Orbital Factory 2: A 1U CubeSat for Additive Manufacturing Tasks in Low Earth Orbit.

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ABSTRACT

Additive manufacturing in space has been recognized as one of the required technologies for space colonization and deep space exploration. The current state of the art indicates that efforts are being done to achieve 3D (Three Dimensional) printing in space, in particular, inside the International Space Station (ISS) in a controlled environment. However, no spacecraft has performed additive manufacturing tasks in open outer space subject to the vacuum, reduced gravity and the extreme temperatures. In this work, a 1U small satellite, nicknamed Orbital Factory II (OFII) will perform a technological demonstration of 3D printing of conductive material. The small satellite features a 3D printing 2-DOF gantry table mechanism that will deposit conductive ink and simulate repairing of a solar cell. The material to 3D print was selected based on bulk resistivity, viscosity and amount of conductive particles, as well as curing time and low outgassing. Up to date, vacuum test has determined that the ink will cure in space after 90 secs and as a such will be conductive after that period of time. A VGA camera and sensor measurements will determine the mission success. Taking advantage of the fact that we house a world-class additive manufacturing center, some of the satellite's parts have been 3D printed in ProtoThermTM 12120 (Three Dimensional), which is a polymer to produce high-temperature tolerant and liquid resistance parts by SLA process. The satellite also includes an S-band patch antenna as a secondary payload. The antenna was entirely designed and built by Lockheed Martin Co. We tested and characterized the antenna and finally integrated into our CubeSat. Since the gain pattern of the S-band antenna is narrow, an attitude controller based on magnetorquers will be implemented to ensure proper pointing to the Earth. Up to now, vibration test, reveals that our payload will withstand the lunch environment given by our lunch provider (NanoRacks). We have also confirmed that due to the small amount that will fly and low outgassing properties of the ink, our payload does not represent any risk during launch and its deployment. Finally, the satellite is scheduled to be launched at the end of this year in an Antares rocket from Wallops and deployed either from a Cygnus spacecraft or the ISS. The full paper will show the design, integration, and the different test and corresponding results performed to the OF-2 satellite.

INTRODUCTION

It is envisioned that in-orbit manufacturing and assembly will allow to creating big and light structures in space that can be used for instance the fabrication of big antennas to support deep space exploration, the establishment of habitats to enable space colonization and construction of large solar arrays for in-space power plants, among many other interesting applications. However, additive manufacturing in space is still in its early developments and several challenges need to be overcome to make this technology ready to fabricate parts in the hostile outer space environment, where vacuum, reduced gravity, extreme temperatures and radiation demand ingenious methods to make it possible. The current technology used in the Earth for additive manufacturing will fail to fabricate parts in space mainly due to: outgassing of materials, difficult nozzle temperature control in the absence of convection and the almost null gravity and lack of an inertial frame causes movements on the system due to reaction forces and torques. This work proposes a single-axis 3D printer to perform a simulated solar cell repair using additive manufacturing techniques. Because this project has the objective of moving forward 3D printing in space, the CubeSat has been nicknamed Orbital Factory 2, OF-2 for short.

OF-2 MISSION OBJECTIVES

OF-2 Mission Primary and Secondary Objectives are as follows:

Primary:

1. Establish ground uplink/downlink (UL/DL) communication though primary UHF communication link.

2. Demonstrate operation of printing mechanism though visual (onboard camera) and electrical continuity validation.

Secondary:

3. Command S-Band DL transmission. Acquire OF-2 printer data, sensor data and images.

4. Demonstrate OF-2 software reconfiguration and BIOS reset via UHF UL.

CONCEPT OF OPERATION

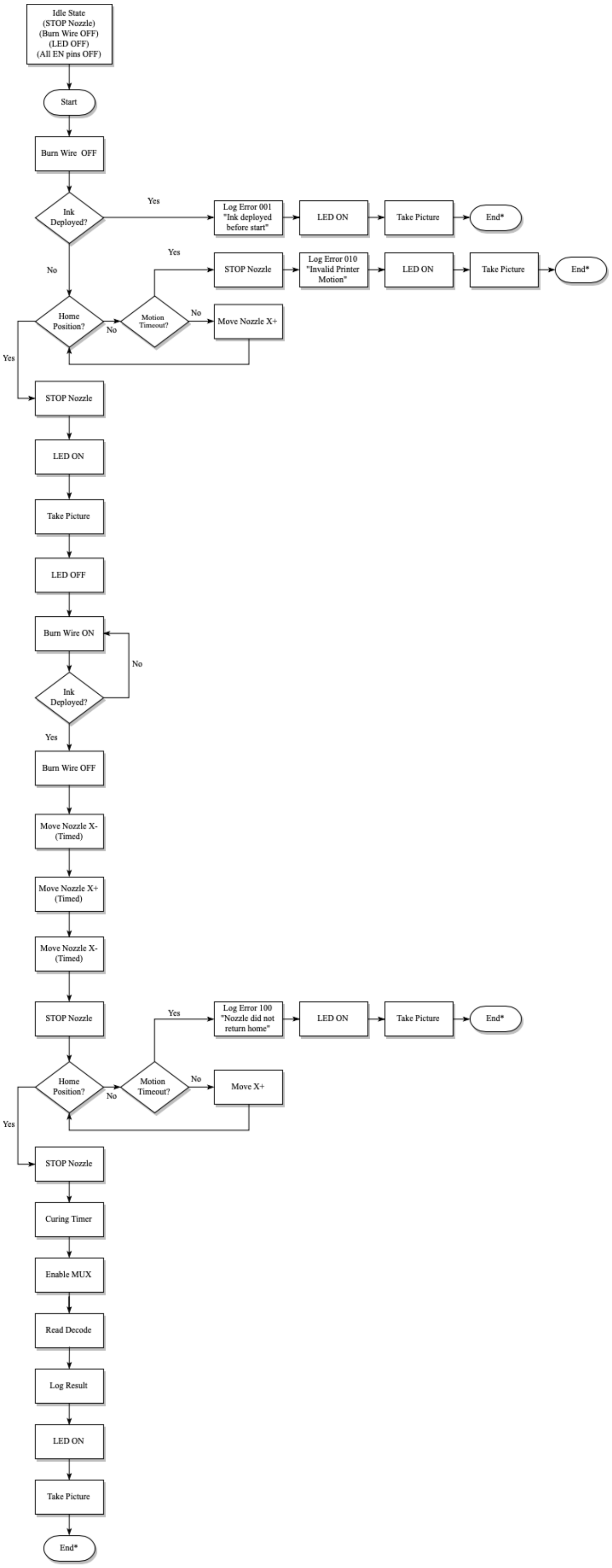


Figure 1: Printer payload Concept of Operations

The concept of operations for the printer motion, ink deployment, error detection and subsequent validation is shown in Figure 1. For clarity, timing and I2C register states are not included in the figure. Upon boot up of the payload processor an idle state is established in which all control components are commanded to the "off" state regardless of their initial state. This includes motor driver, illumination, burn wire and all continuity mux and decode enable pins. As the printer processes is initiated, logic and timer errors are placed during key decision blocks, if error conditions are met, a specific error bit is asserted, a photo is taken by the satellite and the logic returns to the Idle state without moving forward. If imitation of the printer payload is successful, the printer may commence with the dispensing of the ink and spreading motion. Pictures are taken before ink dispensing and nozzle movement and after continuity validation. Once nozzle movement has taken place a timer is set to allow the ink to cure. Upon expiration of the curing timer, 5V is distributed to the test printer board via an 8 channel MUX. Continuity is evaluated based on 5V TTL criteria on the encoder output. A picture is taken and is stored along with the continuity results. The micro processor enters it's idle state where it once again turns off all control and enable components.

