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NASA's In-Space Manufacturing Project: Update on Manufacturing Technologies and Materials to Enable More Sustainable and Safer Exploration

Tracie Prater, Ph.D.[a]*, Jennifer Edmunsson, Ph.D.[b], Mike Fiske[b], Frank Ledbetter[c], Ph.D.[c], Curtis Hill[b], Meyya Meyyappan, Ph.D.[d], Christopher Roberts, Ph.D[a], Lawrence Huebner[e], Phil Hall[a] , Niki Werkheiser[d]

[a] NASA Marshall Space Flight Center
[b] Jacobs Engineering, ESSCA contract, NASA Marshall Space Flight Center
[c] MIPPS contract SME, NASA Marshall Space Flight Center
[d] NASA Ames Research Center
[e] NASA Langley Research Center
* Corresponding Author (tracie.j.prater@nasa.gov)

Abstract:

NASA's In-Space Manufacturing (ISM) project seeks to develop the materials, processes, and manufacturing technologies needed to provide an on-demand manufacturing capability for deep space exploration missions. The ability to manufacture and recycle some parts on demand rather than launch them from earth has the potential to reduce logistics requirements on long duration missions and enhance crew safety. With the launch of the first 3D printer (built and operated by Made in Space through a Small Business Innovative Research – SBIR -- contract) to the International Space Station (ISS) in 2014, the ISM project demonstrated the feasibility of operating an on-demand manufacturing system in a microgravity environment. This paper will provide an update on recent advancements in ISM under three key technology areas: manufacturing, recycling, and development of a design database.

ISM continues to pursue development of manufacturing technologies for space applications and use the ISS as a critical test bed to prove out these technologies before deploying them on next generation exploration systems. Activities under this focus area include: characterization of materials manufactured using the Additive Manufacturing Facility (AMF), the second generation commercial 3D-printer on ISS, also owned and operated by Made in Space; development of prototype payloads for metal manufacturing through phase II SBIR contracts with Tethers Unlimited, Made in Space, and Ultra Tech Machinery; development of a multi-material fabrication laboratory capable of processing metals and providing inspection of manufactured parts through a Broad Agency Announcement (Techshot, Interlog, and Tethers Unlimited); an in-line sensing system for ISM platforms; and development of higher strength feedstocks for 3D polymer printers.

In the area of recycling, the Tethers Unlimited Refabricator payload (an integrated 3D printer and recycler for ULTEM 9085) launched to ISS in November 2018 and began operating in early 2019. This payload represents the first demonstration of on-orbit recycling; downmassed specimens will assess material degradation in the polymer over multiple recycling cycles to define limits on material re-use. Other work in the recycling area includes development of common use materials intended to be reused and recycled on space missions (Tethers Unlimited and Cornerstone Research Group) and a sterilization capability for multiple-use materials (ERASMUS from Tethers Unlimited). Concurrent with manufacturing technology and materials development work is creation of a design database, a curated list of parts that can be manufactured using the suite of In-Space Manufacturing capabilities.

Acronyms

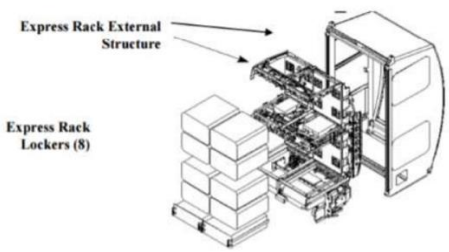
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
AMF	Additive Manufacturing Facility
AMI	Actuated Medical, Inc.
ARC	Ames Research Center
BFF	BioFabrication Facility
CNC	Computer Numerical Control
CT	Computed Tomography
CRG	Cornerstone Research Group
CRISSP	Customizable Recyclable International Space Station Packaging
EXPRESS	Expedite the Processing of Experiments for Space Station
FCE	Flight Crew Equipment
FFF	Fused Filament Fabrication
GFE	Government Furnished Equipment
HDPE	High Density Polyethylene
ISM	In-Space Manufacturing
ISS	International Space Station
IVA	Intra-Vehicular Activity
LEO	Low-earth Orbit
MAMBA	Metal Advanced Manufacturing Bot-Assisted Assembly
MIS	Made in Space
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
PC	Polycarbonate
PEEK	Polyether ether ketone
PLA	Polylactic acid
SBIR	Small Business Innovative Research
SIMPLE	Sintered Inductive Printer with Laser Exposure
TUI	Tethers Unlimited
UAM	Ultrasonic Additive Manufacturing

