Exploring Additive Manufacturing in a Space Environment - A Capstone Design Project Experience

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Abstract
This paper discusses the experiential learning from engaging in a capstone design project, which would answer the question, "Is it possible to achieve accurate additive manufacturing in a high external load environment such as within a sounding rocket?" With limited research available on additive manufacturing in space, conducting a 3D print on a sounding rocket platform provided valuable information for future such elaborate experiments in space. The additive manufacturing mission parameters were dictated by the 2021 - 2022 RockSat-C program and NASA Wallops Flight Facilities safety requirements. The experiment was conducted within a canister with a height of 4.5 inches and a radius of 9 inches. With these guidelines in mind, the team designed a small form factor FDM Bowden-style PLA 3D printer that would start printing upon rocket launch and be complete upon re-entry. This printer was subjected to 25 – 50 Gs of external force, 10 rev/s, and a vibration test. The printer needed to weigh no more than 4.3 lbs and needed independent power. Most of the structure was 7075 grade aluminum manufactured to support the printer. The power source was a custom 6V lithium polymer battery pack that was converted to a 24V DC to run the printer. Four small stepper motors and belts controlled all printer movement, X and Y-axis movement was mounted on linear rails for accurate motion under high stresses, and Z axis was controlled by a lead screw powered via a belt by one of the stepper motors. The direct drive extruder fed the filament into the micro hot end.

While the experimental setup was not able to credibly demonstrate additive manufacturing in space, the instrument powered ON. It was observed from the outcome of the experiment that there was a need to subject the battery and its circuit, structural components, and the printer head to 50 Gs of force. After the launch of the payload, inspection revealed a stress crack in the PLA motor mount, a loose battery, and filament that was not fed to the hot end. The team was able to see evidence of some extruded PLA and movement of the printer head. If shaft encoders, motor voltage requests, and thermal sensors been used, the team would have been able to “replay” the motions and states the components experienced. This data would have allowed for a troubleshooting process that would have allowed a process to improve the prior design weaknesses. These sensors will be used in the future, therefore mission results can be evaluated and improved upon.

Keywords

Additive manufacturing, In-Space Servicing, Assembly, and Manufacturing (ISAM), On-orbit Servicing, Assembly, and Manufacturing (OSAM), RockSat-C

1. Introduction
Additive manufacturing, a relatively modern and rapidly growing field, is a manufacturing strategy that provides a more efficient alternative to conventional methods of manufacturing.

Contrary to traditional methods like subtractive manufacturing where the process begins with a bulk supply of material and removes material until a final product is achieved, additive manufacturing produces objects by summating layers of the design material until the final geometry is achieved. By utilizing additive manufacturing, material waste is reduced in comparison to the subtraction process and higher levels of complexity and precision are possible. Despite substantial research and application of additive manufacturing in the real-world environment, the implementation of this process in the aerospace industry is continuing to develop under a cautious eye due to the high-risk environment for which it is intended.

The employment of additive manufacturing in the aerospace industry has the potential to be an advanced utility not only in the pre-flight production of aeronautical components and structures, but also for the on-board manufacturing of components and tools necessary for future space missions. Specifically, the ability to produce tools and structural components on the International Space Station provides the international space community the opportunity to make repairs and upgrades to the space station without wasting time and resources transporting such materials through additional rocket missions. Likewise, being able to produce parts and components on demand will also reduce the unnecessary transport of pre-determined spare-parts and leave room for more essential cargo with the weight alleviated. As mentioned by Zhang, Jin, and Zhang in their discussion of 3D printing applications in future manned space missions, 3D printing has the potential to, "greatly improve the efficiency, reduce the cost, enhance the support ability and promote the further development of space exploration activities," [2]. At the moment, the company Made In Space has actually developed a 3D printer, an additive manufacturing machine, capable of operating in microgravity and is currently being employed on the International Space Station [3]. Despite this achievement, the design capability of this 3D printer is limited to operating in a micro gravitational environment and withstanding the stresses of rocket transportation. Looking towards the future, it may become necessary to manufacture components during a rocket's launch trajectory given the extended launch sequence necessary for deep space travel or it may become necessary to manufacture components on planets that exhibit stronger gravitational fields than that of Earth's which would imply the operation of the 3D printer in a greater acceleration environment. As a result, the need for more robust structural and operational systems for 3D printing is evident and can be achieved through advancements in strength-weight ratios, mechanical drive systems, and dynamic control systems.

