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3D PRINTED PARTS FOR CUBESATS; EXPERIENCES FROM KYSAT-2 AND PRINTSAT USING WINDFORM XT 2.0

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The recent predominance of consumer level 3D printers has brought much attention towards the additive manufacturing process. On November 19th 2013 29 small satellites were launched from NASA's Wallops Flight Facility including KySat-2, a 1U CubeSat. KySat-2 was built with 10 additively manufactured, also called 3D printed, parts made from Windform XT 2.0, a material whose previous uses were mainly for automotive racing. Another 1U CubeSat, PrintSat, will be launched in 2014 and whose entire structure is built from the same material. This paper will discuss how each satellite used 3D printing, an overview of Windform XT 2.0, pros, cons and design considerations of 3D printing, and its future potential uses in the design and construction of spacecraft.

INTRODUCTION

Between November 19th 2013 and March 1st 2014 ninety-four micro satellites or smaller were put into Earth orbit [1] [2] [3]. This staggering amount has been the result of several factors including acceptance by launch vehicle providers and primary missions, miniaturization and increased efficiency of subsystems, and over a decade of flight heritage with CubeSats. A further and the more recent development of consumer level additive manufacturing have lowered another barrier for designing these small spacecraft. This paper outlines the missions and designs of two 1U CubeSats, PrintSat and KySat-2, and how they used additive manufacturing for both development and its use in their designs.

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PRINTSAT: DEMONSTRATOR FOR 3D PRINTING OF SATELLITE STRUCTURES

PrintSat is a 1U CubeSat technology demonstration illustrating the utility of using Additive Manufacturing for space-based structures and mechanisms. These structures and mechanisms are constructed from Windform XT 2.0, a proprietary polyamide based material filled with carbon fiber developed by CRP Technology of Modena Italy and printed by CRP's United States subsidiary CRP USA LLC. PrintSat will measure the performance of this material during a nominal 1-year mission life, possibly extended beyond that time. Concurrent Earthbound measurements will be made on an identical structure during the mission to allow for comparisons.

The PrintSat team is a multi-organization conglomerate comprising of the following participants:

- Montana State University – Lead and Owner
- Colorado Satellite Services, LLC – Systems Engineering and Avionics Development
- Project Starshine – Co-PI and Project Management
- Planetary Systems, Inc. – Mechanical Lead and Mechanical Load Cell Design
- Kentucky Space – Structure Design and Mechanical Load Cell Test
- CRP USA LLC – Windform XT2.0 Supplier
- University of New Mexico – High Efficiency Solar Cell Experiment PI

Origins of PrintSat

PrintSat (Figure 1) is the lineal descendant of an all volunteer, multiple-institution, and CubeSat project named RAMPART, which was designed to raise the orbit of a POPACS sphere from a circular polar orbit into a highly elliptical polar orbit. Walter Holemans of Planetary Systems Corporation designed and 3D-printed an ABS full-scale model of a RAMPART 3U CubeSat that was used in a presentation to the Department of Defense Space Experiments Advisory Board (SERB) in Washington, DC in November of 2008. The SERB approved RAMPART for flight on the next available Air Force Space Test Program (AFSTP) polar mission. RAMPART Project Director Gil Moore then introduced Walter Holemans to Stewart Davis of CRP USA and suggested that Windform XT 2.0 be used as the material from which to manufacture the RAMPART structure. Holemans agreed and collaborated with Davis and the other members of the project on all further revisions of RAMPART.

Unfortunately for RAMPART, even though the SERB continued to approve the project during the next few years for flight by AFSTP, no military polar mission ever became available. Moore therefore decided to fly his POPACS spheres on a commercial SpaceX Falcon 9v1.1 launch from Vandenberg AFB and suggested to the original team that the RAMPART project be revised to become a 1U CubeSat designed principally to measure the long-term survivability of satellites additively manufactured from Windform XT 2.0. The volunteer team agreed, and the project was renamed and assigned to Montana State University as the lead institution for proposal to NASA as a candidate for an ELaNa mission. NASA accepted the proposal in 2012, and PrintSat is currently schedule for launch in Q4 of 2014 [4] [5].

