Orbital Factory II: a 3D Printer CubeSat with Self-repairing Purposes

Michael Everett, Angel Flores-Abad, Kazi Md Masum Billah, Arifur Khan and Ahsan Choudhuri
Center for Space Exploration Technology Research
The University of Texas at El Paso, El Paso TX, 79968, USA
mleverett@utep.edu

ABSTRACT
A spacecraft in orbit might experience undesired events such as electron charges and debris impacts that can damage the solar cells. If this occurs, the Electric Power System of the CubeSat will fail to provide energy to the system, and as a result, the whole Satellite will be unable to keep operating. In 2016, the Center for Space Exploration and Technology Research of UTEP planned to develop a 1U small satellite (commonly termed CubeSat) that will 3D print a conductive trace to repair a damaged solar cell using additive manufacturing techniques. Such a CubeSat was proposed to the United Launch Alliance initiative that would award free rides to space of 1U CubeSats. The UTEP team obtained the first place to be launched to GTO in an Atlas V rocket. The concept is innovative and challenging in several senses: as of May 2018, no University-developed CubeSat has traveled to GTO and face the difficult radiation environment of Van Allen Radiation Belt, and attempting to 3D print in space is challenging due to the reduced gravity, vacuum and extreme temperatures environment. The 3D printer includes three main subsystems, the material dispenser, the gantry table mechanism and the motion controller. This paper describes the development of the 3D printed including the conductive ink material selection, the design of the printer mechanism, the assembly and integration of the components as well as prelaminar tests results.

INTRODUCTION
Recent progress in miniaturization and affordability aerospace technology, along with the interest of the space agencies to keep space exploration sustainable, have enabled universities and industry to develop small spacecraft to conduct a variety of technological and scientific missions. The type of proposed missions is diverse and the vast majority of CubeSats have been deployed in Low Earth Orbit (LEO), but it is envisioned that in the near future more and more CubeSat missions will go far beyond LEO. For example, MarCO CubeSat [1] has been the first one going to deep space, it was launched on May 5, 2018 and it is expected to be a breakthrough technology that will open new opportunities for more CubeSats. In this work, we introduce another CubeSat that will be deployed beyond LEO limits as it will travel to GTO (Geostationary Transfer Orbit). The CubeSat is called Orbital Factory II and is the awardee of the 1st place in the ULA CubeCorp competition to launch a 1U Cube Satellite into Orbit. The main payload of this spacecraft consists of a 3D printer that will perform self-repair of a simulated open-circuit solar cell using additive manufacturing techniques. The satellite is expected to be launched on 2019.

MATERIAL SELECTION
To accommodate the low power nature of a 1U platform a novel approach to 3D printing had to be devised for achieving both electrical conductivity and power requirements employed a single part, high silver content vacuum curable media, such as gels and inks are part of the materials considered here. Candidate materials for this concept included Ercon E1660 (Ercon Incorporated, Wareham, MA USA) and the DuPont CB102 conductive paste. These materials were under consideration due to previous success in 3D printing by the W.M. Keck Center for 3D innovation [2]. Table 1 shows a comparison of the two material in regards the properties that matter the most for this project, like, conductivity, viscosity, curing time and size of the silver particles. Both materials have very similar properties and have been tested to make a final selection. The CB102 outgassing performance is below the 1.0% of NASA requirements. Also, the collected volatile condensable material is 0.026%, which is less than the maximum NASA acceptable value 0.10%. The challenges of the CB102 are the shelf life (less than 3 months) and storage temperature (below 5˚C). According to manufacturer report, E1660 silver flake based conductive inks have the shelf life of 6 months at room temperature (22˚C). It has the viscosity of 17.5Pa.s, that is favorable for flow-based direct writing
technology and three-dimensional printing. Controlled trace thickness (as there was no swelling or expansion after dispensing) and a short time to conduct electricity (approximately 1 to 5 minutes) at an elevated temperature increased the curiosity for experimental study in vacuum condition. Until recently, there is no information about the space application of E1660.