Research and development concerning additive manufacturing in adverse environments currently exists in the engineering field today but has not been tailored toward the space industry specifically and therefore necessitates attention towards the subject. Particularly, Rugged 3D [4] is developing and producing military-grade 3D printing systems designed to operate in rugged wartime environments where measures have been taken to mitigate impulses and temperature variations. Similarly, Ozark Integrated Circuits [5] is currently performing research on high-temperature 3D printer components for harsher environments. However, in order to operate in higher acceleration environments, the substitution of originally plastic and metal structural components with high-strength composite materials will be a topic of interest and may hold the key to achieving more robust structures without substantially increasing weight. Furthermore, the introduction of higher sustained stress levels may be problematic for belt-driven printer head systems and the reinforcement of this belt drive will be an important consideration regarding manufacturing accuracy and quality assurance. Considering the accuracy of the printer head, an upgraded dynamic control system will become necessary in order to detect print error and take corrective measures and appropriate mitigations to maintain the quality of the manufactured product. Focusing efforts into these aspects of the 3D printer design will improve the resilience of the machine and ultimately lead to the capability of additive manufacturing in high acceleration environments.

The design and implementation of a reinforced 3D printer intended for space application should prove to be a useful utility for future space missions and contribute to the conversation concerning additive manufacturing beyond our planet's orbit. Given the opportunity and platform provided by the RockSat-C program, the purpose of this study will be to:

- Research and potentially implement composite materials into the design of a 3D printer.
- Design and manufacture a 3D printer capable of operating under high acceleration and microgravitational environments.
- Produce a 3D printed control benchmark to be compared to a test benchmark 3D printed in the RockSat-C sounding rocket.
- Perform physical inspections and strength tests on the 3D printed benchmarks to assess quality.
- Collect environmental rocket data (accelerations, orientations, temperature, etc.) and adhere to all RockSat-C guidelines and requirements.

2. Team Composition

The 2022 Old Dominion University's (ODU's) RockSat-C team (Team Monarch-X) consisted of six undergraduate students as part of the core team and an academic advisor. The team also received significant and valuable support from a mentor undergraduate student who had participated in a previous RockSat-C competition. All the students and the academic advisor were from ODU's Department of Mechanical and Aerospace Engineering. Two of the undergraduate students had previous experience with additive manufacturing and one of those students had experience with additive manufacturing in an industrial setting too.

3. Technical Design

The initial phase of the project focused heavily on the research and development of a custom fabricated Fused Deposition Modeling (FDM) 3D printer [6] with a Bowden style extrusion system [7]. The FDM-style printers use melted plastic filament to its glass transition point to accurately construct the model. The 3D printing system consisted of 4 different subsystems - the structural subsystem, the XY axis subsystem, the Z bed subsystem, and the bottom plate that houses the components of the electrical system. Using the separate part files, the Monarch X team was able to construct a complete model in Fusion 360. The complete model can be seen in Figure 1 and consist of the 4 integrated subsystems where black components represent the structural system, yellow components represent the printer head as well as the electrical subsystem, red components represent the battery packs, blue components represent stepper motors, and gray components encompass the Z bed plate and the base mounting plate of the full system.