PAYLOAD

An overall 3D model of the OF-II small satellite's 3D printer payload is shown in Figure 2. The mounting structure is the mechanical interface of payload with the rest of the components that are housed inside the 1U spacecraft chassis. A PC-104 connector provides the required electrical interface to control and monitor the payload. ULTEM plastic has been used to 3D print the mounting structure, which provides fast and low-cost customization of the parts. It was chosen because of its widely used space applications due to its low-outgassing nature. The syringe-like nozzle component made from ProtoTherm stores the conductive ink inside its body. A pusher with a (compressed) spring assembly constantly applies pressure to push the ink out, but a paraffin wax seal at the nozzle tip prevents the ink from coming out until ready to perform the experiment. Nichrome wire is wrapped around the nozzle tip and used as a burn wire to melt the wax. The nozzle itself is mounted on two metal rails that serve as guides once the nozzle moves. A coupling connects the stepper motor to a threaded rod which goes through the nozzle. Since a small fastener (nut) is placed inside the nozzle, once the motor is powered on, the threaded rod begins to turn and consequently, the nozzle begins to move back and forth with a programmed sequence which helps to deposit the ink on the PCB Printing Board. Two cameras also form part of the assembly: an out-facing camera which will take pictures of the Earth, and an inward-facing camera which will continuously take pictures throughout the duration of the experiment which is not expected to last more than two minutes. As an added precaution, a Kapton enclosure will be placed around the printer assembly to mitigate any risks associated with ink run off which may in turn affect the components.

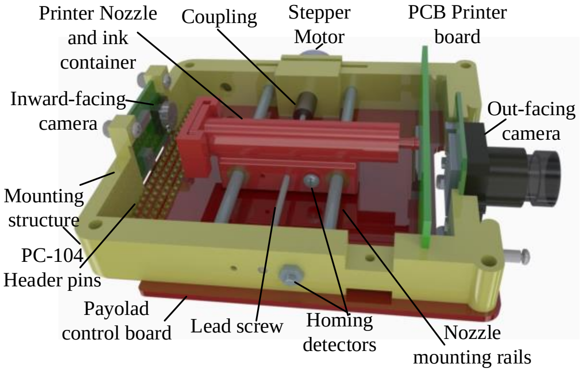


Figure 2: The single-axis 3D printer payload

Nozzle Stress Analysis

The static pressure calculated of the pressure exerted by the spring inside the nozzle was obtained at the maximum spring displacement observed when adding ink. At a maximum spring deflection of x = .8125 in, a spring force of 4.21lbf is obtained using Hooke's Law. That force is exerted throughout the pusher, which is about the size of the inside diameter of the nozzle. A total of 43.74psi is the pressure exerted on the nozzle using the equation P=F/A. Using SolidWorks simulation, a static pressure analysis was performed using the calculated pressure inside the nozzle and using the material properties of ProtoTherm. As shown in Figure 3, in the study, the maximum von Mises stress was 3.118*106 Pa (~452.2psi) which is less than the 70.2MPa tensile strength of the material, confirming that the material is able to withstand the pressure exerted from the spring.

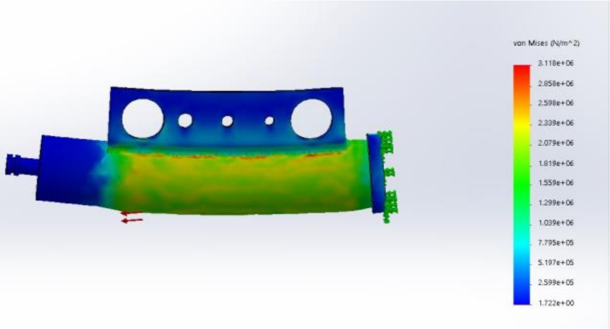


Figure 3: Nozzle Stress analysis results

Dynamic Modelling

The spacecraft will be deployed in LEO, as such, the displacement of the nozzle with respect the satellite is negligible in comparison with its orbital displacement. To describe the kinematics and dynamics of the 3D printer, the inertial frame *{I}* is considered to be coincident with the geometric center of the nozzle as shown in Figure 4. Another local frame *{P}* is located initially at the same position as {*I*} but attached to the nozzle so that it moves with it. Our mechanism represents a single-axis printer, then, the nozzle is allowed to move only in the *x* direction. The position vector of frame {P} is denoted by $\mathbf{n} = \begin{bmatrix} x_n(t) & 0 & 0 \end{bmatrix}^T$. The printer will move from *{I}* to a limit point *P* back and ford repeatedly to perform the simulated solar cell repair by build conductive traces using additive manufacturing techniques.

