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Effects of Microgravity on Extrusion based Additive Manufacturing

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Made In Space, Inc. participated in four weeks of microgravity testing with NASA's Flight Opportunities Program during the Fall of 2011 and Summer of 2013. The company tested the effects of microgravity on custom built and commercially available extrusion additive manufacturing machines, more commonly known as 3D printers. The testing took place on board a modified Boeing 727 aircraft flown by the Zero-G corporation, in conjunction with NASA's Reduced Gravity Office and Flight Opportunities Program. The company has utilized the knowledge gained through this campaign on the project that will deliver the first 3D printer to the International Space Station (ISS). 3D printing in space is an enabling technology that is crucial to the exploration of space beyond the low Earth orbit environment. In order for 3D printing to finally be realized as a permanent fixture in space exploration, the behavior must be fully understood in microgravity. Various 3D printers were flown and tested, as well as multiple individual sub-components. With some modification to the key systems, Made In Space was able to demonstrate that additive manufacturing with extrusion-based machines functions similarly in microgravity as it does on the ground, allowing for a full proof of concept. The microgravity flights enabled the Technology Readiness Level (TRL) of the technology to be elevated to a TRL-6.

I. Introduction

MADE In Space, Inc. was founded in 2010 and is based out of NASA's Ames Research Park. The company initiated the directives to build the infrastructure for in-space additive manufacturing. Three progressive goals were to[1]:

- **Study** the underlying physics and fundamentals of 3D printing in the microgravity environment by flying 3D printers on a microgravity flight.
- **Adapt** commercial 3D Printing technology for use in microgravity.
- **Fly** a 3D printer on board the ISS.

All of these goals were aimed at implementing additive manufacturing in space within a short three year time frame. Made In Space accomplished the first goal, to study the effects of 3D Printing in microgravity under a contract with NASA's Flight Opportunities Program (FOP). The FOP program provides flight opportunities for space technologies to be tested in relevant environments. Under this contract Made In Space flew a series of reduced gravity flight campaigns to study the effects of extrusion-based additive manufacturing in micro-, lunar-, and Martian- gravity. These flight campaigns were conducted during the months of July, August, and September of 2011, and again in June of 2013. In 2012 Made In Space took the lessons learned from the initial FOP campaigns and designed the 3D Printer for the ISS, satisfying the second goal of adapting commercial 3D Printing technology for use in microgravity. Now on the third goal, Made In Space is currently building the first printer under a Phase III contract that will launch to the ISS on SpaceX-5 in 2014.

Additive Manufacturing (AM) has only recently become a competing manufacturing method to typical methods such as CNC Machining. This is due to the increasing capability in micro-electronics, micro-computers, and microcontrollers over the past two years that has allowed for precision controlled mechanical drives at relatively low cost.

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Unlike today, in the early 2000's additive manufacturing was not commercially capable of building complex geometries out of titanium, aluminum, and space grade polymers with tolerances approaching precision CNC machined parts. Conclusively, in 2002, a method was proposed by Skycorp for in-space assembly of a spacecraft in which all components would be built on the ground and shipped to space[2]. The main benefit was the clever packaging of components for launch could reduce final structural mass of the spacecraft components. Reducing spacecraft mass has many obvious advantages, and thus the idea was quite valid. However, with today's additive manufacturing capabilities another layer of abstraction can be removed for in-space assembly of a spacecraft when it incorporates in-space manufacturing.

While the general consensus a decade ago didn't recognize the benefit of AM for in-space manufacturing, some pioneering work had been performed at Marshall Space Flight Center by Ken Cooper. In 1999, recognizing the potential for AM to achieve the goal on in-space manufacturing he began to test various AM methods in simulated microgravity environments.

Testing a circa 1999 Stratasys Fused Deposition Modeling (FDM) 3D printer on its side, Cooper found that the extrusion based technology could still function without gravity acting in the typical direction. In later tests, Cooper flew the same extrusion-based FDM machine on the NASA KC135 reduced gravity plane[3]. These flights mark the first and only other documented microgravity 3D printing tests flights aside from those made by Made In Space.