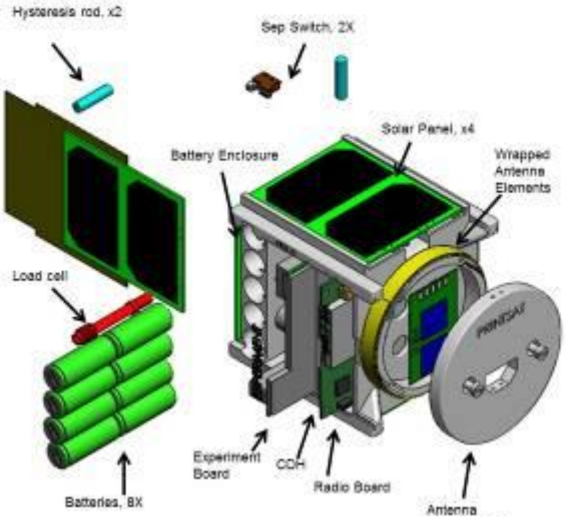


Figure 1: PrintSat Exploded View

Structure and Mechanisms

The entire PrintSat structure is printed from Windform XT 2.0. The structure was constructed in two pieces: the 1U card cage and the antenna cap shown in Figure 2. 3D printing offers design functionality that is not possible with traditional design fabrication techniques. As such, only six screws are utilized in the entire structure. These screws are utilized as a throw limiter for the antenna cap and to hold two deployment switches. Essentially, the antenna cap is recessed into the +Z face until the antenna deployment event that occurs after deployment from the launch vehicle. There are two springs that are placed between the card cage +Z face and the antenna cap. The antenna cap is then compressed against the card cage +Z face, against the springs, and is restrained by monofilament line. The monofilament is tied to a nichrome burn-wire that will, upon initialization of the antenna deployment event, burn the monofilament, allowing the cap to deploy radially along the Z-axis and subsequently release the antenna elements. Other features designed into the card cage structure are the battery and load cell enclosures, wire routing channels, and PCB slots.

It is noteworthy to mention that carbon fiber is a non-conductor; however, it will act as a semi-conductor along the individual fiber lines. This behavior is important to note in the overall design, as that the Windform XT 2.0 material can add a loaded short to ground. This effect can provide inconsistent electrical properties and should be taken into consideration for antenna and electrical design [6].

