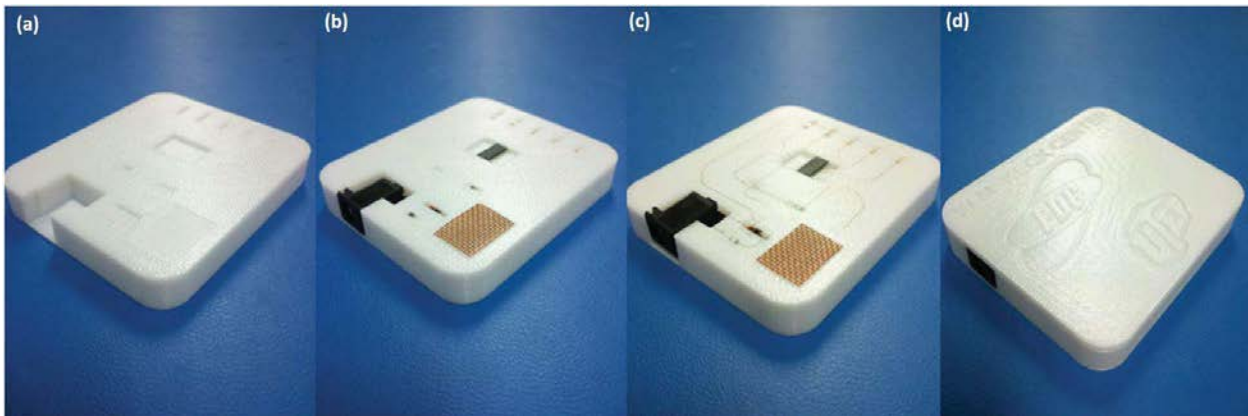

Figure 3: Fully encapsulated capacitive sensor fabrication procedure. This sensor represents proof of concept for embedded electronics and bulk conductive interconnects in fully encapsulated extrusion based 3D printing. (a) Polycarbonate (PC) substrate with recesses designed for all electronic components. (b) Components arranged in in the PC substrate. (c) Electrical components with corresponding embedded wiring. (d) Completed capacitive sensor with fully embedded wiring, diodes, LEDs, resistors, and a microcontroller (from Ref. 7)

C. Applications to Spacecraft

By definition and requirement, CubeSats are mass and volume constrained.[16] CubeSats are usually fabricated from off-the-shelf components, piecemeal. A structural frame holds various components, circuit boards and the wiring needed to communicate between boards and components. A typical 1U CubeSat build is shown in Figure 4. When building more complex structures, such as multiple-U spacecraft, it becomes increasingly difficult to effectively route the various wires and components in such a volume limited space. Figure 5 illustrates the complexity of wiring that can occur in a 6U CubeSat structure.
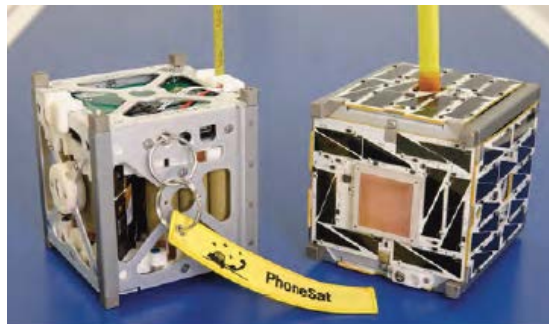

Figure 4: NASA PhoneSat, a 1U CubeSat build. Left: structural frame with internal boards and components shown. Right: completed CubeSat with solar panels attached. (credit: NASA Ames Research Center)
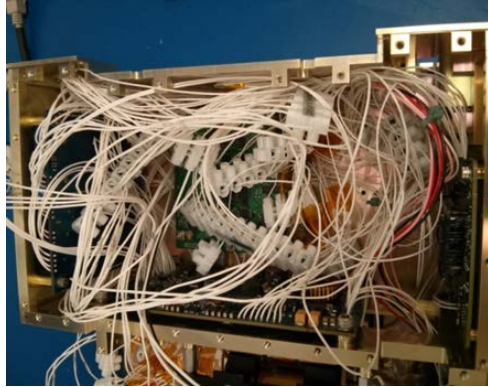
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Figure 5: A 6U CubeSat prototype, showing the complexity of wiring internal to the structure.[6]

It would be advantageous for a spacecraft designer to be able to utilize the structure of the spacecraft to incorporate wiring and other components, in order to free up valuable space internal to the spacecraft. Because of the scale of small spacecraft and their traditional one-off nature, AM is an attractive fabrication technique. The recent advances in AM and embedded electronics provides the designer with the ability to more effectively utilize space within the spacecraft structure, as well as the ability to develop these small-satellite structures at reduced cost and schedule due to the rapid build nature of AM. Due to the proliferation of art-to-part CAD software, a user can now create a design on their computer and print out the majority of structure and components in a single on-demand, non-assembly process, significantly reducing the amount of touch labor and additional components required to assemble a functional end-use system. To date, numerous efforts have already explored the possibility of using AM to fabricate components for CubeSat applications.[4, 5, 17-19] The next major hurdle in developing this effort is how to intelligently embed items such as propulsion, antennas, health monitoring, and other electronic components into the printed structure. Thus a more complete system can be built in a single process step. Rather than just using AM to print specific components, this effort will focus on using AM to fabricate a complete, integrated system.