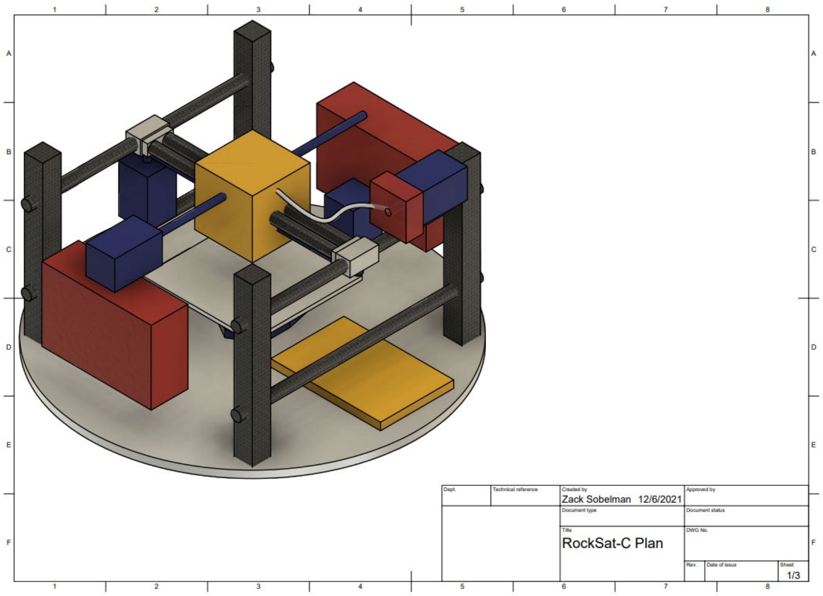

Figure 1: Overall Physical 3D-Model

Focusing on the different subsystems, the structural subsystem consists of two brackets that will serve as the rails to the Y-axis movement connected by another rail centered on the brackets that will serve as the X-axis movement of the printer head. The structural components will consist of either aluminum or composite materials. The structural subsystem will be supporting the XY subsystem as conveyed in Figure 2.

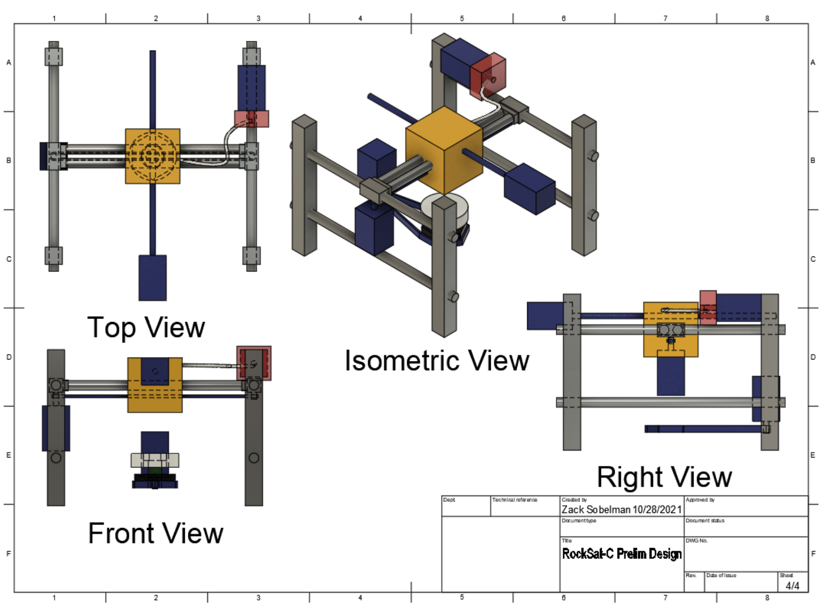

Figure 2: XY Subsystem Model

As mentioned before, the printer head will move along the two main rails to achieve Y-axis movement and along the single rail to achieve X-axis movement. In the illustration, the rails are represented by grey components, the printer head is represented by the yellow component, and the stepper motors are represented by the blue components. Movement in the Z-axis serves as its own subsystem as depicted in Figure 4. In order to achieve movement in the Z-axis direction, a screw and bearing assembly will be used to raise and lower the print bed and will have its own stepper motor.