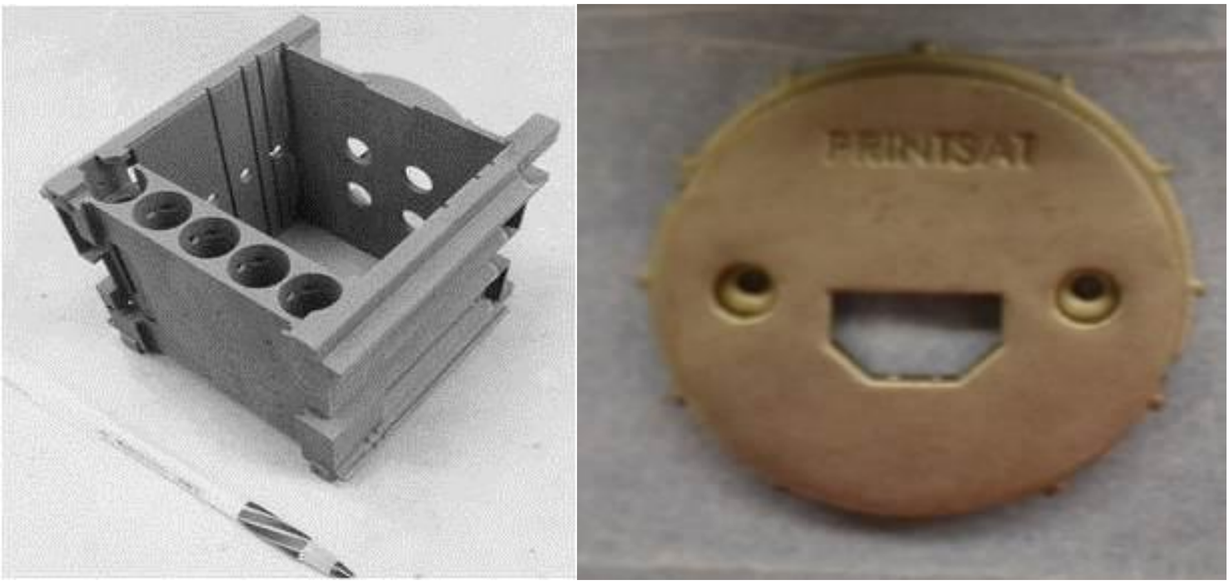


Figure 2: PrintSat Card Cage (L) and Antenna Cap (R)

Plating

PrintSat was plated with a 0.013mm layer of High Phosphorus Electroless Nickel as shown in Figure 3. This was done to provide RADAR reflectivity for tracking and to act as a ground plane for the antennas. Quaker City Plating located in Whittier, California, under the direction of Mr. Frank Huizar, did the plating process. Several materials were considered, but ultimately were limited to Gold and Nickel. Gold was eventually eliminated due to the poor absorptivity to emissivity ratio in the Infrared in an attempt to avoid thermal runaway. Masks were applied to the Windform XT 2.0 structure to avoid applying conductive plating in certain key areas, including the rails, feet, surface traces, portions of the +Z face, and portions of the antenna cap. The plating is tied to the spacecraft electrical ground, except in certain key locations; foremost, the surface trace experiments. Masks were applied to the feet and rails to avoid the possibility of cold-welding inside of the NLAS CubeSat dispenser. Similar masks were applied to the +Z face and the antenna cap to isolate the plating ground from the antenna elements. The surface of the Nickel plating is dull and matted; it presents the friction characteristics of 180 grit sandpaper.

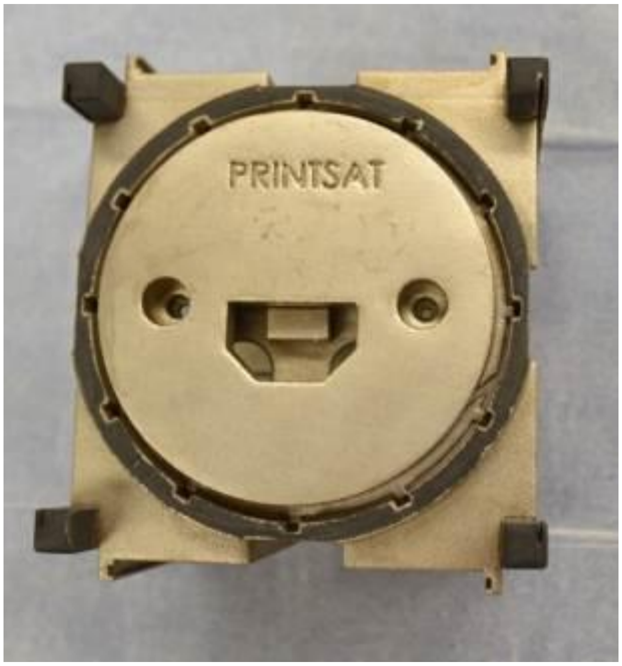


Figure 3: PrintSat after Nickel Plating

Experiments

The primary PrintSat science objective is the in-situ measurements and reports, as a function of time, for both the Windform XT 2.0 material and Nickel plating in the LEO environment. The mechanical load cell is constructed of AL 7075-T6 and is a threaded stress device that applies tensile stress to the card cage. As the stress upon the card cage changes, we will see a voltage deflection on the integrated strain gauges that are arranged in a Wheatstone bridge, in order to cancel out any bending moment. This voltage deflection has been calibrated so that a given voltage deflection corresponds to a given change in stress. The load cell will be a natural fatigue test due to the mismatch of the coefficients of thermal expansion (CTE) between the load cell and the structure as the spacecraft cycles between sunlight and eclipse. The PrintSat Experiment Board is a support module that hosts the interface of the temperature sensors and three current sense experiments. The Experiment Board contains four temperature sensors to correspond to thermal stresses applied due to temperature. The current sense experiments use the surface Nickel traces as fixed resistors to study any loss of plating as a function of time. This will give insight into the performance of the Nickel plating [7].