One area where significant work has been done to investigate the use of AM for CubeSats is on the subject of embedded antennas.[6] Many CubeSats flown to date have utilized some form of deployable whip-style antenna (ref. Figure 1). However, AM techniques are able to increase the integration of subsystems into the CubeSat structure itself, allowing a significant portion of components (e.g. antennas, feed networks, connectors, electronics) to be located within the structural walls of the satellite and thus increasing available payload space. AM also has the benefit of facilitating rapid prototyping and testing of designs which complements the relatively rapid design cycle of many CubeSats. This work has included studies of additively manufactured antennas and has looked at antennas fabricated by ultrasonically embedding conductive materials such as wire and mesh into a printable thermoplastic substrate. This further demonstrates how AM can more effectively utilize the structural space in a CubeSat. Some tested designs are shown in Figure 6: (a) a 2.1 GHz circularly polarized Archimedean spiral dipole antenna which was also tested with a microstrip balun and phase shifter integrated into the polycarbonate structure behind the spiral; and (b) two planar but non-parallel microstrip patches at a 10° offset with ground plane formed by embedding copper mesh in the thermoplastic behind the patches.
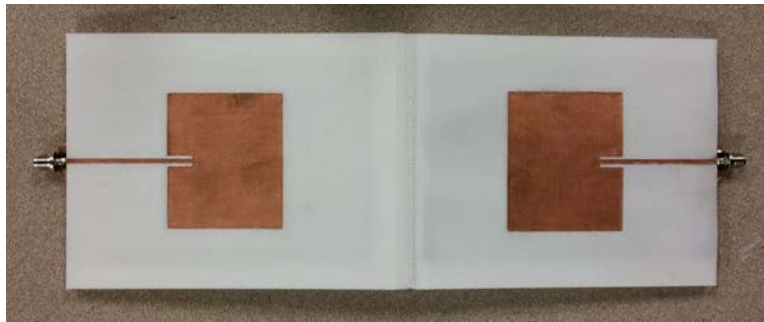
(a.)   (b.)

Figure 6: (a) Two-arm Archimedian spiral dipole antenna printed into polycarbonate substrate with integrated microstrip balun and phase shifter; (b) two non-parallel microstrip patch antennas utilizing the polycarbonate

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III. Propulsion Concepts

The primary focus of this paper, propulsion, is being examined by the team as a required asset for small-satellite missions, especially for CubeSats. Interest in propulsion systems for small spacecraft use is rapidly gaining interest.[19, 20] While the focus of this project is not specifically on developing the propulsion systems themselves, an objective is to see how to incorporate such systems into the integrated spacecraft using AM techniques. Thus, the team has explored a few potential propulsion system concepts for inclusion into an AM fabricated CubeSat.

In order to define which propulsion system concept to use, the team needed to identify what the propulsion system would be primarily used for. A delta-Velocity (ΔV) system used for orbit insertion and translation could have significantly different features than a system used primarily for reaction control and pointing. In addition, there are a number of potential propulsion concepts being developed specifically for CubeSats. References 17 and 20-25 are just a few references of innumeral sources which discuss potential propulsion concepts for CubeSats. After considering the limitations of available spacecraft volume, maturity of existing technologies, and feasibility of fabricating using a materials extrusion processes, the team settled on an application for reaction control and momentum wheel desaturation. This application could be served by several possible propulsion system concepts which are potentially feasible to print, including cold-gas systems or some electric propulsion systems. These systems are uniquely suited for the role of satellite attitude control and pointing due to their low thrust and small impulse bits.

Presently, CubeSats are often free-floating satellites, with magnetic torque rods or momentum wheels typically available for attitude control in low Earth orbit (LEO).[19] Both of these attitude control systems, torque rods and momentum wheels, have their limitations, however. Magnetic torque rods rely on Earth's magnetic field, and would thus be potentially ineffective at higher orbits or lunar/outer planet missions. This would limit CubeSats to LEO and effectively bar their use from other exploratory missions. Momentum wheels, which use a spinning wheel to provide attitude controlling torque, are prone to saturation wherein the wheels spin up to a limiting velocity, and must then be counteracted by another system in order to de-spin back to a usable speed. Saturation of these wheels is common, as a number of forces (such as drag forces) continue to act upon a spacecraft during orbital periods. Without a secondary attitude control system to desaturate the momentum wheels, a CubeSat would be limited in useful life, reaching a point where any tumble could no longer be controlled. Missions which would otherwise be limited due to momentum wheel saturation could now be extended to an ever increasing duration. The challenge, of course, is how to package a propulsion system into such a volume limited spacecraft such as a CubeSat. Utilizing AM provides a means to neatly package a propulsion system within the structure, reserving valuable internal space for sensors and other scientific payloads. While the focus of the effort is on an integrated, complete-build system, many concepts will have some touch labor involved in the process, regardless of which propulsion system is chosen. However, by utilizing AM, much of this touch labor can be significantly reduced from traditional build configurations.

