

3D Printing In Zero-G ISS Technology Demonstration

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The National Aeronautics and Space Administration (NASA) has a long term strategy to fabricate components and equipment on-demand for manned missions to the Moon, Mars, and beyond. To support this strategy, NASA and Made in Space, Inc. are developing the 3D Printing In Zero-G payload as a Technology Demonstration for the International Space Station. The 3D Printing In Zero-G experiment will be the first machine to perform 3D printing in space. The greater the distance from Earth and the longer the mission duration, the more difficult resupply becomes; this requires a change from the current spares, maintenance, repair, and hardware design model that has been used on the International Space Station up until now. Given the extension of the ISS Program, which will inevitably result in replacement parts being required, the ISS is an ideal platform to begin changing the current model for resupply and repair to one that is more suitable for all exploration missions. 3D Printing, more formally known as Additive Manufacturing, is the method of building parts/ objects/tools layer-by-layer. The 3D Print experiment will use extrusion-based additive manufacturing, which involves building an object out of plastic deposited by a wire-feed via an extruder head. Parts can be printed from data files loaded on the device at launch, as well as additional files uplinked to the device while on-orbit. The plastic extrusion additive manufacturing process is a low-energy, low-mass solution to many common needs on board the ISS. The 3D Print payload will serve as the ideal first step to proving that process in space. It is unreasonable to expect NASA to launch large blocks of material from which parts or tools can be traditionally machined, and even more unreasonable to fly up specialized manufacturing hardware to perform the entire range of function traditionally machining requires. The technology to produce parts on demand, in space, offers unique design options that are not possible through traditional manufacturing methods while offering cost-effective, high-precision, low-unit on-demand manufacturing. Thus, Additive Manufacturing capabilities are the foundation of an advanced manufacturing in space roadmap.

I. Introduction

The 3D Printing In Zero-G Technology Demonstration (3D Print) serves as a proof-of-concept test of the properties of fused filament fabrication additive manufacturing in the microgravity environment of the International Space Station (ISS). The lessons learned from this technology demonstration will be applied in the next generation of fused filament fabrication in the permanent Made In Space (MIS) Additive Manufacturing Facility (AMF), as well as for any future additive manufacturing technology. This includes any future additive manufacturing technologies the National Aeronautics and Space Administration (NASA) may plan to use, such as metals or electronics in-space manufacturing, on both the ISS and missions to deep space. This demonstration is the first step towards realizing a manufacturing capability in space. The 3D Print project's goal is to raise the technology readiness level (TRL) of the 3D Printing In Zero-G printer technology from 5 to 6, making it the first demonstration of additive manufacturing in space. The lessons learned are infused into industry with the production of the permanent AMF.

A. History of Fused Filament Fabrication at NASA Marshall Space Flight Center

Fused filament fabrication was developed and then later commercialized during the late 1980s and early 1990s. Fused filament fabrication is the process of extruding small beads of a thermoplastic material and additively applying layers to build a three-dimensional structure. The filament material is

typically fed through an extrusion head, and the material hardens nearly immediately creating a solid base for the next additive layer to be applied. The additive layers for a 3D structure are created by applying various mathematical algorithms to a computer-aided model to define the additive layer thickness, the rate at which the filament material is forced through the extruder head, and other parameters that may affect the physical design and mechanical properties of the final product. There is current research for on-ground applications to better understand the effects of these parameters that aids in the development of a public database for AM design and fabrication both for on-ground and in-orbit applications. 3D Print leverages terrestrial technology to drive innovation for in-space sustainment and human exploration.

NASA Marshall Space Flight Center (MSFC) procured a fused filament fabrication system in 1993 with intentions to develop a system for space flight operations on-board the ISS. MSFC worked with the vendor to evolve previous technology to expand the operational temperature range for the melting and additive layering of filament material. With a wider temperature range, more filament materials were developed and tested. Originally working with waxes and nylon filament materials, current filament materials used include acrylonitrile butadiene styrene (ABS), polyphenylsulfone (PPSF), polycarbonate (PC), and Ultem 9085. Known material properties and toxicology levels make ABS and Ultem 9085 filament material candidates for on-board 3D printed structures.

With Johnson Space Center and Milwaukee School of Engineering as partners, fused filament fabrication endured further testing in the lab environment as a viable in-space manufacturing process. In the summer of 1999, the technology advanced further when a total of four flights were successfully conducted on NASA's KC-135 aircraft. The fused filament fabrication system experienced a weightless environment due to the KC-135's parabolic arc flight path. The total flight time was 10-12 hours with a total time of one hour and twenty minutes spent in a weightless environment. Due to nature of the parabolic arc, continuous operation time in a weightless environment is limited to around 25 seconds.

B. NASA's partnership with Made In Space

The California-based company accurately called "Made In Space" came to be in 2010 with the goal of sending a 3D printer to the International Space Station. After several KC-135 flights awarded through NASA's Flight Opportunities Program during the summer of 2011, Made In Space was awarded a Phase 1 from NAA Small Business Innovation Research (SBIR) program in December of 2011 to further study and understand technical requirements of potentially 3D printing in zero-gravity. A technical interchange meeting occurred at MSFC in the fall of 2012 with NASA subject matter experts in various technical disciplines, payload integration, and crew operations and Made In Space. In January of 2013 and then February of 2013, Made In Space was awarded a Phase 2 SBIR and a Phase 3 SBIR, with contracts to provide flight-certified hardware and an ISS-bound flight.