PrintSat also features a secondary high-efficiency solar cell experiment. This cell is a 36% efficient Emcore 6-junction IMM solar cell. The IMM concept of operations revolves around in-situ measurements of the cell’s on-orbit performance by producing I-V curves through a fixed 16-resistor network. This test also contains a well-known and characterized reference cell of the same surface area.

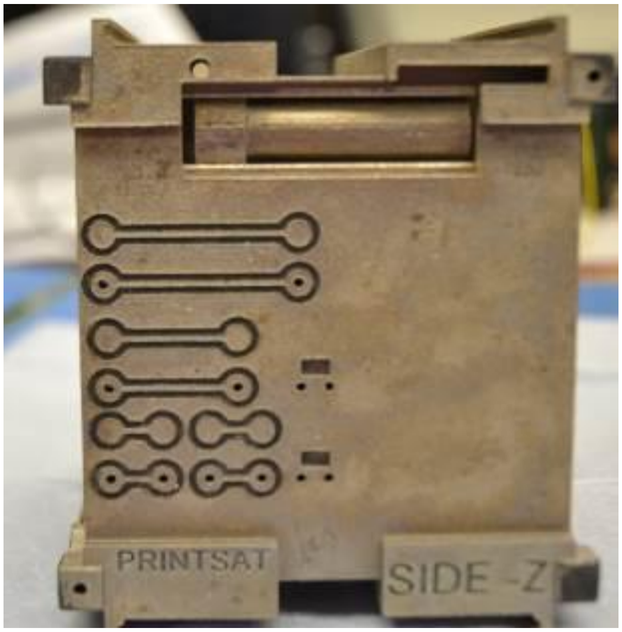


Figure 4: PrintSat Nickel Plating Surface Traces

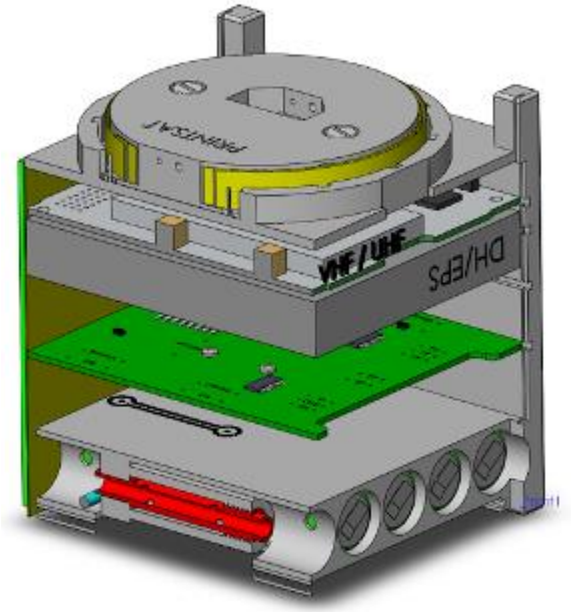


Figure 5: PrintSat Load Cell Integrated into Spacecraft

PrintSat Operations

The Windform XT 2.0 material has undergone a NASA Launch Services Program verification regimen to prove its viability for space applications. This regimen included: material strength, Coefficient of Thermal Expansion (CTE), Total Mass Loss (TML), Collected Volatile Condensable Mass (CVCM), and surface roughness testing. Some of these results are shown in Table 1 while others may be found in the Windform XT 2.0 material datasheet [8] [9].

Table 1: WindformXT 2.0 Material Properties

Surface Roughness (μm)	CTE (X,Y, Z) [1/K]	TML [%]	CVCM [%]
1.8	25.7E-6 104.8E-8 216.7E-6	0.51	0.00

PrintSat Launch

PrintSat is manifested aboard ELaNa-7 mission, slated for a 4th Quarter 2014 launch from the Pacific Missile Range Facility (PMRF), which is located in Barking Sands Kauai, Hawaii aboard the newly innovated Super Strypi launch vehicle. PrintSat has been allocated launch space via the NASA LSP ELaNa program.