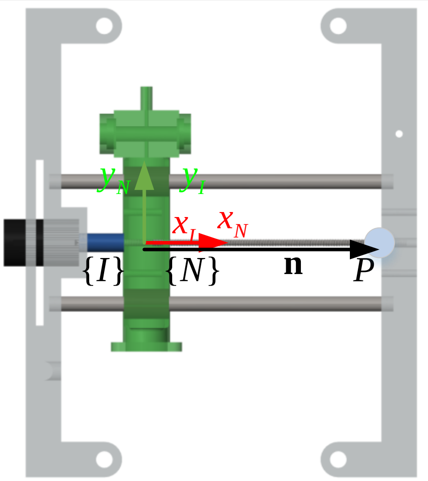


Figure 4: Printer nozzle dynamic model

The dynamic model of the printer nozzle is represented by:

$$f_d = f_f + m_n \ddot{x} \tag{1}$$

Where f_f is the friction generated at the different contact points of the mechanism, f_d is the force applied by the lead screw mechanism as result of the torque generated by the stepper motor and m_n is the mass of the nozzle. Equation (1) is solved to obtain the displacement of the nozzle, which is depicted in Figure 5.

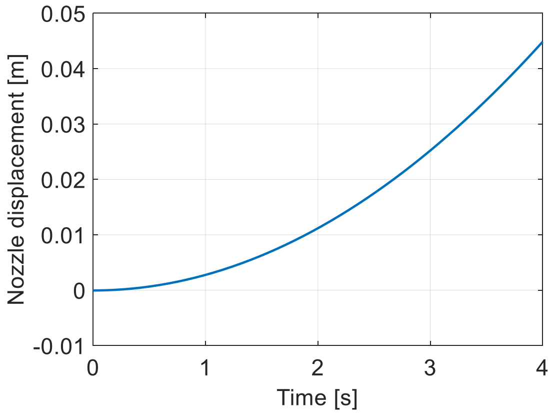
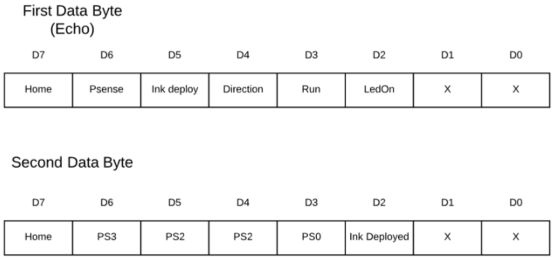


Figure 5: One cycle displacement of the nozzle in the x-direction.

Payload Control and Status Board

The payload control circuit is designed around the ability to control and read sensor statuses of the printer assembly operation. The center of the design is a MSP430FR microprocessor acting as an I2C slave to the OF-2 Onboard Computer Module (OBC) over the PC104 bus. All controls and status are contained in 2 bytes of I2C packaged data, as seen in Figure 6. The first byte of the I2C command is an echo response of the received command from the OBC. This serves as an error checking mechanism for the OBC. The second byte is a response generated by the payload MSP processor in response to the OBC command. Every I2C communication is contains these 2 bytes, regardless of state. With the exception of subcomponent timing and error detection, the OBC commands operations and requests all payload data and statuses.


