ISS-GAS 2022 PROPOSAL

NOVEL METHOD OF 3-D PRINTING IN MICROGRAVITY

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Contents

DATE: July 10, 2020
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SUBJECT: ISS-GAS Proposal: Novel Method of 3-D Printing in Microgravity

I. Introduction

Recently, NASA announced the revival of the getaway special (GAS) program in order to promote more small experiments in space. Purdue University's Student Space Programs Lab has provided our group with funds and resources to develop a possible experiment that fits the mission profile for the new ISS-GAS program. We have prepared this proposal for you to review and to demonstrate what success of this experiment on the Q1 2022 Dragon could mean for science. We will outline our reasoning for developing this experiment, our research on previous methods, and our preliminary design. Then, we present a tentative timeline for completion of the work, as well as anticipated results.

Today, astronauts aboard the ISS depend on resupply missions to ferry parts, tools, and supplies from the earth, sometimes waiting weeks or months for critical maintenance supplies. As humanity ventures farther into the solar system, these cargo resupply missions will become more costly and complex. Alternative manufacturing techniques are currently being researched to become a tool for astronauts in space to fabricate necessary parts and supplies on-demand [1].

Humans must employ advanced manufacturing techniques in order to further the development of space. 3-D printing is one such technology that will pave the way for future space exploration by allowing the shipping of raw materials for fabrication in space. This will open new doors for structures that can be built in space and other planets. To better understand how to best 3-D print in space, we have developed an experiment to test self-powered, low-temperature printing in microgravity. This proposal explains the details of our goals for the experiment and beyond.

II. Project Description

A. Background

The recent addition of a 3D manufacturing facility to the ISS has changed the way NASA thinks about performing repairs [2]. Made In Space's Additive Manufacturing Facility (AMF) won the bid for an extended test period on the ISS after performing well during parabolic flight testing. Starting in 2016, this device has been printing specialized tools, replacement parts, and small structural pieces for the space station [3].

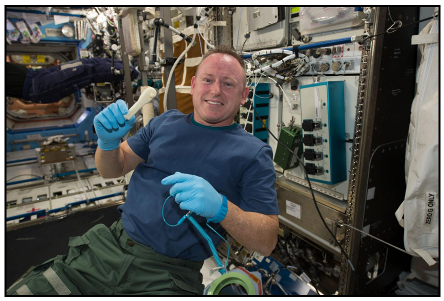

Figure 01. NASA Astronaut Barry (Butch) Wilmore holds a 3-D printed ratchet wrench from the 3-D printer aboard the International Space Station [3].

The AMF uses Fused Filament Fabrication (FFF), a process where a thermoplastic filament is melted and then forced out a nozzle in thin lines. These lines are then layered on top of each other to create 3D objects. Because of the incredible variety of thermoplastics available to modern engineering, the parts can have carefully chosen properties that reflect their intended uses. However, the layering process requires that higher layers be added on top of already existing layers, or the plastic will not be extruded properly. The process of printing without supporting material underneath is called "overhanging." There are some conditions where "overhangs" are successful, but it is difficult to predict and can change the expected fit or properties of the part. The team at Made In Space advises against printing those parts, as any potential failures are very expensive [4].

The limiting factor of the AMF is the maximum size of the parts that can be created. All discrete parts that are printed using the AMF must fit entirely within the 140x100x100 mm print volume [4]. This represents the extremes of the print head travel during operation. Since the development of the AMF, there have been several advancements in Earth-based 3D printing technology. One promising development has been the conveyor belt 3D printer. This modification to traditional FFF printing involves using a movable belt as the print bed. Additionally, the YZ-plane of the printer is tilted at an angle. These two changes allow for two significant improvements over the traditional setup. The first is an effectively infinite print direction along the x axis [5]. The print bed will move the conveyor as more layers are deposited, and complex profiles can be extruded for large distances. Secondly, an angled direction of deposition changes the orientation of "overhangs" and makes previously impossible parts more feasible. The idea of a belt 3D printer is still in development on Earth, but has promising space applications.

Figure 02. An image of the BLACKBELT 3D printer, a commercial solution that is currently available for purchase [6].