Cold-gas systems are a relatively simple propulsion system, relying only on a pressurized tank and valve/nozzle to expel ambient gas out for a propulsive thrust. They offer a benign system suitable for secondary payload considerations.[19] The team initially considered cold-gas systems as a means to provide modest thrust (mN's) while still offering a system that can be easily fabricated as part of the overall spacecraft structure. It was estimated this type of system could provide 10's of m/s of delta-V, depending on payload mass, sufficient for proximity operations (translation around a small fixed body such as another satellite) and reaction control purposes. Figure 7 shows an early concept of what a printed cold-gas propulsion system integrated with the spacecraft structure might look like in a 1.5U volume. It should be noted this was an early concept as a bolt-on unit to another payload, and not optimized for internal volume considerations.

However, one drawback of cold-gas or chemical propulsion is the required high pressure (up to ~2.75 MPa [400 psia]) needed for most propellants to provide sufficient ΔV when considering blow-down systems. Because this effort was focused on the inclusions of electronics and circuits into the structure, the build process was limited to materials extrusion process as was discussed earlier, which has more difficulty sufficiently sealing parts.[26] It is recognized here, other papers have noted success with fabricating pressurized systems for cold-gas applications utilizing stereolithography processes (SLA),[18] but applying that method was outside the scope of this activity. Thus, another propulsion concept was identified which did not require the high storage pressures of cold-gas or chemical propulsion systems.

While various electric propulsion concepts are available, micro pulsed plasma thrusters (μPPT) offer a system which can be tightly packaged, easily printed, and that provides sufficient propulsive capabilities for operations like attitude control.[27-29] There are a couple of μPPT designs which are suitable for inclusion into a CubeSat design. The first, referred to here as the Surrey design,[29] is a μPPT concept that does not use Polytetrafluoroethylene (PTFE) as is common in many PPTs. A conceptual schematic of Surrey thrusters in a 3U CubeSat structure is shown in Figure 8.
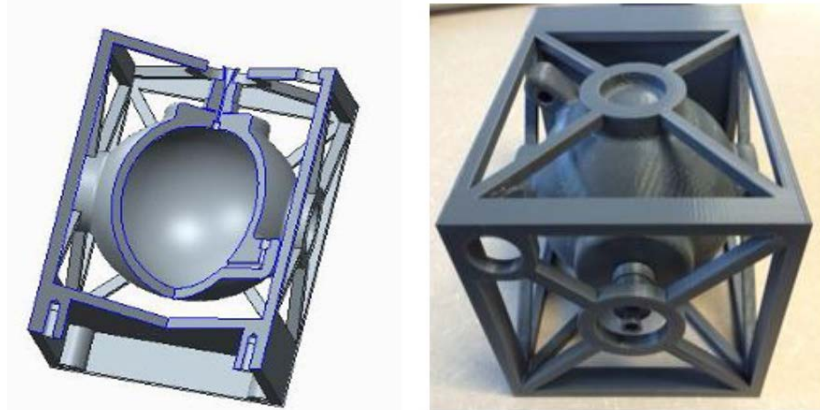
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Figure 7: Early concept cold-gas printed CubeSat module. Left: CAD model; Right: Printed model using material extrusion process

In this concept, applying high voltage across the blades (electrodes) of the thruster creates a spark. The spark ablates a small portion of the electrode, and electrostatic forces expel the material to create a thrust force.

The second, a more tested type,[27, 28] is the Busek PTFE stick design referred to as a co-axial μPPT. Figure 9 shows a conceptual drawing of what a co-axial μPPT could look like. Here, a rod of PTFE holds one electrode, while a metal sheath provides the second electrode. Applying high voltage across the electrodes produces a spark, which ablates PTFE material. Electrostatic forces cause the PTFE to be expelled, creating a thrust force. Because of commercial availability and historical data to compare with, the team has focused on utilizing the co-axial style μPPT.
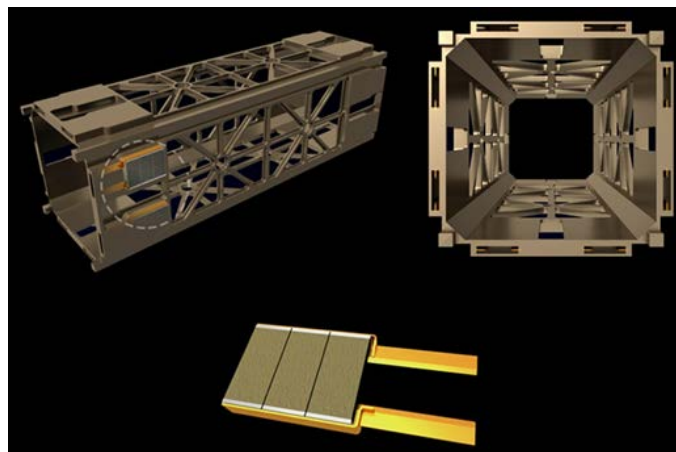