These reduced gravity flights marked the near end of Cooper's research on this subject. Some of his final recommendations for moving forward were:

- Acquire candidate polymer hardware geometry currently stocked as spare parts on the space shuttle or station, and fabricate these designs using ground-based FDM systems with ABS plastic.
- Determine build time requirements for each component, in order to properly schedule parts to be built in space during a short duration mission.
- Determine maximum allowable factors for a space-based demonstration FDM unit, including weight and physical dimensions, environmental effects, i.e. toxicity, heat output and power consumption limits.
- Determine, from parts inventory and feasibility study, the maximum build envelope capacity of the reduced FDM system.
- Design and build part storage containers for safe return of test articles to Earth.
- Place the FDM demonstration flight unit in the queue for Space Shuttle flight experiments.

The technology finally began to catch up with Cooper's vision a decade after his research began, when Made In Space conducted its own microgravity flight testing in 2011.

II. Research Goals

The fundamental concepts of what parameters are capable of working in microgravity had to be learned before significant progress could be made in the technology. Parameters such as feedstock flow rates, extruder temperatures, construction materials, environmental controls, power sources, and general sizing of all components had to be investigated before the design of a 3D printer for space could be solidified.

During the microgravity flight campaigns, the Made In Space team set out with a list of research goals:

- Confirming that extrusion-based 3D printing works in microgravity.
- Researching and understanding the fundamental physics of 3D printing microgravity and its effectiveness when compared to ground-based 3D printing.
- Investigate the feasibility of using commercially available components and machines in microgravity.
- Determine how to adapt commercial technology to function in microgravity to reduce the time from initial concept to final flight design.

The primary objectives for the flight campaigns was to evaluate the functionality of extrusion-based 3D printing for use in microgravity environments. Initial experimental plans stemmed from the work by Cooper et al., which was the first study of an extrusion-based 3D printer in microgravity. The first goal was to replicate the work done in 1999 to establish a baseline for future research within Made In Space.

Moving beyond the replication of the Cooper study, another primary goal was to understand on a deeper level just how well the manufacturing process works in microgravity. Very little empirical data exists to establish certainty that the manufacturing process compares well to Earth built parts when built in reduced gravity. Therefore, it was extremely important to validate the extrusion-based process by studying characteristics such as layer adhesion, layer height, and strength of the 3D printed parts created in microgravity.

Initial hypothesis for the functionality of 3D printing in microgravity stemmed off the previous research. It was hypothesised that the 3D printing would function in microgravity similarly to how it would nominally function in

Earth gravity. No change in layer heights or strength of printed parts was expected as a result of the microgravity environment.

III. Experiment Setup

Due to power, mass, and budget constraints a simple experiment box was constructed out of 80/20, 10 series aluminum rails and Acrylite FF panels. Three 3D printers were chosen to be installed within the experiment box for the flights. The first printer chosen was the Extended Structure Additive Manufacturing Machine (ESAMM) which is a Made In Space 3D printer designed to build structure larger than itself. The second choice for a printer was MakerBot brand 3D printer. The MakerBot was chosen to test the functionality of 3D printer that is on the lower end of the price market and is widely available to the public. The last 3D printer chosen to fly was Bits From Bytes' BFB 3000. The BFB 3D printer is a more advanced commercially available printer. Aside from minor alterations to the structures in order to properly secure the 3D printers to the experiment box, the MakerBot and BFB had no alterations made to the internal workings of the 3D printers at the beginning of testing.

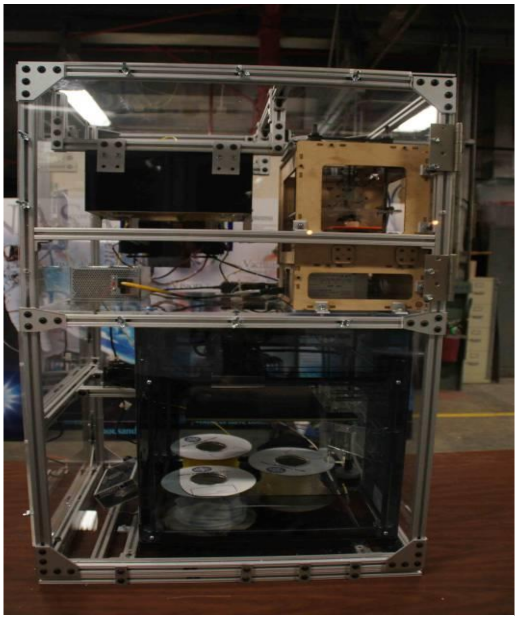

Figure 1: Experiment Box 3D printers Mounted.