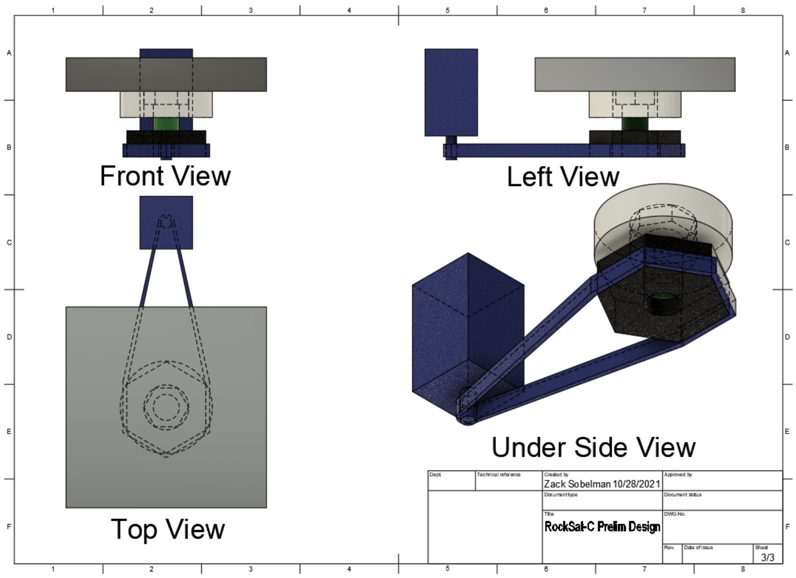

Figure 3: Z Subsystem Model

With the 3D models complete, significant progress can be made towards utilizing composite materials manufacturing by applying the cross-sectional Fusion 360 files. The 3D printer is currently being designed to operate with the printer head moving in the X and Y axis. Custom design aspects will be implemented to orchestrate the movement of the heated bed in the Z direction utilizing a bearing and screw assembly. Using such an arrangement is not commonly seen on stock 3D printers. Regarding the 3D printing-specific components, such as the stepper motors, print extruder, belts, filament, etc., stock parts from Creality [8] will be utilized and modified to fit project-specific design requirements.

In addition to the main structural/mechanical subsystems of the overall 3D printing system, the electrical subsystem will also be integrated and mounted on the base plate of the canister. The electrical subsystem will consist of two control boards, a Raspberry Pi and an Arduino, controlling the telemetry sensors and stepper motors/3D printing components respectively. The control boards will be powered by a 24 volt, 15 amp-hour battery supply that will be directed through a G-switch activation board which will restrict the operation of the 3D printing system to when the canister is subject to the accelerations present in the rocket flight environment. The battery supply is expected to be connected in series to meet voltage and amperage requirements while allowing for flexible distribution of mass. A flow chart style diagram is illustrated in Figure 5 and represents the electrical subsystem arrangement.

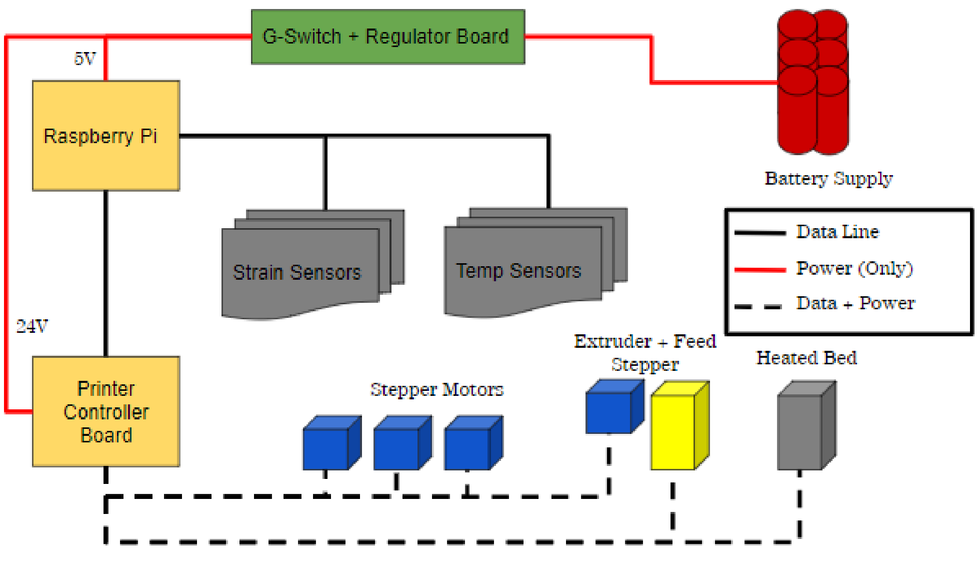

Figure 4: Electrical Subsystem Model

The manufacturing process has been divided into three main phases. Initially, focus was directed towards three-dimensional design and rapid prototyping in the first phase. The second and third phases consisted of manufacturing out of aluminum and composite materials to perform the necessary analysis and testing. The separation of the design phases provided a more structured approach to integrate the other subsystems into the design while providing ample time to troubleshoot any potential problems. After the first and second phases were completed, the Monarch X team began system and integrated system testing.