1. Project Purpose and Overview

NASA's In-Space Manufacturing (ISM) project is managed at NASA's Marshall Space Flight Center in Huntsville, Alabama. The primary focus of ISM is to facilitate use of the International Space Station (ISS) as a testbed to mature the manufacturing technologies needed to support sparing, repair, and recycling within the crewed environment on long duration, long endurance missions. Long duration missions correspond to the typical time a crew member spends on ISS (6 months to 1 year). Long endurance refers to mission scenarios where cargo resupply is limited. While ISS is long duration, it is not long endurance since it can be readily accessed by multiple launch vehicles and the time from launch to docking is relatively short compared to non-low earth orbit (LEO) missions. For the class of missions which can be characterized as long duration and long endurance, In-Space Manufacturing shows immense potential to achieve gains in logistics reduction by a) reducing the number of spare parts and orbital replacement units which much be upmassed and b) enabling recycling of materials which would otherwise be nuisance materials (scrap/trash) or consumables [1, 2]. This "make it, don't take it" philosophy represents a fundamental paradigm shift from traditional logistics models, which rely on changeout of orbital replacement units (stowed on the ISS) rather than repair of a unit at the component level. The implementation of ISM on future space mission thus depends on design of exploration systems which are accessible and intended to be repaired rather than simply changed out with an identical full-scale unit stored on-orbit.

Testing of manufacturing technologies on ISS as payloads allows NASA to evaluate the potential of various processes to meet on-demand manufacturing needs on missions beyond (LEO). ISS is a unique environment for manufacturing which presents numerous challenges. Manufacturing hardware for operation in an IVA environment must satisfy all safety considerations and demonstrate sufficient mitigation of all standard and unique hazards. Any debris generated during the manufacturing process must be completely removed from the system prior to opening for part removal. Materials must satisfy ISS requirements for flammability and toxicity. Payload accommodations for ISS constrain the manufacturing processes which can be adapted for testing (Figure 1). In an ISS EXPRESS rack configuration, systems must consume no more than a maximum of 2000 W of power (this is for a system occupying a full rack, smaller payload accommodations may have an upper limit that is proportionally less than this value), weigh less than 576 pounds (assumed weight is for a full rack, subsize accommodations will be scaled from this value), and occupy less than 16 cubic feet. The 16 cubic feet in volume is for a full rack consisting of 8 lockers; this proportionally scales to 4 cubic feet for a double locker configuration and 2 cubic feet for an individual locker. Additionally, it is anticipated that many manufacturing processes will be impacted in

some way by operation in the absence of gravity (for example, a process where the feedstock is melted and resolidifies may result in parts with a greater porosity than those produced terrestrially due to the dominance of surface tension effects in 0g). The ISS environment uniquely enables comparison of specimens manufactured in space with those made on the ground. Characterizing the impact of microgravity on material outcomes enables design for manufacturing using a particular process in microgravity. Once manufacturing processes and systems have been proven on ISS, they can be considered for use in exploration class systems on the long duration, long endurance missions envisioned for the future. This paper considers the portfolio of technologies currently being developed under the In-Space Manufacturing project, with a particular emphasis on how these processes serve to advance the state of the art for future human spaceflight.



Fig, 1. Diagram of EXPRESS Rack. Each rack is divided into 8 lockers.