The ESAMM and MakerBot printers were placed on the top half of the experiment box while the BFB was placed in the lower half of the experiment box as shown in Figure 1. The experiment box was designed to function with minimal interaction from the flight crew during the parabolas. The addition of high definition cameras at strategic locations to capture the printing process ensured that the flight crew would have video data to analyze after the flights in order to make adjustments where necessary.

The outside of the experiment box contained a series of D-rings that allowed cargo straps that were connected to the aircraft floor to be attached to the experiment box. The straps were mounted within a 60" x 60" area around the 24.5" x 29.5" experiment. The location of the experiment box within the aircraft is shown in Figure 2.

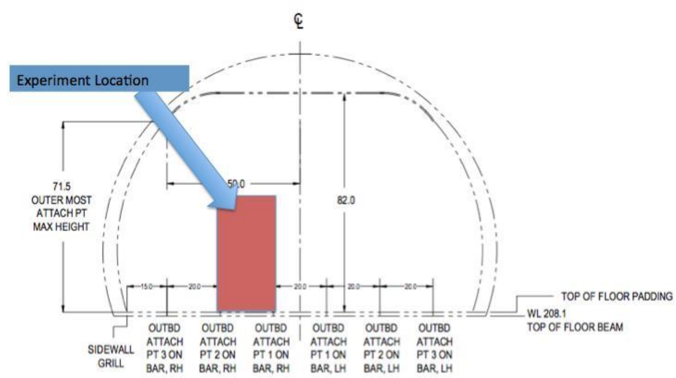

Figure 2: Location of Experiment Inside Aircraft

The 3D printers in the experiment box each had a specific purpose and job to complete during the flight campaigns. The purpose of the ESAMM during the flight campaigns was to build a core sample and operate throughout the entire flight, thus creating parts that were built in fluctuating gravity environments, and prove the functionality of the ESAMM in a microgravity environment. The MakerBot printer and BFB 3D printers were not altered for the first flight campaign in order to determine their functionality in microgravity environment straight "out of the box." Once functionality was determined, the MakerBot was tasked with creating coupons to determine material properties when printing in a reduced gravity enviroment. The BFB was tasked with building columns during reduced gravity that would later be analyzed for layer thickness. The BFB also printed the same columns while on the ground before flights in order to obtain a baseline value for layer thickness.

IV. Experiment Methodology

The final experiment box layout and the 3D printers chosen for the microgravity flights came as a result of the weight and power limitations of the aircraft in which the experiment was mounted in for the flights. These limitations are in place to ensure the safety of personnel aboard the aircraft.

Since the experiment had relatively low prior development, some issues arose during the initial flights. The commercially available off the shelf 3D printer tests revealed areas that needed modification to work in microgravity. Several 3D printer mechanisms experienced issues working properly outside of Earth gravity. It had been anticipated that such modifications would be required and so the first flight week video data was used to determine the required changes that had to be made to each individual printer in order to ensure proper functionality in microgravity. It was observed during the following flight weeks that the proper functionality of the 3D printers had been restored after a large amount of modifications.

The purpose of the columns construed by the BFB 3000 was to determine the difference in layer to layer resolution of a 3D printed part made in different gravity regimes; one-g, Lunar-g, Martian-g, and microgravity. The main question to answer was how do the layer thicknesses differ in a 3D printed part in various gravity regimes? Subsequent questions were on the feasibility to control the layer-to-layer resolution in different gravity regimes to equal that on Earth. To characterize the layer-to-layer resolution, layer distance was defined as the distance from mid-point of two consecutive layers, as shown in Figure 3. The columns printed during the flights were stained with graphite to expose the ridges of individual layers.