Table 1: Material properties of the two ink candidates

<table>
<thead>
<tr>
<th>Materials</th>
<th>Viscosity (Pa.s)</th>
<th>Bulk Resistivity (Ω/cm³)</th>
<th>Silver Particles Size (μm)</th>
<th>Curing Time at Atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ercon E1660</td>
<td>17.5</td>
<td>2.1 x 10⁻⁴</td>
<td>20</td>
<td>1-5 Minutes for 121°C</td>
</tr>
<tr>
<td>DuPont CB102</td>
<td>85</td>
<td>1.8 x 10⁻⁴</td>
<td>1-5</td>
<td>60 Minutes for 150°C</td>
</tr>
</tbody>
</table>

DISPENSER DESIGN AND PROTOTYPING

To inject the electric conductive material, a micro dispenser was designed and build. The dispenser injector contains a spring-loaded valve and a spring-loaded piston within the injector. The spring inside the injector is compressed and exerted a force on the piston to inject the ink. Another spring was used to create a normally-closed (NC) valve at the tip of the injector. To open the NC valve, a burn wire (30 AWG type Chromel C) mechanism released the compressed spring, to inject the conductive ink. Figures 1 a) and b) show the CAD model of the designed dispenser and Figure 3 is a 3D printed prototype of the system.

Figure 1: Main components of the micro ink dispenser.

Figure 2: A 3D printed functional prototype of the dispenser with a length of 65 mm and inside diameter of the ink barrel of 8.66 mm.

THE 3D PRINTER

The printer represents the primary payload and as such is considered a major component. Despite the significance of this module, it is vital to maintain a compact volume with a targeted mass of 30 grams. To accomplish this task the following design requirements have been established:

- The printer shall comply with NASA Low Outgassing Requirements
- The printer shall apply a controlled three dimensional bead of electrically conductive material
- The printer shall utilize a pre-charged extrusion system for power reduction
- No power systems shall be employed other than to control the printers traverse and nozzle positions
- The printer shall attain its power from the primary EPS system
- Command and control signals shall originate from the primary OBC
- The printing media shall be contained to prevent inadvertent access to sensitive electronic systems.
- Feedback systems shall be employed to permit a homing action and a estimated position measurement
Final printing media shall possess a measurable conductivity.

Figure 3 is an artistic depiction of the printer and Figure 4 is the physical prototype mounted on the CubeSat structure, where the main parts are labeled for a consist explanation of the system.

**Figure 3: CAD Rendering of Printer Concept**

- Feedback Switch
- Home Switch
- Printer Dispensing Nozzle
- Ercon E1660 Conductive Ink
- Printer Guide Rails
- Mechanical coupling
- Printer Supports
- PCB Substrate
- Burning Wire
- Stepper Motor
- Lead screw

**Figure 4: Key components of the 3D printer**

The 3D printing experiment sequence is as follows an will performed in 2 minutes. The printer nozzle will begin a self-calibration process by moving in the negative x-axis direction through the printer guide rails until the home switch is activated. The stepper motor on one of the printer supports is spinning in the direction of where the printer nozzle needs to move. Once the home switch is activated, the burning wire mechanism heats the injection spring until the printer valve opens. When the printer valve opens, the printer orifice opens, and the feedback switch sends the signal for the printer nozzle to start moving in the positive x-axis direction. The printer will then release the conductive ink and will print on the PCB substrate as it moves in the negative x-axis direction simulating the process of closing an open circuit of a solar cell. The printer will then have drawn a conductive trace between two terminal points on the print substrate, simulating a self-repairing of a solar cell. The conductivity of the trace will be measured to determine the success of the mission.

**CUBESAT MAIN COMPONENTS**

The main components of the OFII CubeSat developed here are shown in Figure 5. It includes the OBC (On Board Computer) from Pumpkin Inc, which has flight heritage but it is not radiation hardness; an UHF (Ultra High Frequency) communications module, the EPS (Electronic Power System) from GomeSpace manufacturers and an in-house designed and built interface board, which has the function of interconnecting all the subsystems. The integration board also houses the UHF (Ultra High Frequency) receiver NanoCom AX100 @ 430-440 MHz.

**Figure 5: Key components of the 3D printer**

*The interface module*

With the purpose of interconnecting all the components, an interface board was designed and build in house. With the acquisition of COTS subsystems, design and development time of electronics equipment was reduced substantially. Despite the reduction however, a single module was required to tie all payload experiments together. To begin the design and
development phase of this device the specific requirements were first defined.