Under the guidance of NASA MSFC, Made In Space reduced technical risk by building a ground test unit (GTU) to be similar in form, fit, and function as the flight unit and back-up flight unit. The GTU was tested prior to the Critical Design Review (CDR). Preliminary testing that consisted of vibration testing, electromagnetic interference/compatibility testing, and acoustic noise emission testing occurred in the summer of 2013. Certified-flight hardware in the form of a flight unit and a back-up flight unit were delivered to Johnson Space Center for payload integration in June 2014. Delivery to the International Space Station is scheduled to occur in the fall of 2014.

II. Goals of 3D Printing in Zero-G ISS Technology Demonstration

The International Space Station is the only currently available true test bed to begin to understand the impacts of zero-g on fused filament fabrication. Along with broadening the technical understanding of the physics affecting the material characteristics of 3D printed parts, the 3D Printing In Zero-G project goals and objectives include:

1. Perform extrusion-based additive manufacturing with ABS filament material on-board the ISS
2. Demonstrate nominal extrusion and traversing activities

3. Perform 'on-demand' print capability via computer-aided drawing (CAD) file uplink for requested parts as defined
4. Mitigate functional risks and design risks for future facilities and technology advancements
5. Test print volume scalability
6. Replace and refill filament material (i.e. feedstock) on-demand
7. Perform science, technology, engineering, art, and mathematics (STEAM) outreach activities



Figure 1 Front view of the MSG Engineering Unit used for integration testing.

Additive manufacturing is a critical enabling technology for NASA to grow the in-space manufacturing initiative. It provides the capability to produce hardware on-demand, directly lowering cost and decreasing risk by having the ability to manufacture a specific part when needed in the time required to design a part, upload a file, and print. The capability provides the much-needed solution to the cost, volume, and up-mass constraints that prohibit launching all supplies needed for long-duration or long-distance missions beyond Earth, including spare parts and replacement systems. A successful mission for the 3D Printing In Zero-G project is the first step to demonstrate the capability of printing on orbit. The data gathered and lessons learned from the technology demonstration help to advance the next generation of additive manufacturing technology on orbit. It is expected that additive manufacturing technologies will quickly become a critical part of any mission's infrastructure.

III. Set-Up and Operations

The 3D Printing In Zero-G hardware to include the printer and the electronics box are expected to operate within the Microgravity Science Glovebox (MSG) within the ISS. MSG provides the power source and a level of containment. As part of the flight-certification process, physical and electrical integration of the hardware was

performed with the MSG Engineering Unit located at NASA/ MSFC. Figure 1 shows the printer and the electronics box inside the MSG Engineering Unit for testing. The 3D Printing In Zero-G Technology Demonstration uses a minimal amount of astronaut crew time with printing being monitored by payload operations on Earth. Software used to operate the printer is compatible with laptops currently on the ISS.

IV. Capabilities Enabled To Provide On-Orbit Solutions

The ability to manufacture components on-orbit alleviates the need to appropriate mass prior to launch and creates flexibility of resources as well as enabling a new way to design solutions to common problems.

A. Replacement and Repair Needs on the ISS

Based on the Problem Resolution and Corresponding Action (PRACA) database maintained by NASA on the ISS, approximately 28.6% of parts that require replacement are plastics and composites.

These parts include but are not limited to gaskets, hoses, valves seals, retainer brackets, and lubricants. Table 1 shows the results of the PRACA database as described by material and/or use.

Replaceable Part on the ISS	Percentage Total (%)
Electrical and electronics	29.6
Plastics and composites	28.6
Metallics	16.5
Ceramics and glass	7.3
Total replaceable	82.0

B. Cases for Applying 3D Printing On-Orbit

There are many cases for applying 3D printing on-orbit. They include but are not limited to the following:

- 1) **Known and Predicted Repair:** As parts wear and degrade with use and time, a preventative maintenance program could be established to avoid the need to stockpile these known parts. This reduces required stowage volume of geometrically-invasive parts and is replaced with filament material loaded on a compact feedstock cartridge.
- 2) **Known Production and Assembly:** Structural and geometrical constraints caused by launch loads and vehicle stowage requirements may be by-passed in order to build components in space and to take advantage of the absence of gravity.
- 3) **Unknown Repair and Replacement:** The ability to create makeshift replacement parts while waiting for resupply could prevent flight experiments from losing critical operation time as well as possibly serving as a life saver in critical human systems equipment.
- 4) **New Experimentation Advantages:** Given the opportunity to build freeform structures in space environment, researchers on the ground and on-orbit alike can discover new and interesting ways to use the technology. One such opportunity is to include educational aspects where students can design and build parts in space.

The 3D Printing In Zero-G project demonstrates the capability of utilizing additive manufacturing technology in space. It serves as the enabling first step to realizing an additive manufacturing, print-on-demand “machine shop” for long-duration missions and sustaining human exploration beyond low-earth orbit, where there is extremely limited ability and availability of Earth-based logistics support.

V. Future In-space Manufacturing Technology Development

Looking into the future, there is a suite of technologies that need to be enabled fully utilize the effectiveness and efficiency of in-space manufacturing to enable human exploration. The path forward includes completing the design lifecycle by developing technologies, databases, and processes that aid in verification and validation of 3D printed parts on-orbit by 3D scanning printed parts, characterizing and understanding the behavior of the printed materials, and broadening the definition of “parts that can be built” with 3D printing. A recycling system to reuse material after a printed part has been utilized helps to further strengthen in-space sustainment with limited resupply from Earth. Leveraging ground-based technology developments to enable in-space manufacturing of functional electronic components, sensors, and circuits to print electronics on-orbit is a precursor to building “on demand” satellites when couples with 3D printed structures. To be prepared for deep-space exploration and habitation in the future, research and technology development concerning the utilization to additively construct structures from in-

situ materials is incorporated into the in-space manufacturing technology development roadmap. The 3D Printing In Zero-G Technology Demonstration is the crucial foundation to advance the in-space manufacturing technology roadmap.