First Data Byte
(Echo)

D7	D6	D5	D4	D3	D2	D1	D0
Home	Psense	Ink deploy	Direction	Run	LedOn	X	X

Second Data Byte

D7	D6	D5	D4	D3	D2	D1	D0
Home	PS3	PS2	PS2	PS0	Ink Deployed	X	X

Figure 6: Payload/OBC I2C protocol

Subcomponents for the payload control include the aforementioned MSP430FR microprocessor, 8 and 16 channel muxes, L293D stepper motor driver, illumination LEDs and burn wire Low R P-FET transistor switch. A. Molex micro headers connects the printer peripherals such as the stepper motor, FSR pressure sensor for ink deployment and burn wire. Another connector runs directly from the internal and external cameras to the SPI and UART buses on the PC-104 header respectively. Imaging is command by the OBC and has no connection to any of the printer operation or data.

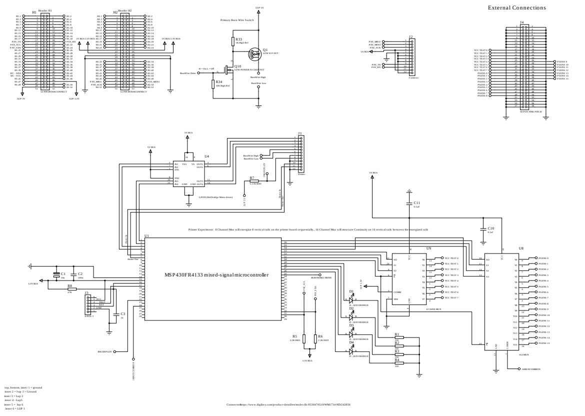


Figure 7: Payload control board schematic

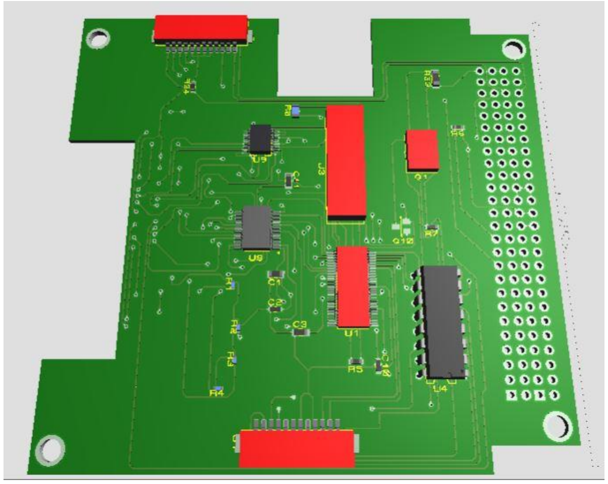


Figure 8: Payload PCB layout

The payload printer test board, figure 9, is design to simulate a broken solar panel assembly. The exposed traces are in the direct path of the printer nozzle as ink is deposited. Upon curing, every other trace will be energized with 5V though the 16-channel mux. The adjacent traces are then routed through the 8-channel mux and relayed to the microprocessor for transmission via I2C. The 8-channel mux inherently evaluated continuity based on TTL gate input signal criteria, where 2V to 5V is acceptable continuity represented by logic 1.

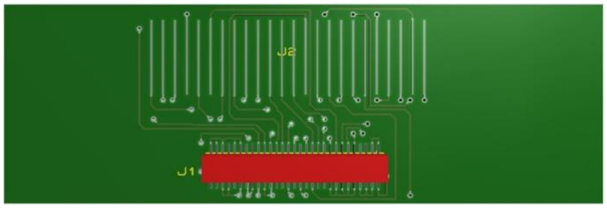


Figure 9: Payload printer test PCB

PAYLOAD TEST

Vibration

During launch, vibration is the first environment that the satellite must survive on its journey to space. Testing launch loads have been provided to comply with NASA guidelines and follow the random vibration profile. For the printer, surviving launch means that the connections (solder will not break), the rails do not break, the nozzle keeps the ink contained and wax plug remains intact, the printing PCB remains in place, and that the threaded rod does not break or bend and prevent turning of the nozzle. Several tests have been conducted in the shaker table, first to check that the wax plug would survive, which it visually did as no ink had escaped the nozzle. Then the whole assembly was then tested. A functional test was first conducted to check that the motor sequence could be performed. Then the printer was placed on top of a metal plate used for mounting to the table. The other ends of the connections were taped directly to the base with Kapton tape. Figures 10 and 11 shown the vibration tests results as seeing from the control accelerometer and the test specimen, respectively.