LET'S TRY THIS AGAIN: THE ROAD TO KYSAT-2

KySat-2 is the third orbital satellite developed either by or in partnership with Kentucky Space; a Lexington Kentucky based company specializing in entrepreneurial space platforms. The first satellite developed by Kentucky Space was KySat-1 a 1U CubeSat developed for Education and Public outreach. This education mission was two pronged: first the satellite was to be used as an on orbital lab for K-12 students in the commonwealth of Kentucky. Secondly it was for college level students to learn the process of building a spacecraft to further build an aerospace economy in the state. KySat-1 was selected for the NASA ELaNa-1 mission that flew with the NASA GLORY satellite as the prime for the mission. Unfortunately due to a launch anomaly the satellites did not reach orbit. Following this Kentucky Space worked with their partner institution Morehead State University on the Cosmic X-Ray Background Satellite (CXBN), which was delivered in January 2012 and launched as part of ELaNa VI on September 19th 2012. In March 2012 work began on KySat-2, which would fulfill the objectives of KySat-1 but with upgraded components and with all hardware designed by Kentucky Space as opposed to the all COTS approach of KySat-1. In addition to the Public Outreach, the spacecraft carried an imaging system that could be used for both earth and star field image capture. The star field images would be used to test a new subsystem which would calculate the spacecraft's roll rate using the differential movement of stars between the quick successive images taken.

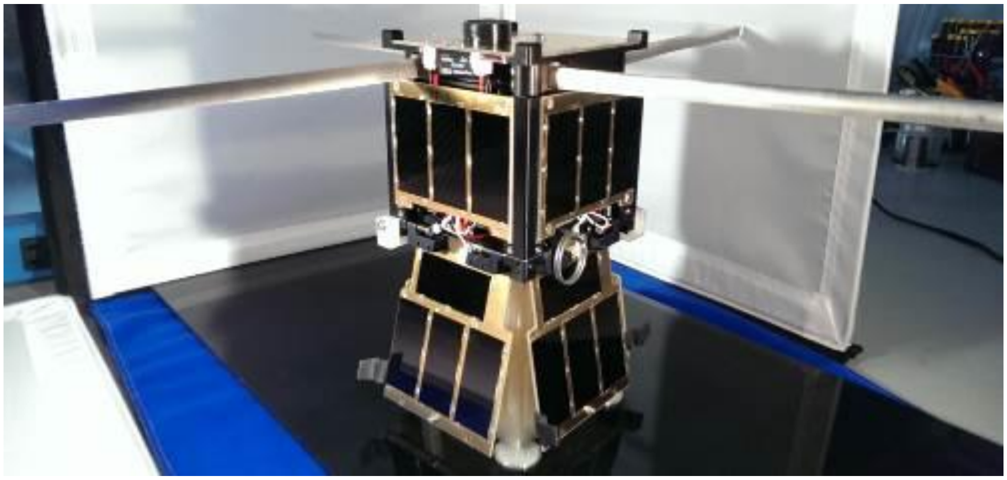
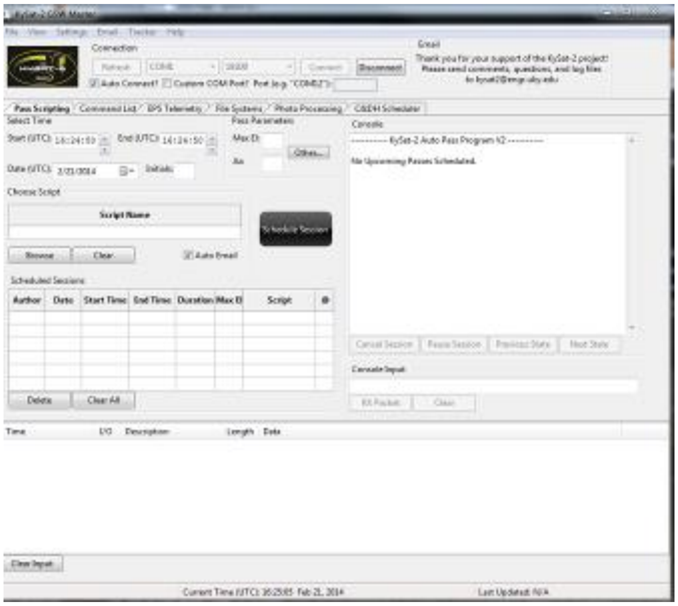