2. Polymer manufacturing

The In-Space Manufacturing project began in 2014 with the launch of the 3D Printing in Zero G technology demonstration mission, developed under a small business innovative research (SBIR) contract with Made in Space (MIS), Inc. This hardware printed 55 parts of acrylonitrile butadiene styrene (ABS) plastic on ISS, which were subsequently downmassed to earth for testing and analysis [3]. In 2016, the project began using the Additive Manufacturing Facility (AMF), a second generation printer also developed by Made in Space, to conduct additional materials characterization studies using the flight printer and a ground-based equivalent unit. The AMF studies derive their testing methodology from composites in that mechanical test specimens are machined from printed panels rather than printed directly [4]. The layup pattern of the panels was varied to consider the directional dependence of properties and the degree of anisotropy. To date, over 100 mechanical test coupons have been evaluated as part of this effort. Typical materials test regimes include density measurements, nondestructive evaluation (structured light scanning to compare dimensions of the printed part with the CAD geometry; sometimes CT scans are also performed), mechanical testing, and fracture analysis using scanning electron microscopy (SEM). While testing for 3DP and AMF have both revealed differences in microgravity and ground-produced specimens of identical geometries, these discrepancies are hypothesized to be the result of variations in manufacturing process parameters and settings rather than a significant microgravity influence. As a forced extrusion process with a wire plastic feedstock, fused filament fabrication can operate independently of the gravity vector. Additionally, computational models of the FFF process in 1g and 0g have not predicted significant impacts on the underlying physics of the manufacturing technique [3].

Fig. 2. 3D Printing in Zero G technology demonstration mission.

Since 2015, the ISM project has supported work on materials recycling and reuse strategies. Foams and films ensure hardware for ISS survives launch loads without incurring damage. Currently a variety of polymer materials are used for launch packaging and the cumulative mass of these materials can be substantial. However, none of these materials are reused or reprocessed on ISS. Instead, packaging materials are organized into small parcels of trash (referred to as “trash footballs”), cached in the Cygnus capsule, and consumed during re-entry. The work under the recycling/reuse component of the In-Space Manufacturing portfolio focuses on reuse of plastics and packaging materials through a) manufacturing technology development for i) recycling and ii) printing with recycled materials and b) development of materials which are intended to be reused and recycled. Under the customizable, reusable ISS Packaging effort (now in a phase II-X SBIR contract), Tethers Unlimited (TUI), Inc.

developed a custom slicing engine to enable 3D printing of custom infill structures of off-the-shelf polymer feedstocks (ULTEM 9085, ABS, HDPE, PLA, and PC). 3D printed foams with various infill patterns were vibration tested to establish a correlation between the structure of the material and the resulting vibration properties (attenuation of acoustic energy). The CRISSP slicer and infill generation software allows a user to print exactly the foam structure needed to protect a component or piece of hardware from specific vibration levels [5]. The CRISSP effort also included degradation studies in polymer materials over multiple recycling cycles to determine which materials are best suited for a space mission recycling ecosystem.

Fig. 3. CRISSP foams from Tethers Unlimited. Image from TUI.

A complementary approach to development of common use materials for ISS packaging is being performed by Cornerstone Research Group, who under multiple phases of SBIR funding have a developed a Polyethylene-based thermally reversible material which can be processed into films and foams and recycled into filament for 3D printing [6]. This material shows negligible degradation in mechanical properties over multiple recycling/printing cycles. The material also passed toxicity testing at White Sands Test Facility. Foam samples which underwent vibration testing also performed strongly relative to foams currently used in ISS applications.

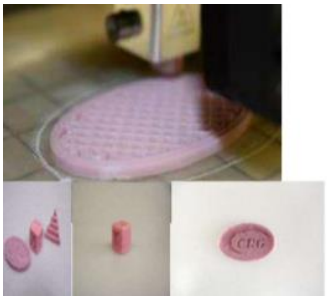


Fig. 4. Example of thermally reversible materials developed by Cornerstone Research Group (CRG) for 3D printing and recycling. Image from CRG.

In early 2019, Tethers Unlimited and NASA's In-Space Manufacturing project installed the Refabricator payload on ISS. The Refabricator has the capability to reprocess a printed block of ULTEM 9085 into filament feedstock (without grinding or pelletizing) via a process known as Positrusion [7]. The extruded filament is fed into a print head to 3D print parts or input blocks that can be used to create additional filament. Specimens produced with the Refabricator system are expected to arrive at MSFC for testing in early 2020. The specimen set will include tensile specimens for mechanical testing and segments of filament for chemical analysis. TUI is working under parallel SBIR efforts to redesign the Refabricator to support recycling of multiple materials.