Figure 8: Concept drawing of Surrey design μPPT embedded into CubeSat structure. Top: Thrusters in CubeSat structure. Bottom: Detail of Surey μPPT thruster.
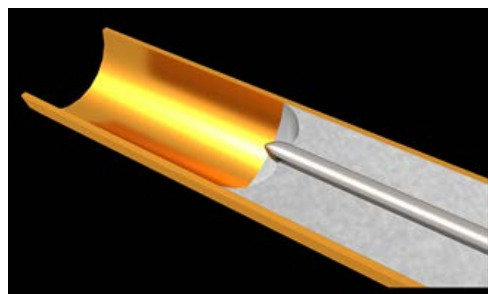

Figure 9: Concept drawing (cut-away) of co-axial μPPT design

IV.   Preliminary Results

To date the team has been investigating how the coaxial μPPT concept could be reassembled into an AM printed CubeSat wall. The team identified a commercially available product, a Busek μPPT device, and sought to embed it into a printed structure along with the required electrical connections. While the thruster itself is not printed in the process, being able to include it, along with wiring, is a critical next step to developing a integrated build process. Two factors were identified for validating the success of embedding these thrusters into the printed structure. The first is ensuring that the dielectric strength of material is sufficient to prevent arcing through the material as the thruster fires. The second is verifying the thruster continues to operate after being exposed to the high temperatures of the printing process. It should be noted that any testing results described here are simply functional and proof-of-concept, and should not be considered suggestive of the performance of the commercial thruster units, as this application is outside the designed scope and handling of the commercial product.

The testing specimens used in this work were fabricated using the Multi^{3D} system located at The University of Texas at El Paso, shown in Figure 10. This system incorporates a 6-axis robot, two Stratasys FDM 400mc 3-D printing systems, and a combination Computer Numerical Control (CNC) machining, micro-dispensing, wire-embedding system. This Multi^{3D} thermal embedding system operates by applying both thermal energy and downward pressure in order to submerge the copper wire below the surface of the 3-D printed part. Due to the non-fully dense nature of the printed part, by submerging the wire, a planar surface is left which allows for subsequent fabrication as there are no obstructions on the last build layer. The Multi^{3D} 6-axis robot seamlessly transports the 3-D printed part between fabrication bays using a heated thermal envelope to prevent warping within the structure by avoiding thermal cycling. The resulting monolithic 3-D printed part can incorporate all of the traditional elements of a 3-D printed structure, as well as electronics, microcontrollers, and antennas structurally integrated internally.
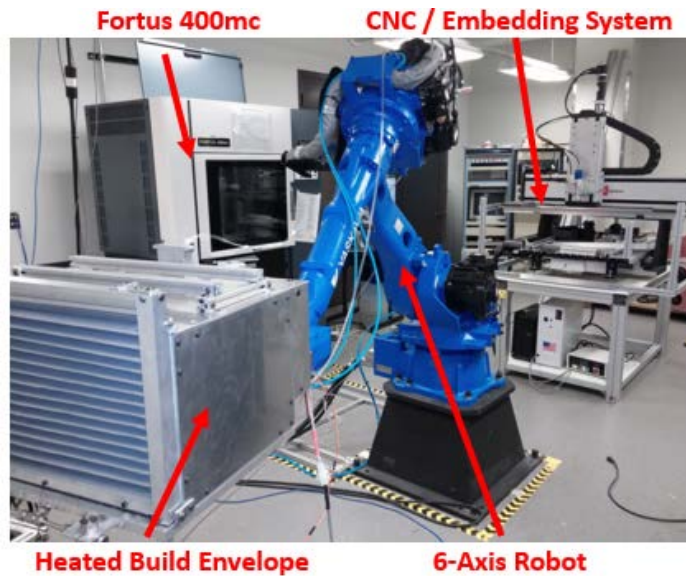

Figure 10: Multi^{3D} system showing FDM 400mc 3-D printer, combination CNC/wire embedding system, heated build envelope, and 6-axis robot.