Testing of the manufactured system will consist of impact testing, acceleration testing, and rotational testing in order to subject the canister system to the same expected loads, stresses, and spin characteristics of the sounding rocket environment. This preliminary testing performed in-house (ODU) will ensure the survival of the system and the satisfaction of the design and safety requirements designated by Wallops Flight Facility (WFF). After conducting in-house testing, the full-canister system will be sent to WFF to undergo vibrations and acceleration testing. During the rocket flight/trajectory, the 3D printer system will print a benchmark during the initial ignition sequence that will qualify as the “high G” print and will continue printing the benchmark throughout the rest of the flight. The benchmark print is expected to be complete after the micro-gravitational (“micro G”) phase of the rocket trajectory but the system will still have time to complete the print on the rocket’s descent to ground. The total flight duration was expected to be approximately 15 minutes with a time in zero gravity of approximately four minutes. The print was expected to last longer than the time in zero gravity, so the print was to finish until complete. Final testing was conducted on the test print consisted of measuring the print’s dimensions, recording the 3D printer motor displacement, and basic tensile strength testing of the test print. Results of these measurements will be compared to values obtained from a control print that will be produced with the 3D printing system prior to flight. Success will be measured by the actual production of a printed object and a decided/standard margin of error that the Monarch X team establishes as minimum success criteria prior to flight.

4. Engineering Standards

Throughout system design and fabrication, we will be strictly adhering to the standards put for by Wallops Island Flight Facility, University of Colorado, and NASA guidelines, in accordance with the Rocksat-C user's guide [1]. Additionally, ASME standard parts have been procured to maintain consistency throughout design. ASME standard Y14.5 [2] was utilized for dimensioning and tolerances of structural components. AIAA S-114A-2020 [3] is the standard for moving mechanical components in relation to space flight. This AIAA standard was referenced for moving components such as our moving axis and linear rails.

Table 1: Wallops Island Flight Facility Standards Status

Standard	***Status/Reason (if needed)***
Center of gravity in 1" mid-can?	1.0" currently
Contained in can	
Connected to can by 4/5 bulkheads on top and bottom only	
Mass at 20±0.2lbs	4.5 lb (Margin used for mounting)
Shared canister clearance	Will not interfere, ½" separation between payloads
No voltage on the can	Checked integrated bottom plate; need top plate still
Activation wires at least 4 ft	
Activation wire at least 24 gauge, Teflon coated	22 gauge
Early Activation: current < 1 A	Not using
T-0 Activation: current < .1 A	Needs to be simulated/tested for check
Battery Type	Lithium Polymer (will not charge at Wallops)

5. Final Results

Testing has been conducted on all individual subsystems in addition to integrated system operation. In order to test our spatial design, our team printed 3D models of our printer structure to perform a test fit. Using the prototype structure, we adjusted and improved our CAD models as required to ensure the structure was within allowable tolerances. The electrical substems were individually tested by utilizing a complete and functional 3D printer. Each electrical component, to include motors and circuit boards, were integrated with the already existing 3D printer control board. By isolating the additional part, we were able to ensure correct operation and troubleshoot if necessary. This step streamlined future testing of integrated circuits.

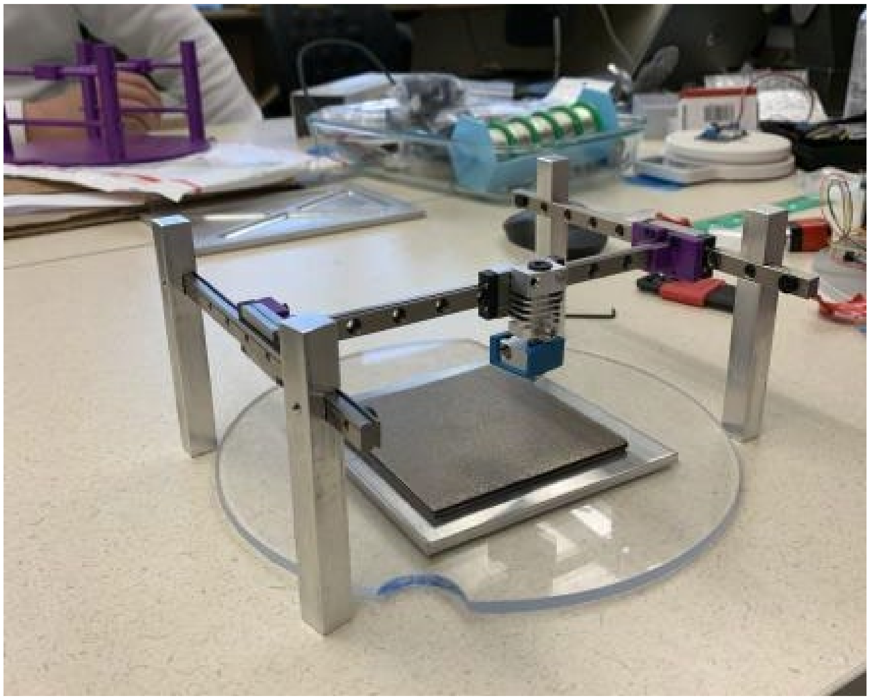

Figure 5. Structural Supports

After subsystem testing was completed, the team assembled of the individual parts and created an integrated design. Components were added sequentially to facilitate troubleshooting of faults immediately. This process resulted in a functional electrical control system with a self contained power supply, voltage regulator, and printer control board. Additionally, an LCD display is connected to provide an interface between the software input and the printer control circuit.