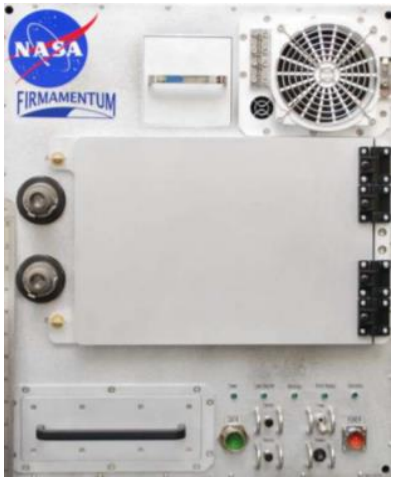


Fig. 5. Refabricator unit.

Manufacture of food tools and medical devices in an IVA environment is seen as a high potential target application for In-Space Manufacturing. However, the value proposition for making this class of parts on-demand rather than prepositioning them in stowage is lessened without an accompanying sterilization capability. Sterilization is needed to minimize the risk of exposure of crew to harmful bacteria and viruses (some of which may be more virulent in the space environment). Traditionally sterilizers are large systems with a high power draw and may be incompatible with ISS payload accommodations. Many sterilizers also require water for decontamination. Water is limited on ISS and is

typically reserved for higher mission priorities (ex. drinking, cooling of space station systems). Under the ERASMUS effort (phase II SBIR), TUI developed a dry heat sterilization system which is can be integrated into their Refabricator recycling system. TUI has developed time and temperature protocols to kill bacteria and viruses for various polymer materials, performing accompanying batch testing to verify that surfaces are within microbial growth limits following sterilization procedures [8]. ERASMUS also included the fabrication and testing of prototype medical devices and food utensils with an upgraded Refabricator system.

Fig. 6. Biomedical devices and food tools manufactured with ERASMUS. Image from TUI.

Work under ISM also includes development of higher strength polymer feedstocks. These feedstocks are intended to be compatible with fused filament fabrication systems with property thresholds approaching those of Aluminum alloys. Under an SBIR, Actuated Medical Inc. (AMI) has developed a carbon fiber reinforced PEEK feedstock for 3D printing of medical devices and parts with strength requirements beyond those of traditional thermoplastic compositions. AMI also developed a retrofit kit for standard desktop printers to enable printing of this feedstock in commercially available systems. Laser-assisted heating following layer deposition significantly reduces anisotropy in the printed part [9]. Geocomposites, a joint venture of Geocent and Adaptive Corporation, is developing a dual nozzle FDM concept to deposit matrix and continuous fiber reinforcement materials [10]. Some material configurations tested to date have strengths greater than 200 MPa in tension. Demonstration of higher strength polymer feedstock printing on ISS will serve to expand the range of applications for ISM, potentially moving ISM capabilities into parts for structural applications. Feedstocks under these research effort are compatible with a process (fused filament fabrication) which has now been demonstrated by multiple ISS payloads. In addition to polymer based composites, Geocomposites has also demonstrated that the FDM process can also be used to fabricate metallic parts which after post fabrication heat treatment have properties comparable to wrought products. The potential to use the same facility to fabricate both composite and metallic parts can reduce the required footprint for manufacturing on ISS and further expand the range of application for ISM.

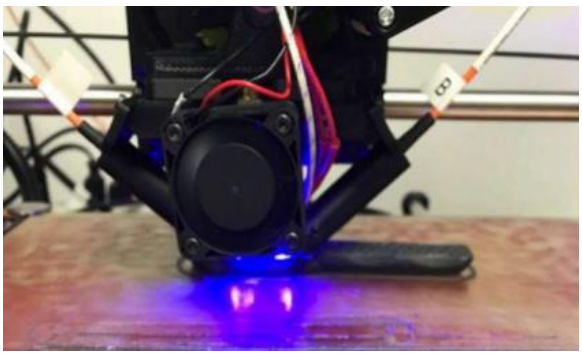


Fig. 7. Retrofitted fused filament fabrication system printing a PEEK wrench. Image from AMI.