1. Interface module shall comply with PC104 configuration

2. PCB shall provide adequate space for cable routing along perimeter

3. Interface shall provide mounting location for GOMSpace AX100U transceiver

4. Interface shall provide adequate means for connecting AX100U transceiver to OBC

5. IIC pull-up resistors shall be applied on interface module in compliance with subsystem requirements

6. Interface module shall be terminated with 104 pin female headers in compliance with subsystem interconnection scheme

7. All unused and accessible pins from OB shall be terminated in accordance with OBC requirements

8. A buffer shall be employed on IIC lines between devices contained within the protected chassis and any device exposed to radiation sources.

9. Interface module shall provide a method of power control (on/off) to each subsystem and payload

10. A low impedance circuit shall be incorporated to accommodate two burn wire devices controllable by OBC

11. All digital logic signals to / from OBC shall be compatible at 3.3V level

12. Critical power circuits shall incorporate redundant current paths

13. Interface shall incorporate all required electronic circuits for payloads

14. ELF shall incorporate an isolated power supply, with ground isolation

15. ELF/SCM operation amplifier outputs to OBC shall be suitably protected via clamp circuit or similar

16. All wires shall terminate to interface module to be transferred to subsystems via standard 104 pin stackable headers, except

a. Any component required for compliance with flight qualifications, e.g. kill switches

b. Primary power distribution, e.g. solar panel terminations

c. Communication system antenna cables

17. Priority shall be given to simplistic designs

Prior to fabrication all applicable circuits were simulated for function utilizing Labcenter Proteus. Simulations were limited to functional testing as it is assumed electro-magnetic issues would be negligible due to the high power and lack of high frequency systems within the interface module.

As examples, some of the main simulation circuits are introduced here. Figure 6 is the circuit for the burn wire activation, which is based on MOSFET transistor operating as switches. Figure 7 is the stepper motor driver circuit to regulate the speed and rotation sense of the motor by means of an H-bridge circuit.

![Figure 6: Parallel MosFET circuit for Power delivery & burn wire activation](image)

![Figure 7: Stepper driver in indexing mode](image)
The physical integration board that was designed and build by our team is depicted in Figures 8 and 9.

Figure 8. Front face of the integration board designed and build in house, housing the UHF transceiver module and some other important electrical components.

Figure 9. Back face of the integration board.

**CubeSat Chassis**

The chassis is a major component and will represent a significant overall percentage of vehicle mass. The design of the chassis began with the definition of specific design requirements of the mission due to its journey to GTO.

- The chassis shall be made of materials compatible with high vacuum, and temperatures from -50°C to the least of critical subsystem temperature maximums +50°C
- The chassis shall provide adequate radiation protection for the mission
- The chassis shall serve as the structural bus to mechanically tie the subsystems together
- The chassis shall comply with dimensional requirements established by the CubeSat specification document
- The chassis shall be as continuous as possible to avoid ingress paths for harmful particles
- There shall exist a method for venting in compliance with ULA requirements
- The chassis shall be electrically conductive, or suitable bonding terminations shall be integrated
- Any non-conductive coatings (anodization, etc.) shall be removable in areas of ground terminations

The allotted mass of the chassis has been omitted as a design requirement in favor of prioritizing radiation protection over mass. However, efforts have been taken to reduce mass where possible. For the chassis to adequately serve its purpose a number of materials have been considered, i.e. Aluminum 6061, Aluminum 7075, AlSiMg and Ti-6Al-4V. Aluminum based alloys have been the clear favorite due to ease of conventional manufacturing processes, as well as the abundance of literature focused upon the effects of these alloys as radiation shields for spacecraft [3]. Typically, aluminum-based alloys have served as the primary shield material for prior space missions, and is often the material behind which radiation dosimeters are placed for future comparative analysis [4]. The differences between 6061 and 7075 are largely moot within literature although the increased density of 7075 (2.81 g/cm³) compared to that of 6061 (2.7 g/cm³) [5] does seem to indicate thinner wall thickness for equivalent shielding performance per unit mass [6]. The potential for thinner walls enhances the margin available for conformance with dimensional constraints at the cost of increased difficulty during machining operations.
Figure 9 shows the designed and the built CubeSat Chassis.

![Figure 9](image)

Figure 9. a) the CAD model and b) the real system made of Aluminum 6061.

Acknowledgments

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References