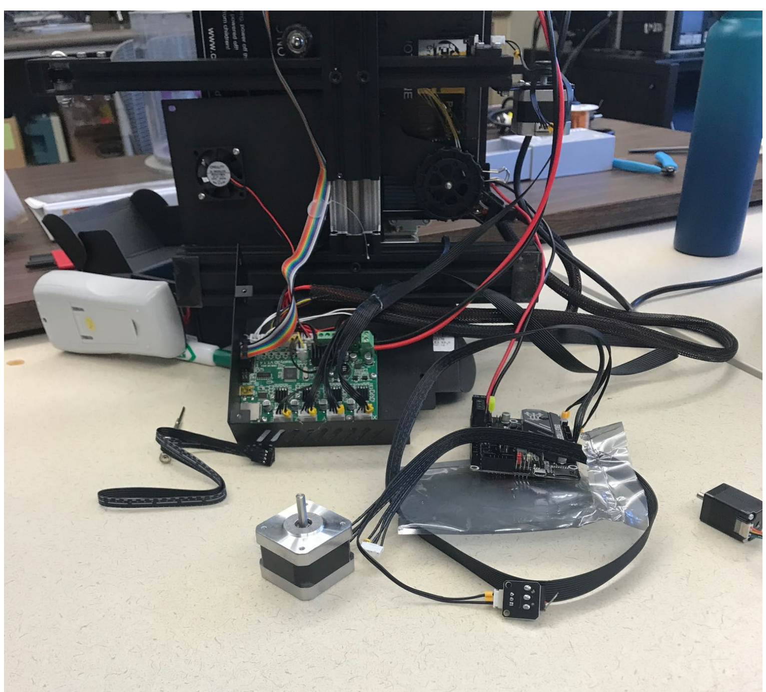

Figure 6: Individual Component Testing

The base plate was fabricated on campus at the machine shop. All drawings were submitted and reviewed, and the completed structure was fabricated in a short period of time. After this step, our team completed the structural and mechanical assembly to the base plate. Lastly, our completed electrical circuit was integrated into the mechanical system and full system operation was tested. The final test print was completed during the launch which occurred in June 2022.

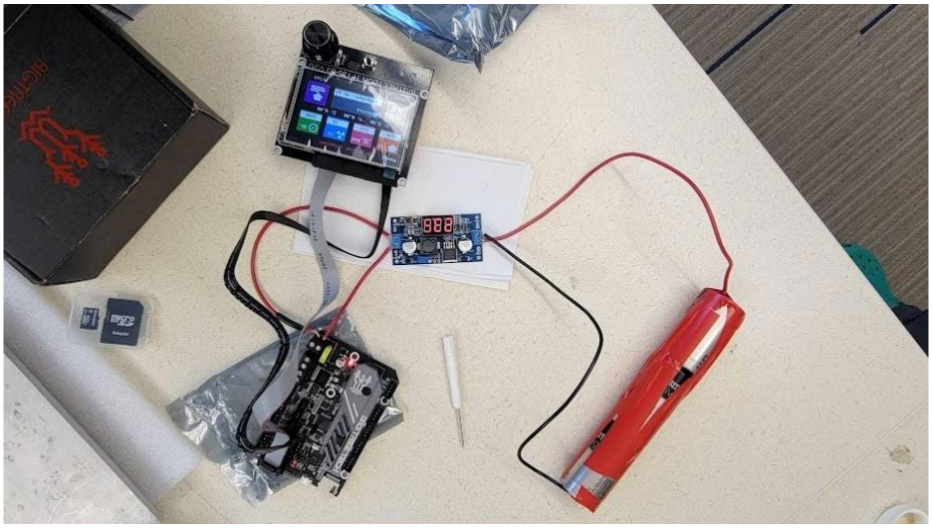

Figure 7: Integrated Testing of Electrical Subsystem

The payload section of the rocket was recovered via a parachute. The payload canister/capsule of the rocket was pressurized at approximately 2 atm. with nitrogen. The rocket was not set up with a camera and due to uncertainties, a detailed technical analysis is yet to be conducted. However, the lessons learned by the team members are captured in detail in the following section.