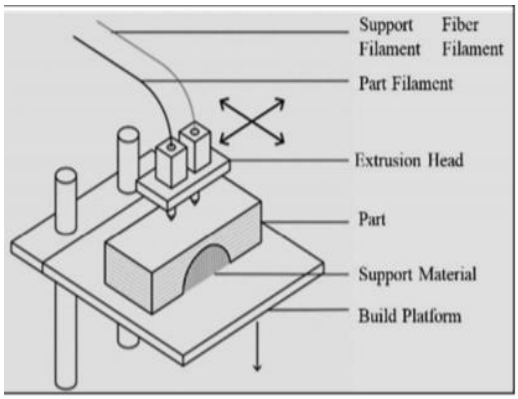


Fig. 8. Geocomposites dual nozzle FFF concept for combination of matrix and continuous fiber reinforcement. Image from Geocomposites.

3. Metals manufacturing

One of the overarching challenges of In-Space Manufacturing is the production of aerospace grade metallics in the IVA environment. One preeminent challenge is scaling down metals manufacturing to fit within the power/volume/mass constraints of ISS. Metals manufacturing processes also may generate significant amounts of debris (for example, via CNC milling in hybrid AM processes). Chip debris must be evacuated and managed appropriately to protect crew from respirable metal dust and particulate hazards. Fusion based metals

manufacturing processes require melting of metal alloys at high temperatures and some are derived from fusion welding processes which produce sparking and arcs. Since 2017, the In-Space Manufacturing effort has been evaluating four metals manufacturing processes for ISS in parallel through the SBIR program. The first of these is the ultrasonic additive manufacturing (UAM) process for UltraTech Machinery and Fabrisonic, Inc. In UAM, a sonotrode imparts vibration into adjacent metal foils. This vibration disperses the oxide layer and creates a metallurgical bond between adjacent foils. UltraTech and Fabrisonic designed a new sonotrode to enable scaling of the process and are building an integrated, ground-based prototype system with a scaled down UAM system and a CNC milling capability for machining features from the printed part [11]. The UAM process is solid state, has low power requirements relatively to most metal AM systems, and occurs at slightly above room temperature.

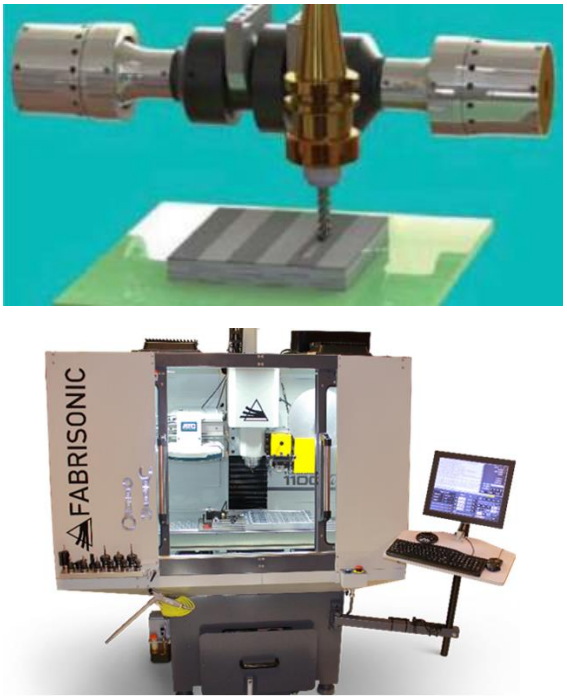


Fig. 9. Illustration of ultrasonic additive manufacturing process (top) and UAM unit (bottom). Images from Ultra Tech and Fabrisonic.

The Vulcan effort from Made in Space uses a welding process to additively manufacture parts. The wire-fed process is compatible with virtually every aerospace grade metal material available in the form of welding wire. In a phase II effort, Made in Space is developing an integrated, ground-based prototype of Vulcan which includes the following subsystems: the additive manufacturing unit, a CNC mill for finish machining, an environmental control unit to manage and collect all chip debris, a polymer manufacturing head based on the additive manufacturing facility (AMF), and a robotic capability to flip the part for machining and remove it from the build plate [12].