Figure 6: KySat-2 in Deployed State before Integration

KySat-2 Operations

KySat-2 was launched on an Orbital Sciences Minotaur-I launch vehicle with the ELaNa IV mission on November 19th 2013. The spacecraft was ejected shortly after burn out of the launch vehicles fourth stage into a 500km circular, 40.6-degree inclination orbit. Once powered on, KySat-2 began beaconing approximately every 15 seconds at 437.405MHz. These beacons contain vital health and status information about the spacecraft, including battery voltages, solar cell currents, and internal mission timers. In order to utilize the goodwill and interest of the international HAM radio enthusiast community, a free-of-charge program was created and released to decode, visualize, and forward these beacons to Kentucky Space. As of March 10th 2014, over 12,000 unique beacons have been collected, attesting to the operational state of KySat-2. According to this dataset, KySat-2 has been continuously powered since 19 November 2013, undergoing no system-wide reset or power loss.



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---------- KySat-2 Auto Pass Program V2 ----------
No Upcoming Passes Scheduled.
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Figure 7: KySat-2 Ground Software with Decoded Beacons

Windform Parts

KySat-2 included five unique (10 total) additively manufactured parts from Windform XT 2.0. Several of these parts had multiple copies throughout the spacecraft. The two parts that took the most advantage of additive manufacturing were components for the imaging system of KySat-2. Since KySat-2 was using an off-the-shelf lens and CMOS imaging board, they were not optimized for being placed inside a CubeSat. After considering the options for design mounting hardware for the imaging components, the team decided to develop two additively manufactured components that would fit together. The first part was to prevent light contamination of the imager's CMOS sensor. The second interface with the CMOS cover via interference fit and provided mechanical connection of the imaging board and lens to the spacecraft's frame (Figure 8).

The other additively manufactured parts included two "straps" to hold the three 18650 Lithium Polymer batteries and four solar panel clips to hold the four UHF antennas when stowed which allowed KySat-2 to not require a second burn wire in addition to the one used to deploy the spacecraft's solar panels. Finally two deployment extensions that come out of the spacecraft's frame and connected to switches that power ON the spacecraft were also made of Windform XT 2.0 as shown in Figure 9. Additive manufacturing allowed the design team to come up with efficient designs and use geometries for each of these unique scenarios that otherwise would have forced substitutes that sacrificed performance for manufacturability. Each of these components would have been difficult to impossible to manufacture using traditional techniques.