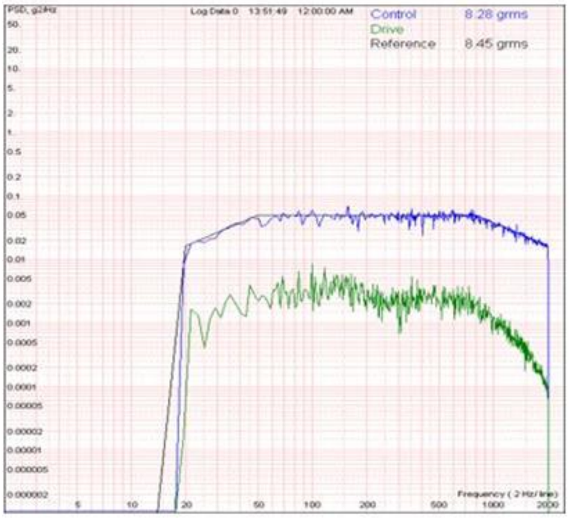


Figure 10: Vibration test and results along the x-axis. Data on the accelerometer

Figure 11: Vibration test and results along the x-axis. Data on the test specimen.

After running the vibration profile on the whole assembly, had survived as all the connections stayed intact, the printing PCB stayed in place, and the nozzle continued to be sealed. The motor did rotate a little, but it was because it had not been epoxied to the rails as intended in the final design. A second functional test was performed, this time after the vibration test, and the printing sequence was performed successfully.

Vacuum

Upon having a working prototype of the printer that worked in atmosphere, several tests have been conducted inside the vacuum chamber to further imitate the conditions in space. A printer assembly is placed inside the chamber with a bread board to route all connections. An Arduino is used to power the motor, and all connections are routed outside the chamber to two separate power supplies: one for the Arduino and one for the burn wire. After one hour in high vacuum ($*10^{-5}$ Torr), the experiment is conducted. First, the burn wire is activated to melt the wax. On average, it takes about 17 seconds for the wax to melt in vacuum. A visual confirmation of the ink coming out the nozzle tip serves as an indicator to start the printing sequence and deactivate the burn wire.

The printer then moves back and forth to deposit the ink trace on the printing board. In every test conducted in vacuum, whether it was a test to check the wax seal, a conductivity test, a functionality test, or else, the ink has always come out of the nozzle after activating the burn wire, except when a smaller amount of ink was once added since not much ink is used in the experiment. However, even adding more ink than necessary inside the nozzle body does not cause ink run off as it congregates inside the nozzle tip.

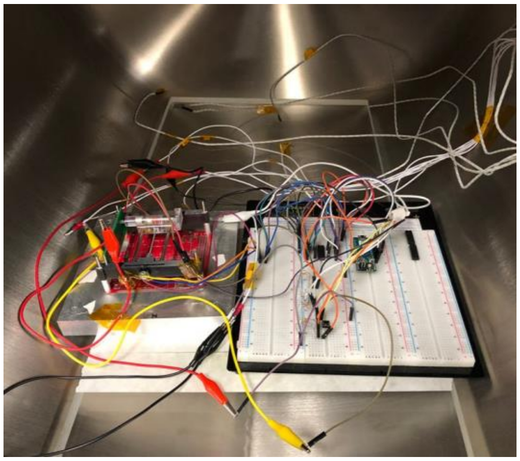


Figure 12: Payload inside the vacuum chamber to determine curing time of the ink.

During the test, the ink was correctly deposited on the PCB printing board and the electrical traces were conductive as an indication of the experiment success as observed in Figure 13.