A. Dielectric Strength Tests

Since μPPTs require high voltage (~ 1.5 kV) across the electrodes to operate, understanding the dielectric strength of the printed components is critical to verifying the operation of the embedded thrusters. Thus, initial tests on the dielectric strength of the printed materials were conducted. For dielectric testing, polycarbonate (PC), nylon 12, and ULTEM 9085, were chosen due to their mechanical, electromagnetic, and outgassing properties. PC was used for initial testing of the embedded micro-pulsed plasma thruster (μPPT). A total of 30 dielectric structures, shown in Figure 11, were printed to act as dielectric strength / leakage test coupons for all three dielectric matierals. All materials and test coupons were printed with T16 tip sets (254μm raster separation). For these coupons, 28-AWG bulk copper wires were embedded for dielectric testing, as these are the required gages for the commercial thruster connections. Distances between wire samples were 0.159; 0.318; 0.795; 1.59; 3.18; 4.76; 6.35; and 9.53 mm (0.00625; 0.0125; 0.0313; 0.0625; 0.1250; 0.1875; 0.2500; and 0.3750 inches, respectively) A voltage was then applied across parallel embedded wires, and the resistance between wires measured. Ideally, the resistance should be high, indicating

no electrical current through the dielectric material. The voltage was increased until the resistance dropped, indicating arcing (breakdown) through the dielectric material. The maximum voltage before breakdown vs. distance between wires gives the dielectric strength of the material.
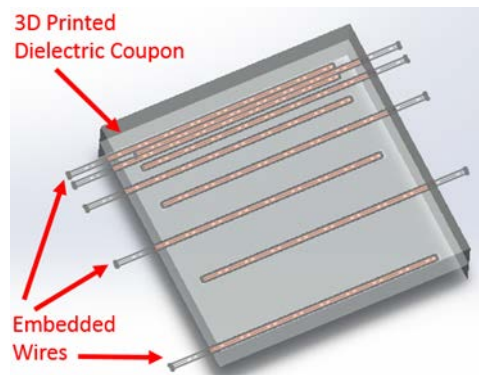

Figure 11: Drawing illustrating the dielectric strength test concept piece. Wires are embedded at multiple horizontal distances to facilitate determining the dielectric strength of the AM part.

Dielectric testing was conducted on polycarbonate samples, but the nylon samples and the Ultem samples were not tested in time for this work. For the polycarbonate samples tested, raster direction was ±45 deg. relative to the placement of the wires and testing was conducted in vacuum. For reference, the minimum expected dielectric strength of the polycarbonate material is 80 V/mil. That value represents the bulk material property for an injection mold process, with no porosity in the part. It is expected this value would be lower for a 3-D printed part due to the inherent porosity introduced by the material extrusion printing process. Samples with different raster orientations relative to wires were printed to determine if porosity impacted dielectric strength, though these were not tested in time for this work. Measurements taken with an Extech MG500 digital high voltage insulation tester. The tester had a maximum voltage generation of 10kV. Table 1 lists the data collected from initial dielectric tests.

Table 1: Data from dielectric testing on 45 deg. polycarbonate samples

Wire Separation	Resistance at 5 kV	Breakdown	Expected Breakdown
4.76 mm (0.1875 in.)	25.1 GΩ	7.5-10 kV	15 kV
9.53 mm (0.375 in.)	22.8 GΩ	>10 kV	30 kV

Results from the dielectric strength tests show that breakdown occurred at slightly lower voltages than the published material values. However, even at the closer distance of 4.76 mm the breakdown was well above the expected operation voltage of 1.5 kV. While the remaining dielectric samples are expected to be tested in future test series, the initial series provides sufficient confidence that the printed material will maintain sufficient dielectric strength to survive operation of the thrusters without breakdown.

B. Thruster Firing Tests

For the thruster firing tests, a flat panel test piece was constructed that would include an embedded µPPT thruster and interface with a µPPT thrust stand. This panel contained a single µPPT stick, and the necessary wiring to provide conductors to the stick. The thruster firing tests described here are proof-of-concept, so the design is not indicative of emplacement in a CubeSat, and the charge pump circuit necessary to operate the thruster is external to the thruster panel. In order to facilitate fabrication, a ramp was included onto the thruster panel so the wires could be readily connected to the thrusters and routed along the panel. Figure 12 shows a drawing of an embedded thruster in a panel, with the wiring required to operate the thruster, while Figure 13 shows photographs of printed panels before test.
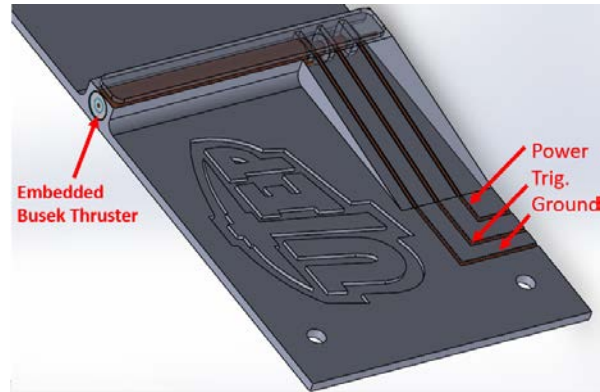
Figure 12: CAD based renderings of the embedded Busek µPPT in a 3-D printed polycarbonate thermoplastic and embedded wires of multiple horizontal seperations used in dielectric strength testing.