6. Discussion of Lessons Learned

Monarch X's purpose was to explore the practicality and accuracy of additive manufacturing while experiencing aggressive changes in gravitational forces, explored in a sounding rocket platform. This payload was a custom-made fused deposition (FDM) modeling printer. The printer had 3 axes of movement and an extruder system. Each movement action was independent with a singular stepper motor for each direction of movement. The extruder was a Bowden-style extruder where the stepper motor was static with a PTF tube going to the hotend of the printer. The hotend of the printer was a MicroSwiss all-metal extruder.

The mission parameters were set for the project by the 2021 RockSat-C program and NASA Wallops Flight Facilities safety requirements. The size of the printer was greatly constrained by the canister. These canisters were set by the RockSat-C program. Even though the small size of the payload restricted the build size, the short flight meant the print had to be a short print. The short print could be achieved by a small print or a quick printer. Due to budget constraints and limited time to design and engineer the payload, the print size could not be too large. The print that was attempted to be printed did not use the entire available print volume.

Some theoretical considerations with the adverse environment were microgravity, high vibrations during launch, structural integrity, limited print time, the print temperature of the nozzle, print bed, and payload capsule. The print temperature of the nozzle was slightly raised from normal printing conditions to ensure no clog of the nozzle. The bed temperature was the same as the ambient air temperature as a print bed was determined to need too much energy. The ambient temperature was not accounted for, however, with the isolated capsule, air currents would not impact the print, which can interfere under normal printing conditions. Vibrations were accounted for using lock-tight on all nuts and bolts. Space-grade aluminum was used for all structural components of the printer. Our print was a wrench that was flat and did not need support, this would mean the plastic would continue until it met the print bed and adhere to the print bed.

7. Conclusion and Future Work

Additive manufacturing is growing in popularity and usage in recent years. This includes the development of metal 3d printers and reduction of price and increase in reliability of plastic 3d printers. FDM printers have become cheap and reliable and are starting to become common in schools and maker labs. This has started a new ability for creators, young and old, to build their own creations at a cheap cost. This allows for those makers to design and iterate. This has already been used in countless aerospace applications. One great example of this is BPS Space, which started a YouTube channel to document the experiments of a model rocket that launches and lands itself using thrust vector control, similar to how SpaceX’s Falcon 9 lands its boosters. Additive manufacturing is also used for quick prototyping of systems to test complex systems.

Additive manufacturing is not just for makers and prototyping. NASA has experimented with it on the ISS to demonstrate that additive manufacturing is a possibility in a zero gravity environment, and this technology can be used to transport material in bulk for printing replacement parts. It can be used for maintenance, upgrades, etc., in zero gravity to extend the lifespan of isolated spacecraft. NASA has envisioned the use of Mars soil to make a radiation and weather shield from a modular base under the 3D printed shelter.

Mass and volume are generally the two constraints in getting things to space. This means the volume of space stations is constrained by the volume of current rockets that can get into orbit. If additive manufacturing technology develops to be able to reliably print metals in space, the only constraint on space stations would be mass. However, since the raw materials can be shaped and formed by the 3d printing process, multiple rockets can be used to bring the material into orbit. If this technology is achieved, it would greatly improve humanity’s ability to explore and expand in space. To look even further into the future, raw materials could be collected from other planets and even asteroids to be processed and then used to print spacecraft. Even though these technologies are very far in the future, the first step to these futuristic dreams is FDM machines like the one on the ISS and the one we used in our project.

Many things need to be researched and studied before any of this can become a reality. Thermal conductivity in space in space will have to be modeled to ensure proper printing in a microgravity environment with no convection. Created heat would need to be dissipated using radiation. Although we have cooling technologies in space, disappearing the amount of thermal energy needed for additive manufacturing would need a lot of research. Developing additive manufacturing in conventional settings. This starts with furthering additive manufacturing technologies. This can be industry leaders developing the technologies, like Huntington Ingalls Industries developing techniques to use powder bed fusion additive manufacturing or furthering commercial and consumer 3d printing technology.

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