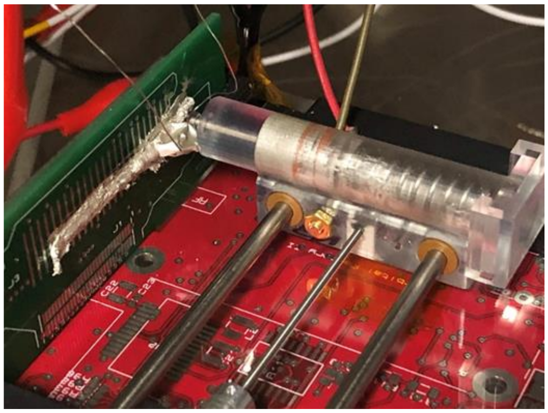


Figure 13: Ink deposition during vacuum test.

Conductivity Test

Ink cure time in vacuum provides a timeframe of when to check for ink conductivity in the test PCB during the experiment. The same setup from the vacuum chamber test was followed, with the addition of test pins added on the test PCB in the path of the ink trace, and the addition of a resistance between the positive pin and the pin on the test PCB. Before the ink cures, the voltage reading from the conductivity test are high since the circuit is open. When the ink cures, the circuit closes and the resistane drops to zero, and the voltage output drops towards zero as well. Figure 14 shows the equivalent circuit for conductivity test.

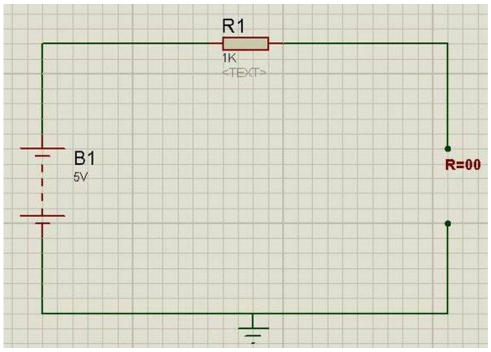


Figure 14: Electrical diagram to determine when the electrical trace has become conductive.

Immediately after the first pass of the printer to deposit the ink trace, the timing of the conductivity test started. An initial voltage output reading of 3.87V corresponded to an open circuit. After 90 seconds, the voltage output dropped below 2V, which is ½ of the initial voltage output. At 152 seconds, the output voltage started dropping below 1V. We consider the ink cures after ~90 secs. Please note that these 90 secs are counted after the first pass has occurred.

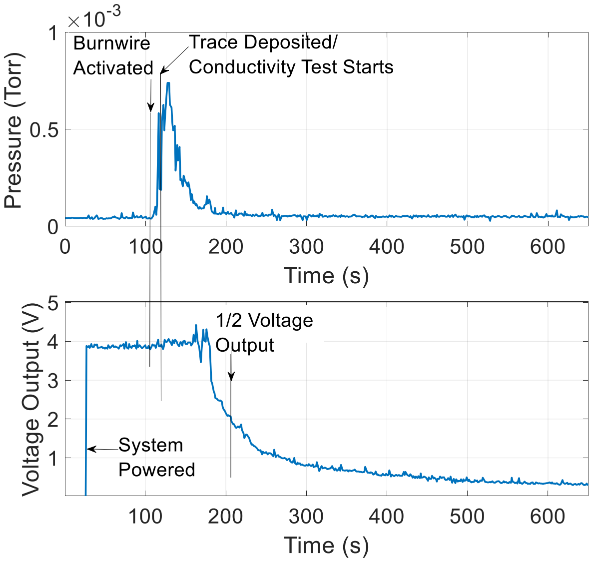


Figure 15: Ink curing test @ 10^{-3} torr

CONCLUSIONS

This paper presented the development and test of a single-axis 3D-printer mechanism that will be launched into LEO to perform additive manufacturing tasks to simulated the repair of a solar cell. Function, vacuum and thermal tests indicate the payload capability to operate in outer space. Additional tests of the fully integrated CubeSat will be performed to confirm overall operation.