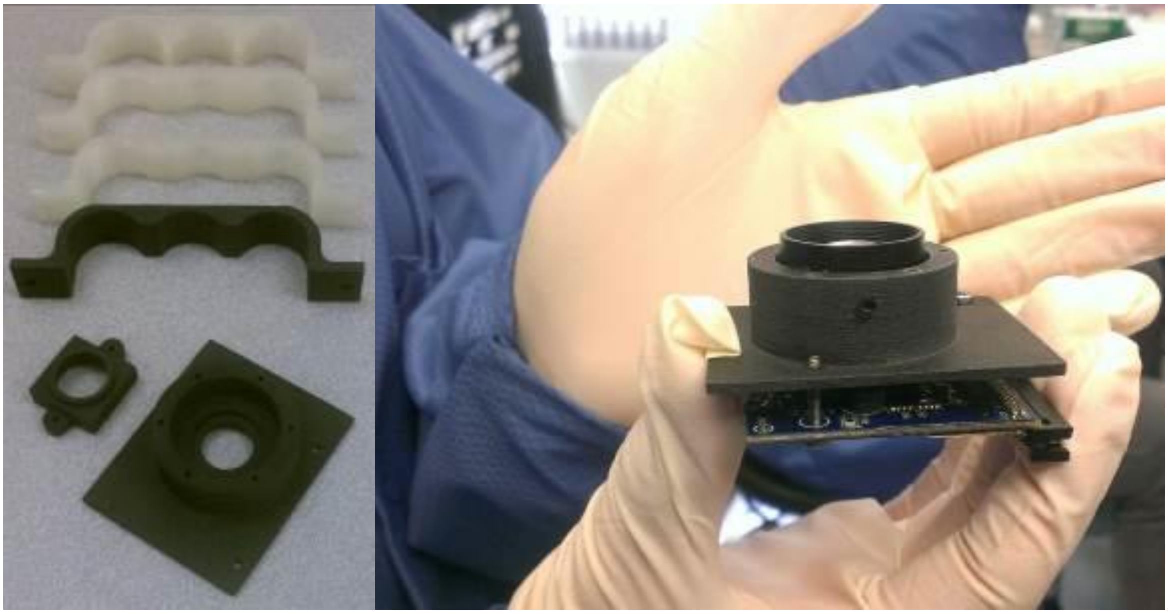

Figure 8: Revisions of KySat-2 battery holders (only bottom holder was made with Windform XT 2.0) along with CMOS cover and lens holder (L). Assembled imaging system just before integration into Flight Model (R)

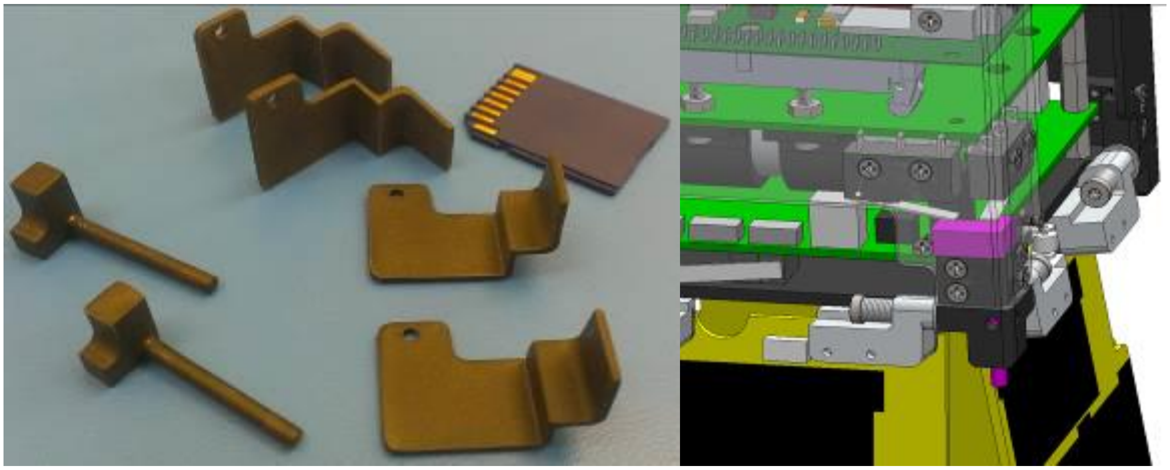

Figure 9: Deployment Extensions and Solar Panels Clips shown before Integration (L). CAD photo of Deployment extension (purple for clarity) integrated into spacecraft (R). Solar Panel clips can been seen in Figure 6 at bottom of deployed Solar Panels

PRINTING MATERIAL: WINDFORM XT 2.0

Windform materials were originally developed for applications in Wind Tunnel operations for Motorsports teams. These materials improved and evolved to allow for their use in applications that include on car applications in the race environment. Windform XT 2.0 is currently being used in NASCAR, Formula One, and Lemans GT series to build components that are utilized in the racing cars at the track at every race. Examples include intake manifolds, air inlet ducting, electronic enclosures, cold air ducting, and retaining clips. Windform has passed outgassing testing per the ASTM E-595-07 testing standard for total mass loss and volatile materials from outgassing in vacuum environments.