Tests of the thrusters in the printed panels were conducted at Busek. The panels were tested at vacuum conditions (~10^{-5} torr) and were run with lab electronics. Due to schedule and funding limitations, quantitative data on thrust or power/current were not collected, but the printed thruster panels were tested around 800-1500 V, 2 J, and 2 Hz. Photographs and video were captured to demonstrate proof-of-concept operation. Figure 14 shows a photograph collected from the test series demonstrating operation of the thruster in the printed panel. Figure 15 shows a photograph post-test, indicating that no degradation of printed material around the thruster exit was observed. Some discoloration near one of the wire junctions was observed, which is believed to be due to arcing between the ground wire and the copper sheath of the thruster, as seen in Figure 16. This arcing did not prevent operation of the thruster, nor did it cause a limit to the test operation. It is not clear at this time if the arcing is due to the printing process or another cause. The thruster continued to fire throughout the test duration.and the arcing phenomenon is expected to be investigated and rectified in future tests
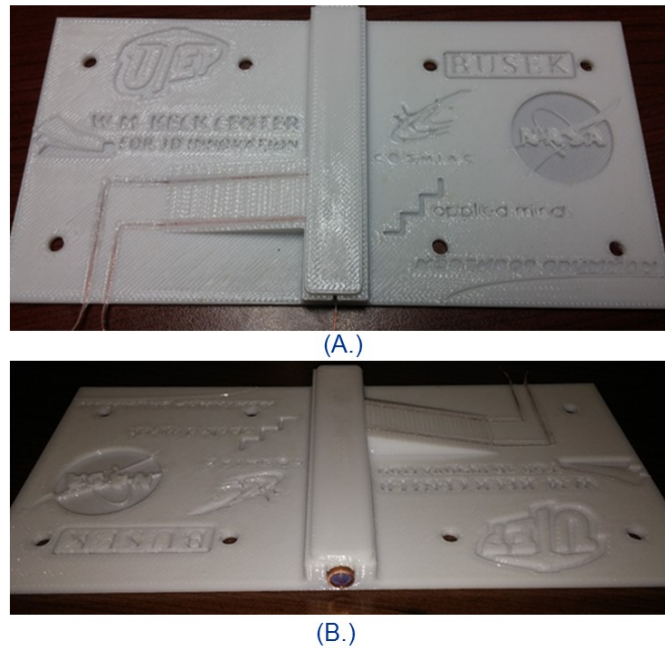

(A.)

(B.)

Figure 13: Photographs of embedded µPPT thrusters. (A.) Top view (B.) Thruster end view

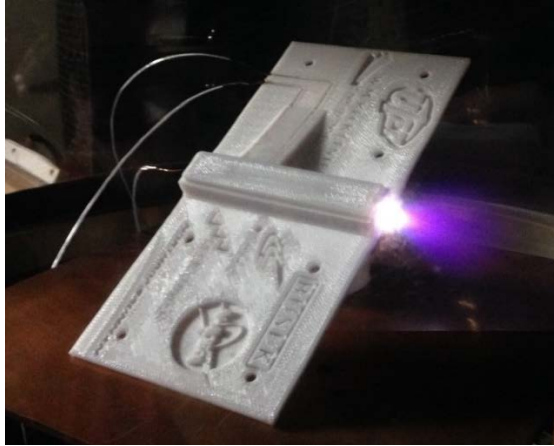American Institute of Aeronautics and Astronautics

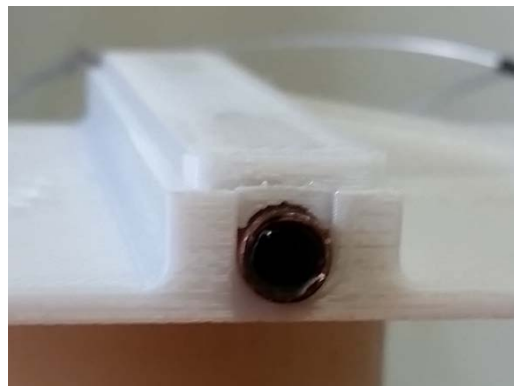*Figure 14: Photograph of printed µPPT thruster panel firing at vacuum conditions.*

Figure 15: Post-test image of µPPT thruster. No external signs of degradation to the supporting printed material near thruster exit is observed.

Figure 16: Light discoloration observed at wire junction due to arcing

V. Conclusion

The ability to embed complex functioning components like propulsion (e.g. µPPTs) into 3-D printed structures is critical to small-satellite users who are looking to exploit AM in a confined space. The work described in this paper, contributes significantly to that goal. Possible propulsion systems were investigated to determine their feasibility to be printed using a materials extrusion process. A µPPT system was identified as having the best characteristics for successful embedding into a printed CubeSat structure. Initial tests with dielectric testing indicates that while dielectric strength of the printed material may be lower than expected, it is still sufficient for the voltages of operation

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expected for the Busek µPPT chosen for this work. Additionally, initial testing in vacuum demonstrated that the printed thrusters were operational without significant degradation to the surrounding material. Further tests of the printed thrusters and dielectric testing will provide greater confidence in the operation of these thrusters once printed into a material. This work demonstrates that it is quite possible to take existing propulsion system designs and incorporate them into a printed CubeSat body, leading to the possibility of one day printing a complete operational CubeSat.