B. Concept

Our team at the SSPL has designed a proof-of-concept experiment primarily to evaluate the performance of a conveyor belt 3D printer in zero gravity. This experiment will be entirely self-contained in the ISS-GAS capsule and will run several prepared prints automatically with zero human interaction after initiating the process. After the experiment is completed, the ISS-GAS capsule will be returned to Earth, and the printer and printed parts will be studied to compare with the same models printed on the surface. The ISS-GAS capsule will stay at atmospheric pressure for the duration of the testing. The following is the expected timeline of our proposal.

1. Timeline

Phase 1: Ordering and receiving of parts (October 2020 - February 2021)

Once approved for the proposal at the end of Q3 2020, orders of the components to the printer will be placed. We will allow extra time for parts that are manufactured by other companies on-demand.

Phase 2: Construction (February 2021 - June 2021)

The construction will take into account mounting the printer and other components to a structure that allows a solid and limited vibration design to ensure components inside the canister will be safe during launch and throughout the remainder of the trip. The general structure will follow a cylindrical shape that follows the inside of the canister. The wiring for the power source and circuitry will be completed during this phase too.

Phase 3: Testing functionality (June 2021 – August 2021)

This period will be to test the functionality of the product. With many chances for error in electronics and mechanics, this phase allows for troubleshooting and any redesign considerations that need to be addressed. Testing will incorporate printing several copies of the prints that will be tested once in space. These prints will be measured to ensure that dimensions follow the tolerance of 10%.

Phase 4: Safety testing (August 2021 – September 2021)

The safety of those in contact with the project and those that could be possibly affected by any failures is a top priority. We will look into preventing failures that could be unsafe such as wiring shorts.

Phase 5: Preparations for launch (October 2021 - January 2022)

The project will be delivered to the site where the project will be reviewed and approved by NASA. The printer will then be fitted and placed inside the GAS container where it will wait for the upcoming launch. Any last details, questions, or concerns prior to launch between us and NASA will be covered here.

2. Physical and Electrical Requirements

In order to be eligible for launch the proposed printer needs to meet specific requirements. Basic size requirements need to be met in order for our experiment to fit into the canister provided by NASA. The printer and batteries needed must fit into the canister which has a radius of 19.75 inches and a height of 28.25 inches. The printer and batteries must also fall within the 200 pound limit for launch. These physical requirements ensure safe transportation and successful completion of our proposed mission.

The physical components required for our apparatus consist of five groups of components: structural, motion, hardware, heating, and electronics. Individual parts and materials for each of these groups were carefully selected to meet the requirements for safe travel and execution in space.

For the structural and hardware components, special considerations were made to insure resilience to vibrations caused by space travel would compromise the experiment. Aluminum extrusion was selected for its strength to weight ratio, cost effectiveness and versatile design for modularity. The machined slots on the exterior faces allow optimal placement of hardware for apparatus construction and capsule mounting. Misumi 20 x 20 (Figure 3 left) and 20 x 40 (Figure 3 right) 5-Series aluminum extrusion was selected to frame our project. Aluminum and rubber washers were implemented between the 20 x 40 extrusion on the mounting points in the capsule to limit vibrational transfer to the apparatus.

The hardware to assemble the apparatus will consist of series-5 metric screws to match the aluminum extrusion slots and mounting points to the capsule. The brackets and external part mounts will be constructed out of carbon fiber nylon with a 3D printer. This material when printed allows for optimized parts with an internal lattice structure reducing the overall weight of the apparatus without sacrificing strength.

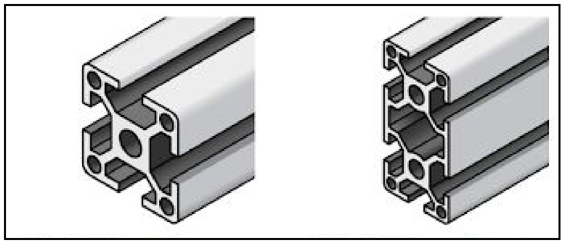

Figure 03. Misumi Series 5 Aluminum Extrusion 20mm x 20 mm and 20mm x 40 mm

The motion components enable our concept to have controlled linear and rotary motion to successfully print parts. Our concept adapts a CoreXY belt configuration to control the x-axis and y-axis motion during a print [7]. CoreXY is an approach for achieving two-dimensional cartesian motion where two motors work together to move the print head in the x and y-axis. In reality CoreXY motion can commonly be seen in an Etch-A-Sketch [7]. This form of XY motion was selected because it consumes less power per print compared to other methods and achieves better print quality. To control this motion linear rails, idler mounts, and two NEMA 17 stepper motors are mounted to the 20 x 20 mm extrusion framing of the XY plane.