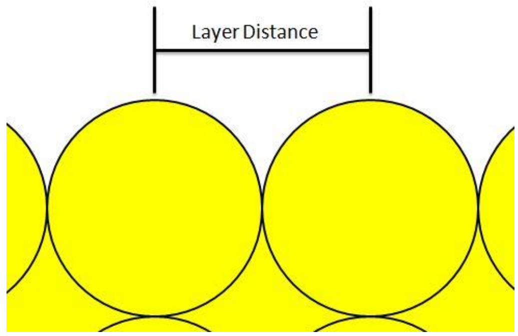

Figure 3: Definition of Layer Distance Represents Mid-Point of One Layer to the Next

A location on the sample was then chosen and photographed at 400x optical zoom, at a 1600 x 1200 resolution, using a Veho VMS-004D Digital Microscope and the MicroCapture software. The microscope was calibrated by capturing an image of a micrometer scale, which allowed for the image frame size to be calculated. The tolerance on the measured values was +/- 12 µm. This particular method of measuring was chosen over others due to the non-destructive nature of the process.

V. Results

Over the course of the three flights weeks several parts were manufactured on each of the 3D printers. During the first flight week the Made In Space designed ESAMM was tested and was found to produce parts identical to those built by the ESAMM in the laboratory. The MakerBot and BFB 3000 mechanisms experience issues functioning in microgravity, and the first flight week was spent making modifications to the printers in order to establish nominal functionality.

During the second flight week a larger focus was placed on the BFB 3000, the most advanced of the 3D printers tested during the flight campaigns. During this week sample columns were built. Each column was built during the microgravity portion of the flight, this resulted in a core sample that had been built in only one gravity regime.

The third flight week offered some new testing opportunities. First and foremost, flying both Lunar and Martian parabolas allowed for new data sets to be collected on manufacturing under those gravity regimes.

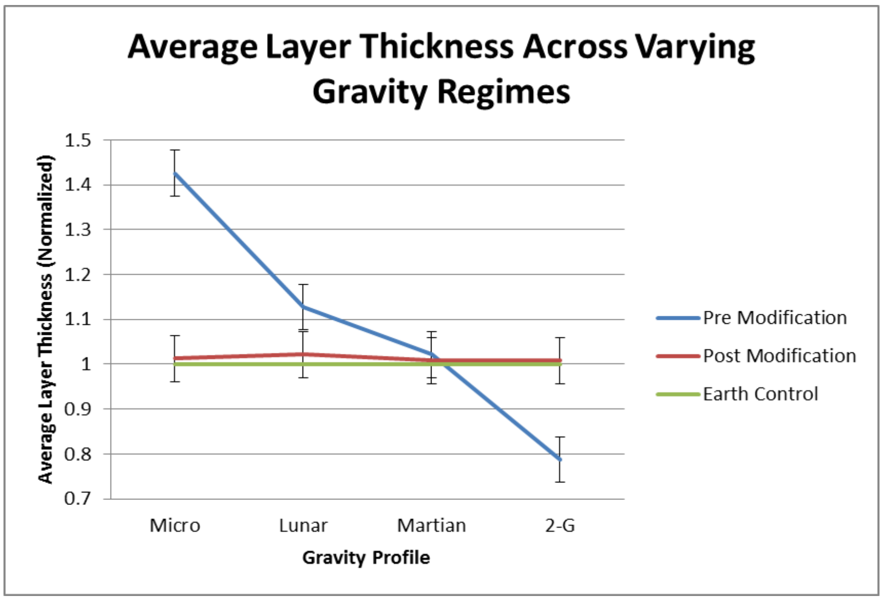

Figure 4: Average Layer Thickness Across Varying Gravity Regimes

The data gathered for the layer thickness for all of the flight campaign is presented in the Figure 4.

This graph illustrates the changes in the layer thickness of the parts printed during the different gravity regimes. The data has been normalized so that the averaged nominal prints in the control fall on 1 on the graph and the remaining data scales equivalently. The parts that were built before the 3D printers were modified had larger layer thickness than the ground samples. The deviation from the ground samples decreased as the gravity regime became closer to Earth gravity. Samples built in microgravity had larger deviations from the ground samples than those built in Martian gravity.

After the 3D printers were modified the deviations from the Earth samples was minimized. The values for the layer thickness across all the gravity regimes was close enough to the Earth samples that any deviations from the Earth samples could be accounted to the error in measurement (+/- 12 µm).

VI. Discussion

The goal of these experiments was not only to demonstrate that extrusion based 3D printing works in microgravity, but it was also a way to determine what commercial components work in microgravity and what components need to be modified in order to properly function in a reduced gravity environment. The goal of demonstrating extrusion based printing in microgravity was achieved as many parts were built during the reduce gravity portions of flight such as the ones shown in Figure 5.