Acknowledgments

References

[1] NASA Space Technology Mission Directorate, "Small Spacecraft Technology Program Overview," http://www.nasa.gov/directorates/spacetech/small_spacecraft/smallsat_overview.html, April 2015.

[2] European Space Agency, "CubeSats Offered Deep-Space Ride on ESA Asteroid Probe," http://www.esa.int/Our_Activities/Space_Engineering_Technology/CubeSats_offered_deep-space_ride_on_ESA_asteroid_probe, 14 April 2015.

[3] Fluitt, D., *Feasibility Study into the Use of 3D Printed Materials in CubeSat Flight Missions*, M.S. Thesis, California Polytechnic State University, June 2012.

[4] Moore, G., Holemans, W., Huang, A., Lee, J., McMullen, M., White, J., Twiggs, R., Malphrus, B., Fite, N., Klumpar, D., Mosleh, E., Mashburn, K., Wilt, D., Lyke, J., Davis, S., Bradley, W., Chiasson, T., Heberle, J. and Patterson, P., 2010, "3D Printing and MEMS Propulsion for the RAMPART 2U CubeSat," SSC10-III-8, *Proceedings of the 24th Annual AIAA/USU Conference on Small Satellites*, in *TidBits*, http://digitalcommons.usu.edu/smallsat/2010/all2010/22/.

[5] Schmuland, D., Carpenter, C., Masse, R. and Overly, J., "New Insights into Additive Manufacturing Processes: Enabling Low-Cost, High-Impulse Propulsion Systems," SSC13-VII-4, *27th Annual AIAA/USU Conference on Small Satellites*, 10-15 August 2013.

[6] Kwas, A., MacDonald, E., Muse, D., Wicker, R., Kief, C., Aarestad, J., Zemba, M., Marshall, B., Tolbert, C. and Connor, B., "Enabling Technologies for Entrepreneurial Opportunities in 3D printing of SmallSats," SSC-14-III-7, *28th AIAA/USU Conference on SmallSats*, Logan, UT, August 5, 2014.

[7] Shemelya, C., Cedillos, F., Aguilera, E., Espalin, D., Muse, D., Wicker, R. and MacDonald, E., "Encapsulated Copper Wire and Copper Mesh Capacitive Sensing for 3-D Printing Applications," *IEEE Sensors Journal*, Vol. 15, No. 2, February 2015, pp. 1280-1286, doi: 0.1109/JSEN.2014.2356973.

[8] Castillo, S., Muse, D., Medina, F., MacDonald, E. and Wicker, R., 2009, "Electronics Integration in Conformal Substrates Fabricated with Additive Layered Manufacturing," *Proceedings of the International Solid Freeform Fabrication Symposium*, University of Texas in Austin, 3-5 August 2009, http://sffsymposium.engr.utexas.edu/Manuscripts/2009/2009-63-Castillo.pdf.

[9] Gutierrez, C., Salas, R., Hernandez, G., Muse, D., Olivas, R., MacDonald, E., Irwin, M. D., Wicker, R., Newton, M., Church, K. and Zufelt, B., "CubeSat Fabrication through Additive Manufacturing and Micro-Dispensing," *7th International Conference and Exhibition on Device Packaging*, Scottsdale, Arizona, 8 – 10 March, 2011, available from: http://www.cosmiacpubs.org/pubs/IMAPS2011_CassieGutierrezUTEP.pdf.

[10] Kief, C. J., Aarestad, J., MacDonald, E., Shemelya, C., Roberson, D., Wicker, R., Kwas, A. M., Zemba, M., Avery, K., Netzer, R. and Kemp, W., "Printing Multi-Functionality: Additive Manufacturing for CubeSats," AIAA 2014-4193, *SPACE Conferences & Exposition*, San Diego, CA, 4-7 August 2014, doi: 10.2514/6.2014-4193

American Institute of Aeronautics and Astronautics

[11] Liang, M., Shemelya, C., MacDonald, E., Wicker, R. and Xin, H., "3D Printed Microwave Patch Antenna via Fused Deposition Method and Ultrasonic Wire Mesh Embedding Technique," *IEEE Antennas and Wireless Propagation Letters*, Vol. PP, No. 99, 2015, doi: 10.1109/LAWP.2015.2405054.

[12] Lopes, A., Navarrete, M., Medina, F., Palmer, J. and MacDonald, E., 2006, "Expanding Rapid Prototyping for Electronic Systems Integration of Arbitrary Form," *Proceedings of the International Solid Freeform Fabrication Symposium*, University of Texas in Austin, 14-16 August 2006, http://sffsymposium.engr.utexas.edu/Manuscripts/2006/2006-56-Lopes.pdf.

[13] MacDonald, E., Salas, R., Espalin, D., Perez, M., Aguilera, E., Muse, D. and Wicker, R. B., "3D Printing for the Rapid Prototyping of Structural Electronics," *IEEE Access*, Vol. 2, No. December 2014, doi: 10.1109/ACCESS.2014.2311810.