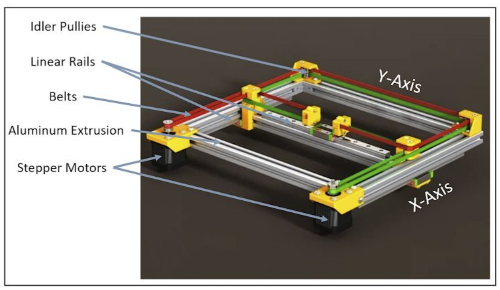

Figure 04. CoreXY motion system for 3D printing Nozzle [16]

One of the goals of this project is to access the ability to adapt additive manufacturing to an assembly line process to streamline mass producing objects in space. Our design implements a conveyor belt as the z-axis print bed for infinite printing length. To achieve this the CoreXY assembly is mounted to the conveyor belt at a fixed 45-degree angle. Refer to figure 2 on page 4 for reference.

The heating components for this design is a print nozzle designed for zero gravity printing created by a company called Made In Space. Their nozzle has successfully executed simple 3D prints in microgravity environments.

The Duet 3D Duet 3 Main Board was the selected electronics board for this project. The Duet 3 Mainboard contains a 32-bit processor in an open-source format allowing us to control the apparatus externally with a Raspberry Pie. This board allows for room for expansion in this project with additional pinheads for more motors, sensors, and heating components. In addition, this board is capable of running on 12, 24, and 32-volt power allowing us to use the same electronics board on future iterations of this project.

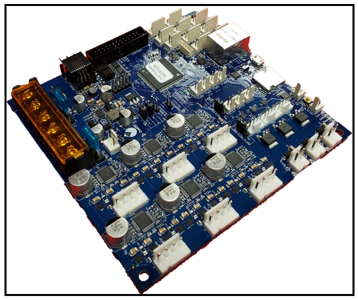

Figure 05. Duet 3D open-source Duet 3 Main Board 6HC

Neither the Dragon Capsule nor the ISS will provide our experiment with any electrical supply. This means that our proposed experiment will need to transport and house its own power supply.

The printer will contain six lithium-ion batteries wired in parallel. Each battery has 7.2V, 2,200mAh, and 15.8Wh giving an estimated minimum print time of six hours. Six hours is a sufficient amount of time that allows the models to be printed. Since the batteries are lithium-ion, a safety precaution must be taken to ensure a difference in voltage between the batteries does not draw a large amount of current that could damage the project or those in contact with the project. To ensure that current cannot flow in the wrong direction, diodes will be placed before the positive terminal and after the negative terminal on each battery. By adding diodes, current cannot travel in the wrong direction which could be potentially harmful. A DC to DC constant-current constant-voltage (DCDC-CCCV) booster will be in place after the batteries and diodes to provide a constant 12V and 5A supply to the printer. This booster will set the needed power source to the printer at the desired supply and hold it there.

Once inside the canister, minimal interaction will be made to start the printer's test. A preloaded file will already be downloaded into the printer. This file will contain the code to home the printer and prepare the printing process without human assistance. A push-button located on the top of the inside of the canister will need to be pressed to initiate the printer's sequences once in space. The printer will run its minimum six hours before powering itself off without the aid of an operator.

C. Risk Assessment

1. Electrical Risks

During launch and operation, it is important to mitigate and manage electrical risks to the Dragon capsule, ISS, and printing equipment. One area of concern is electromagnetic interference (EMI) from electrical components in use for our experiment. The canister provided by NASA is 16 millimeters thick on the sidewalls of the cylinder and 76 millimeters thick on the bottom and top. This thickness provides ample shielding from EMI that could be transmitted from the experiment and to the experiment [8].

Another large area of concern is the storage and transport of the batteries for the experiment. Lithium-ion batteries were chosen for their excellent characteristics. However, with Lithium-ion batteries, specific risks exist. Lithium-ion batteries can experience internal short circuits when they are not properly cared for. If exposed to high temperatures or physically damaging conditions the battery can short. When the battery shorts the lithium metal comes in contact with organic compounds used to store energy and can result in smoke and fire [9].