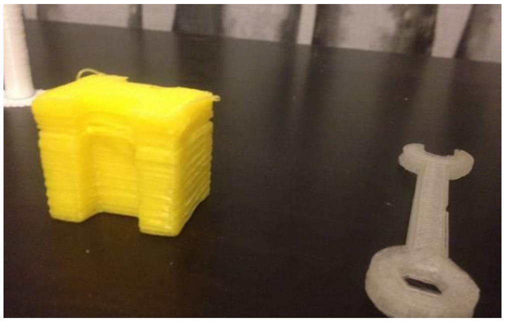

Figure 5: Two Parts Printed in Microgravity; a Standard ESAMM Coupon and a Wrench

The secondary goals of determining if commercial printers function in microgravity was also achieved. The MakerBot and the BFB 3D printers both required modifications to their internal workings in order for the 3D printers to function properly in microgravity. The changes were achieved during the first flight week and an example of the results can be seen Figure 6.

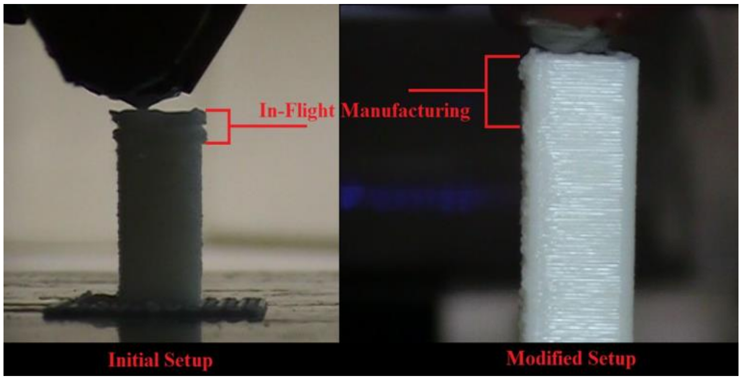

Figure 6: In Flight 3D Printed Part Before and After Modification

Made In Space used the findings from these experiments to design the 3D Printer for the ISS under a NASA contract in 2012. Due to the nature by which the 3D Printers were modified to work in microgravity a secondary benefit is that they also would work in all other gravity regmies as well. In the end, the 3D Printer developed for the ISS is essentially a gravity indpendent 3D Printer; the first of it's kind.

In June of 2013 Made In Space brought a prototype of this 3D Printer on another parabolic flight campaign. Testing of the device showed that it was indeed gravity independent. The first version of this technology to fly to the ISS will arrive in 2014 on SpaceX-5.

VII. Conclusion

Overall, the three flight weeks presented an amazing amount of opportunity and fast paced research and development for Made In Space. Having just three weeks between each flight week caused the team to rapidly developed experiment modifications and data processing from previous flight to prepare for the next. This fast paced development helped advance the company much further and faster than if the flight opportunity was not available.

The flight opportunity was extremely successful. The initial goal of understanding how well the 3D printing process works in microgravity was met, and additional questions were answered. The data collected has helped solidify the Made In Space business model and provide steps forward to the next phase of the mission-flying a 3D printer to space.

The next steps for maturing the technology comes in two forms: First, continuing to analyze the parts that were 3D printed during the 2011 and 2013 microgravity flight weeks. Second, pushing the technology to the next level, specifically into the space environment.

Made In Space will launch and integrate the in-space 3D printer with the ISS in 2014. Once integrated, the in-space 3D printer will undergo further research and the capability will be further demonstrated by building usable and workable parts for the crew. The company will then seek to build a business around 3D printing parts and hardware in space, further advancing the technology and its uses.

References

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[2]Wingo, D., "Transforming Spacecraft Economics Via On Orbit Assembly," *Space Daily* [online article], URL: http://www.spacedaily.com/news/satellite-tech-02a.html [cited 15 July 2013].

[3]Cooper, K.G. and Griffin M.R., "Microgravity Manufacturing ViaFused Deposition," Marshall Space Flight Center, Marshall Space Flight Center, Alabama, USA, NASA/TM - 2003-212636, July 2003.