Fig. 10. VULCAN unit from Made in Space. Left image is the rendering of the payload in a double locker and the right image is an example of a metal part produced with the system. Images from Made in Space.

Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA) from TUI represents an approach to metal recycling and reuse. MAMBA includes an inductively heated press capable of processing virgin or scrap metallic material into ingots and a zero-G CNC mill for converting those ingots into usable parts. In the MAMBA concept, a small robotic arm assists in moving the part from the recycling chamber to the chamber for CNC milling. The unit also includes a vacuum system for capture of chips generated during machining. When a sufficient volume of chips are collected, they can be inserted into the press to make an ingot [13]. Additionally, the CNC mill provides the ability to perform high precision, final machining on parts created with additive manufacturing technologies by other platforms outside of MAMBA.

Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) from Techshot is a wire-fed process for metal additive manufacturing. The process is compatible with ferromagnetic materials, which are inductively heated prior to extrusion. The process has also been demonstrated using Aluminum wire feedstock. After deposition on the build plate, a low power laser completes melting of the material. Recently SIMPLE has been integrated into a vacuum chamber for additional testing; vacuum provides thermal control for material deposition and ensures adhesion of the material to the build plate [14].

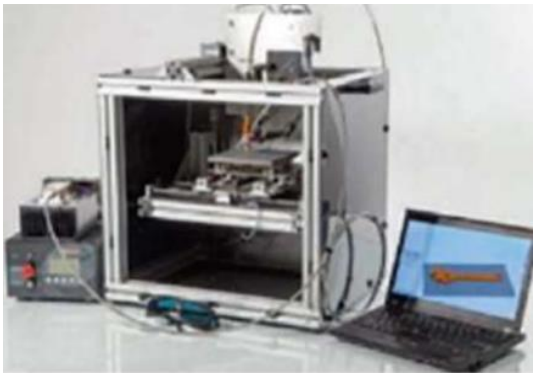


Fig. 11. SIMPLE unit from Techshot. Image from Techshot, Inc.

While the SBIR efforts represent technology demonstration payloads which would occupy a fraction of a rack, the ISM project also has three parallel efforts to develop larger scale facilities for multi-material manufacturing which also include inspection capabilities [15, 16]. Objectives for the facilities are outlined in the table below.

Table 1. Objectives for Multimaterial Fabrication Laboratory [15].

Minimum Target Capabilities for a Ground Based Demonstration Prototype at End of Phase A	**Objective Target Capabilities** Flight Demonstration on the ISS Express Rack for Phase C
I. The system should have the ability for on-demand manufacturing of metallic components, designed to work in the micro gravity environment.	I. On-demand manufacturing of multiple materials in micro gravity, including various aerospace-grade metallics, polymers, composites and conductive (i.e. 'digital') inks are highly desired.
II. ISM FabLab Design must meet ISS Express Rack operational constraints (i.e. volume, power, etc.) as defined in Attachment 1 and maintain a minimum build envelope of 6"x6"x6".	II. ISM FabLab Design must meet ISS Express Rack operational constraints (i.e. volume, power, etc.) as defined in Attachment 1 and provide as large of a build volume as possible.
III. The system should limit required astronaut operations by optimizing Earth-based remote commanding capability for all nominal tasks, including part removal and handling. No nominal task should require more than 15 minutes of astronaut tended time.	III. In addition to the minimum objective, the system will incorporate earth-based remote commanding and/or autonomous capability for all nominal, maintenance, off-nominal† tasks, including part removal and handling.
IV. The system should incorporate remote and/or autonomous validation & verification capabilities to assure	IV. The system should incorporate remediation capability for defects identified during the in-line validation