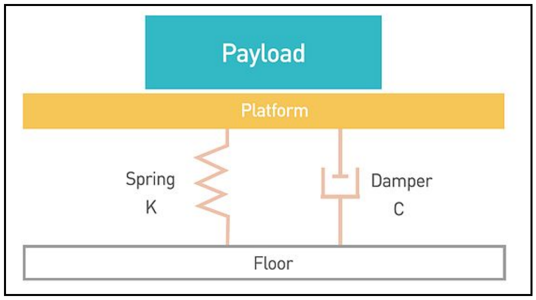

Figure 06. Vibrational Insulation for Battery Payload Example [10]

In order to prevent overheating and physical damage, several specific steps will be taken. Securing batteries on a plate that is dampened will allow for mitigation of vibrationally induced damage during launch and reentry, see Figure 6. Additionally, specific lithium batteries with cells that are insulated from one another will allow for a halt of any reaction that may occur. Finally, the batteries will be enclosed in the canister provided by NASA and thus should not be exposed to temperatures higher than temperatures within the normal ranges. Combining these mitigation strategies will ensure a low risk for our use of Lithium-ion batteries for our experiment.

The controller and wiring of the system are already at low risk for damage and failure during the experiment. However, in order to prevent unseen occurrences, extra steps will be taken to further lower risk. In order to lower the risk of disconnection during launch cables will be fastened down to the sidewalls of the canister. Additionally, each cable will be braided and measured so that there is minimal slack to prevent both shorting and interference.

2. Risk of physical damage

More so than normal experiments, this experiment will be exposed to extreme conditions that may lead to failure of the experiment. In order to prevent failure, redundancies, and mitigation strategies have been used. To prevent damage to the printing head active vibrational dampening systems have been applied to the printing nozzle. This active damping will ensure that the sensitive nozzle does not become damaged during launch. The nozzle mount will also have a secondary nozzle in case of failure of the first.

The general structure of the printer is also prone to damage during launch. In order to ensure the success of the mission, it is imperative to prevent snapping of control arms for the printer head or cracking of the printing bed. The control arms will be made out of thicker and stronger material than normal to minimize risk. Additionally, the bed will be secured in a similar fashion to the Lithium-ion batteries to reduce vibrations on the bed and to prevent cracking.

D. Intended Outcomes

The intended outcome of this project focuses on the capabilities of additive manufacturing with Fused Filament Fabrication (FFF). For this experiment, we want to compare the print quality of the Made In Space nozzle configured in the infinite z-axis angle of 45 degrees with and without gravity present. The experiment will be considered successful if the parts that are retrieved after landing display properties that match or excel the properties of the parts printed on earth.

To determine the quality of the prints made while in orbit, all pieces will have a set of tests run on them. The first will be a detailed visual inspection of each part. If any printed part shows signs of failure of the plastic to properly fuse together, or if there are miniature holes or gaps in the layers, these will be noted and studied. Also, various stress and strain tests will be performed on different axes, to determine the part's strength and reaction to high strain. These tests will characterize the basic static properties of the material, and these values can be compared to the parts printed on earth.

All results from the studies on the final parts will be traced back to the functionality of the printer while in orbit. The differences in quality will lead to the set of decisions that our team will take in changing and improving our printer for the future.

E. Further Advancement

There are several directions in which the belt 3D printer can be taken in the future. If the results of this experiment are promising, we will look into pursuing a more direct collaboration with NASA and Made In Space to possibly establish a usable model onboard the space station. This will open the possibilities to more advanced thermoplastics with better material properties. Of course, our model will have to be adjusted to handle these material changes.These changes will possibly require further studies as they are added.

The advancements to the space manufacturing industry by having a printer like this on the space station would be enormous. Currently, companies NanoRacks and Made In Space have a partnership where a set of standard components are stored on the ISS, a prospective satellite design is sent up to have the structural parts 3D printed, and then the entire device is assembled in orbit [12]. The satellite is then deployed via bespoke launchers from the ISS into a set of possible orbits. This process is currently being tested and will be fully operational by Q1 2021 [13].