Manufacturing Description

The LS (Laser Sintering) manufacturing process utilizes a layer additive system. A powder is rolled out in a gas inert chamber at 0.10mm (0.004”) layers. After the layer of powdered material is applied, a CO_2 laser is used to melt or sinter a two-dimensional cross section of the part. This process continues layer upon layer with each successive layer of powder being sintered on to the next creating a three-dimensional part. The non-sintered powder areas of the chamber support the part being built and are removed from around the component when the build is complete. At the end of the building process the part "cake" is taken from the machine, and the parts are removed from the un-melted powder.

Key elements in producing parts for Motorsport racing are how the part performs and the possibility to produce a new high-quality component in a very short time. When modifications are needed, Additive Manufacturing (3D Printing) gives the advantage of saving time, weight, design flexibility and cost when only few parts are produced. This allows tremendous design flexibility for creating complex shapes in a short period of time.

FUTURE OF 3D PRINTING

A wider use of 3D printing has two large consequences for small satellite design moving forward. The first is from the low-end consumer level printers. With the rapid drop in price being within the budget of most universities and small companies it allows for rapid iteration of components designs. As an example the deployment mechanism for KySat-2 was prototyped with different designs an estimated 40 times using a consumer level printer before being sent off for flight quality machining. This iterative process can allow the designer to add more complicated designs such as deployable solar panels or antennas that normally would not be taken on due to unfamiliarity by the designer.

The second is the use of industrial level printing such as a material like Windform XT 2.0. Such a material can withstand the LEO environment that a spacecraft must endure, fall within tight tolerances, meet launch vehicle outgas requirements and have the ability to create shapes and features that would be extremely difficult (thus expensive) or impossible via traditionally subtractive manufacturing.

The PrintSat and KySat-2 teams have compiled the list below of benefits, drawbacks and design considerations when using additive manufacturing:

Pros:

1. Opportunity for building functionality of mechanisms directly into the structure.
2. Build time is independent of object geometry complexity, but dependent on part volume and build height.
3. Lead-time between submission and construction is very short.
4. It is possible to reduce mass by creating hollow parts with internal reinforcement.
5. 3D printed/SLS parts may be easily machined to maintain critical dimensions.
6. The layered construction process is free from geometrical constraints, and is possible to build hollow parts, undercuts and internal ducting.
7. It is possible to integrate multi-functional capability within printed structures or mechanisms. For example, it is possible to embed thermodynamic control, mechanical reinforcement, and/or electrical features into the typical build process. These may be used for such applications as embedded antennas, electrical interconnects and transmission lines.
8. Additive Manufacturing (AM) is more efficient with material usage. This in turns requires less material to be sacrificed in post processing, such as polishing.

9. Because parts are 'grown' as Stewart has often described, designers may approximate the designs in nature that are grown and attain the specific stiffness and strength of nature's design. That is a single part can be made instead of many, deleting the bureaucracy of mechanical design.

Design Considerations:

1. Minimum feasible structure thickness is 1mm, but recommended at 1.5mm to 2mm.
2. Keep features greater than 1mm.
3. Excessive structure thickness, greater than 10mm, can cause undesired warping or shrinking.
4. Avoid enclosed volumes. Hollow parts will need holes to allow the removal of unsintered powder.
5. When designing parts that are to be assembled later, maintain a minimum 0.2mm clearance between the parts.
6. Hole features will often need to be machined to achieve a truly round hole.

While 3D printing offers great improvements in utility of structures and mechanisms, several important limitations should be pointed out:

Cons:

1. Over the 100-millimeter distance of a CubeSat it is probable to measure a 1-millimeter difference from nominal dimension. Consequently engineers in charge of the 3D printing need to manipulate the CAD model to counteract this tendency.

2. Dimensions of printed parts continue to change as a function of time, (possibly due to humidity and temperature cycling)

3. CTE mismatch between metals and Windform can be problematic

4. In mechanisms, such as the antenna stow and release system, where precision is highly important, the variation of nominal dimensions, necessitates the printing of moving mechanical hardware in the assembled state as a means to nullify the effect of the variation. For example, if you want a door hinge out of Windform, print the two halves at the same time in the assembled state. Though the whole assembly may be off dimensionally, the relative variation will be negligible, allowing the mechanism to work best.

5. Windform is neither a good electrical conductor nor insulator.

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