Systems must fit into an EXPRESS rack and are limited to peak power consumption of 2000 Watts, a weight of 576 lbm, and a volume of 16 cubic feet. These 18 month phase A efforts, focused on development of ground-based prototype systems and technology demonstration, are funded under a NASA Broad Agency Announcement: In-Space Manufacturing Multi-material Fabrication Laboratory (FabLab). Under this award, Techshot, Inc. is developing a fully integrated manufacturing system with partner nScrypt (the original equipment manufacturer of a multimaterial printing system for electronics, metals, and polymers). The TechShot "FabLab" is capable of processing multiple materials, ranging from aerospace grade metals (ex. Ti-64) to polymers and even biomaterials in the space environment. The Techshot FabLab also includes a furnace, an endmill for finish machining, and a laser line profilometer for monitoring the build process during additive manufacturing. Of primary interest to the phase A effort is the Techshot FabLab's metal printing process which resembles bound metal deposition (BMD) except the part is printed before debinding and sintering. Some mechanical and electronics elements of the FabLab system have now been demonstrated on ISS as part of the BioFabrication Facility (BFF), also a partnership with nScrypt. The BFF payload launched in July 2019 to ISS and has demonstrated 3D printing with several types of human cellsin microgravity [17].

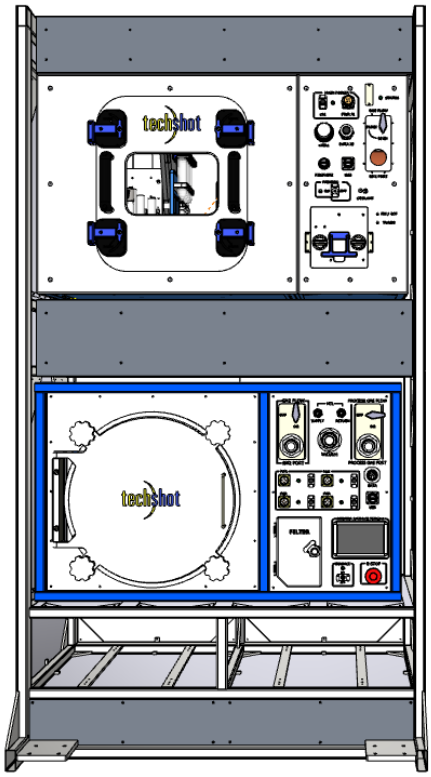


Fig. 12. Techshot rendering of Multimaterial Fabrication Laboratory system, which includes capabilities for printing of metals, postprocessing of material, and dimensional inspection. Image from Techshot.

Interlog also received a phase A BAA contract to develop their wire-fed ultrasonic AM process for ISS. Tethers Unlimited is working on the Empyrean Fabrication Laboratory under phase A, which focuses on ancillary technologies to support operation of ISM platforms. This development effort includes a robotic arm to grasp and move the part between an additive manufacturing unit and an inspection chamber or stowage drawer. The inspection system uses a structured light scanning technique to compare the dimensions of a printed part against a CAD model and verify that it meets tolerances. Fixturing, gimbaling of the part, and data processing and acquisition will be automated to limit crew involvement with the system. Systems developed under the phase A must be compatible with an EXPRESS rack. Demonstration of the Fabrication Laboratory on ISS, currently targeted to take place before 2024, will represent the first true exploration-class manufacturing system and a game changing technology for expanding the breadth of ISM applications.

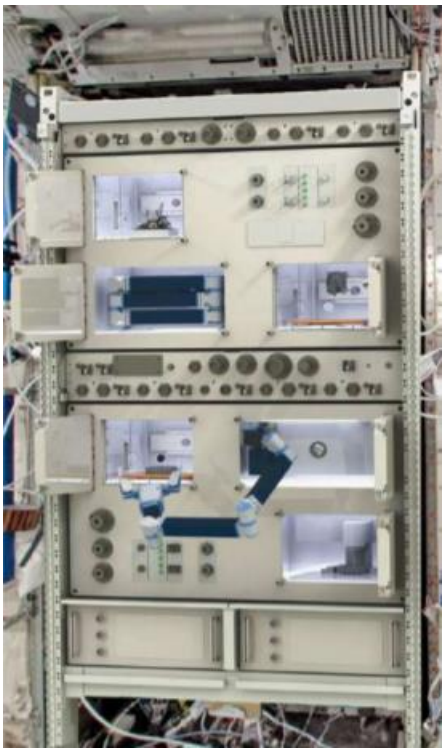


Fig. 13. Empyrean Fabrication Laboratory concept rendering. Rack includes a robotic arm capability, control systems, and part inspection. Image from TUI.