With a belt printer onboard the ISS, the parts for these on-demand smallsats will not have to be limited to the 1U component size that they currently are. Larger pieces could be easily manufactured and assembled, allowing a wider range of missions to be entirely built in orbit. This would save massive amounts of money that would be spent launching parts that were manufactured on Earth.

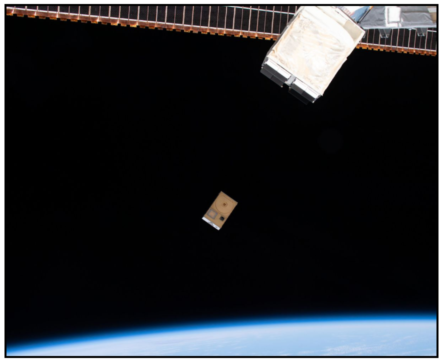

Figure 08. A photograph of a 2U CubeSat being deployed by the NanoRacks launch rails onboard the ISS [13].

In addition to this specific satellite project, a larger print size would assist in making even more repairs or additions to the ISS and future space stations. All components that are currently in use on the ISS were limited by the size of the Space Shuttle's cargo bay, as the shuttle had the most efficient method of carrying finished products up to low Earth orbit. The 112 ft long solar panel arrays had to be carried up in several pieces, as the space shuttle bay was only 60 ft long [14]. With manufacturing facilities for large parts in space, then large arrays similar to the ones on the ISS could be designed to take advantage of hundred-foot long prints using advanced materials.

This idea can be taken even further into the future. There have been several designs for spacecraft that are impossible to manufacture on Earth, or would not be able to survive the stresses put on spacecraft during launch. The most studied type of craft like this is the solar sail. These are ships that are propelled by the force of sunlight hitting the incredibly lightweight film "sail" [15]. Testing is already being done on this form of craft, but the most efficient theoretical sails are too fragile to be manufactured on Earth and would have to be made in space [16]. This would be a great opportunity for other types of fabrication machines to be operational in space, to serve as a sort of shipyard for crafts that can go further and faster than before. Testing the concept of large 3D printers here would be a great way to begin experimenting with large-scale construction off-Earth.

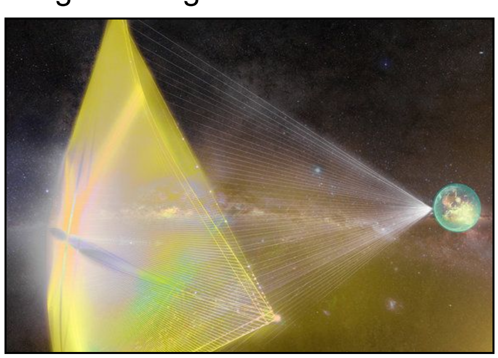

Figure 09. A render of a CubeSat-based solar sail that will be 3D printed and deployed by Cornell University in 2020 [15].

III. Conclusion

This experiment is written in conjunction with the researchers at Purdue University Student Space Programs Lab (SSPL), a working group dedicated to providing undergraduate students with the opportunity to conduct research devoted to space flight projects. We work alongside faculty and industry partners to design, fabricate, and integrate space systems. In the past, Purdue students involved with SSPL have delivered payloads for multiple high-altitude balloons, microgravity experiments, sounding rockets, and space shuttle GAS missions. The Cosmic Printers are confident that working with SSPL will bring this vision of 3-D printing to life.

Space is a vital part of human history and it's future. Cosmic Printers believes that 3-D printing in space will allow for unforeseen progress and advancement in our world and beyond. With proper research and development, the applications of additive manufacturing in space could revolutionize mission requirements for space travel. Providing humanity with the tools to colonize the moon and distant planets or even safely travel farther into deep space will provide inspiration for generations.

As a group of seasoned aerospace engineers, we are sure that our expertise in the field and practical knowledge will ensure the safety and success of the project. We will use the background that Purdue's SSPL has in successful space launches to ensure that every step of the manufacturing, testing, and validation will be up to professional standards. We urge you to accept this proposal for the ISS-GAS program, as we believe that our project will take an important step in advancing humanity's space manufacturing capabilities.

Thank you for taking time to consider this project. We look forward to hearing from you in the future.

Any questions can be directed to the cosmic printers can be sent to Purdue SSPL at print.sspl@purdue.edu, or to the office at (765) 494-3006.

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