[14] Shemelya, C. M., Zemba, M., Liang, M., Espalin, D., Kief, C., Xin, H., MacDonald, E. W. and Wicker, R. B., "3D Printing Multi-Functionality: Embedded RF Antennas and Components," *IEEE Xplore Digital Library*, Vol. No.

[15] Adams, J. J., Duoss, E. B., Malkowski, T. F., Motala, M. J., Ahn, B. Y., Nuzzo, R. G., Bernhard, J. T. and Lewis, J. A., "Conformal Printing of Electrically Small Antennas on Three-Dimensional Surfaces," *Applied Materials*, Vol. 23, No. 11, March 2011, pp. 1335-1340, doi: 10.1002/adma.201003734.

[16] "CubeSat Design Specification," California Polytechnic State University, Rev. 14, February 2014.

[17] Carpenter, C. B., Schmuland, D., Overly, J. and Masse, R., "CubeSat Modular Propulsion Systems Product Line Development Status and Mission Applications," AIAA-2013-3760, *49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, San Jose, CA, 14-17 July 2013, doi: 10.2514/6.2013-3760.

[18] Arestie, S., Lightsey, E. G. and Hudson, B., "Development of a Modular, Cold Gas Propulsion System for Small Satellite Applications," *Journal of Small Satellites*, Vol. 1, No. 2, pp. 63-74, Available from: http://www.jossonline.com/downloads/0102%20Development%20of%20A%20Modular,%20Cold%20Gas%20Propulsion%20System%20for%20Small%20Satellite%20Applications.pdf.

[19] "Small Spacecraft Technology State of the Art," NASA TP–2014–216648 (REV1), National Aeronautics and Space Administration, Moffett Field,CA, 2014,Available from: http://www.nasa.gov/sites/default/files/files/Small_Spacecraft_Technology_State_of_the_Art_2014.pdf.

[20] Mueller, J., Hofer, R., Parker, M. and Ziemer, J., "Survey of Propulsion Options for CubeSats," JANNAF-1425, *57th JANNAF Propulsion Meeting*, Colorado Springs, CO, 3-7 May 2010, available from: http://richard.hofer.com/pdf/jannaf_mueller_2010.pdf.

[21] Guarducci, F., Coletti, M. and Gabriel, S. B., "Design and Testing of a Micro Pulsed Plasma Thruster for CubeSat Application," IEPC-2011-239, *The 32nd International Electric Propulsion Conference*, Wiesbaden, Germany, 11-15 September 2011, available from: http://erps.spacegrant.org/uploads/images/images/iepc_articledownload_1988-2007/2011index/IEPC-2011-239.pdf.

[22] Schmuland, D. T., Carpenter, C. and Masse, R. K., "Mission Applications of the MRS-142 CubeSat High-Impulse Adaptable Monopropellant Propulsion System (CHAMPS)," AIAA 2012-4269, *48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Atlanta, GA, July 30-August 1, 2012.

[23] Schmuland, D. T., Masse, R. K. and Sota, C. G., "Hydrazine Propulsion Module for CubeSats," SSC-X-4, *25th Annual AIAA/USU Conference on Small Satellites*, 2012.

[24] Zeledon, R. A. and Peck, M. A., "Electrolysis Propulsion for CubeSat-Scale Spacecraft " AIAA 2011-7134, *AIAA SPACE 2011 Conference & Exposition* Long Beach, CA, September 27 - 29, 2011.

[25] Nguyen, H., Kohler, J. and Stenmark, L., "The Merits of Cold Gas Micropropulsion in State-of-the-Art Space Missions," IAC-02-S.2.07, 2002, available from: http://www.diva-portal.org/smash/get/diva2:75729/FULLTEXT01.pdf.

[26] Mireles, J., Adame, A., Espalin, D., Medina, F., Winker, R., Hoppe, T., Zinniel, B. and Wicker, R., 2011, "Analysis of Sealing Methods for FDM-fabricated Parts," *Proceedings of the Solid Freeform Fabrication Symposium*, The University of Texas at Austin, August 2011, http://sffsymposium.engr.utexas.edu/Manuscripts/2011/2011-15-Mireles.pdf.

American Institute of Aeronautics and Astronautics

[27] Spanjers, G. G., Bromaghim, D. R., Lake, J., Dulligan, M., White, D., Schilling, J. H., Bushman, S., Antonsen, E. L., Burton, R. L., Keidar, M. and Boyd, I. D., "AFRL MicroPPT Development for Small Spacecraft Propulsion," AIAA 2002-3974, *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Indianapolis, Indiana, 7-10 July 2002.

[28] Selstrom, J. J., *Thrust and Performance Study of Micro Pulsed Plasma Thrusters*, M.S. Thesis, Air Force Institute of Technology, March 2010.

[29] Shaw, P. V., *Pulsed Plasma Thrusters for Small Satellites*, Ph.D. Dissertation, University of Surrey, June 2011.

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