4. Printable electronics for in-space manufacturing

On earth, 3D printing processes have been successfully applied to many materials, including polymers, metals, and even biologicals. Recently 3D printing technology has extended into electronics. Based on data archived in ISS databases, there are numerous instances of failures of electronic components and subsystems on ISS. It is anticipated that a manufacturing capability for electronics will be needed to fabricate, assemble, and repair electronic parts on the long duration, long endurance missions NASA will pursue in the post-ISS era. To date, researchers in the field of printable electronics have demonstrated printed circuit boards, electronic substrates, connection of conductive traces, deposition of solder paste, and pick and place of prefabricated circuit components. 3D printing of electronics is a nascent technology and most of the functionality of current printed boards comes from the prefabricated components that are added rather than the additively manufactured elements. Teams at NASA Marshall Space Flight Center (MSFC) and NASA Ames Research Center (ARC) are working to mature printable electronics technologies for earth and for space.

Under the ISM project, NASA is developing new on-demand printing and packaging technologies for next generation flexible, wearable sensor devices which can be used in crew health monitoring applications. Printed sensors and sensor devices can additionally be used for habitat monitoring and vehicle structural health monitoring. ISM is utilizing technology development capabilities at MSFC and ARC to develop the printed sensors for these efforts. Sensors fabricated to date include environmental sensors (monitoring of CO_2, humidity, temperature, and pressure) and biosensors (cortisol sensor for stress monitoring and a hydration sensor). The printed cortisol sensor is shown in Figure 14. Cortisol is a hormone secreted by the body in response to stress. This wearable sensor provides continuous monitoring of cortisol levels and can be used to indirectly assess a crew member's stress level during transition events (for example, launch and landing) as well as EVAs.

Fig. 14. Image of cortisol sensor. Coin is shown for scale.

Gas/vapor sensors and humidity monitoring are needed to continuously monitor the cabin air quality in ISS and future habitats. These small, compact sensors could potentially replace bulky instruments currently used for this purpose. For example, mass spectrometers provide very accurate quantitative information about the constituents of the ambient, but they are heavy, have a large power draw, and cannot characterize variations in elemental concentrations across the cabin environment. In contrast, postage stamp-sized chip-based sensors are small, have very low power requirements, and, if calibrated properly, will provide reliable measurements of gases and vapors across a volume (it is possible to deploy multiple printed sensors across the cabin in a networked fashion) [18]. NASA has developed printed sensors for monitoring carbon dioxide and ammonia (ammonia has a high level of toxicity and leakage of ammonia in systems which use it for cooling represents a serious safety concern). The NASA research group has used machine learning to convert the measured signal of ammonia – which is resistance in this case – into analyte concentrations.

Fig. 15. Image of first-generation CO2 sensor.

Radiation exposure is also serious concern in space missions, particularly for exploration missions beyond low earth orbit where radiation exposure levels increase by orders of magnitude. Radiation exposure poses threats to both crew health (increased risk of cancer) and payload electronics. Radiation sensors capable of fingerprinting various types of radiation based on their energy levels and intensity are needed. Towards this goal, a printed gamma ray detector was developed [19]. This sensor detects the conductivity change in carbon nanotubes upon exposure to radiation; the magnitude of this conductivity change is indicative of particular radiation levels. It is also able to detect gamma radiation at flux levels.

Additional developments with on-demand printing capabilities include energy storage and power generation. Most modern printed sensors require only milliwatt (mW) levels of power for operation, which can be locally generated from vibrations and other movements. NASA's printable electronics research group has exploited triboelectric power generation mechanisms to print energy scavenging devices which can provide a continuous supply of tens of mW power (this harvested energy is used to run the printed sensors). Supercapacitors are ideal devices for energy storage, as they have charging rates which far exceed conventional batteries. Through optimization of various inks for electrodes and active layers, NASA has printed supercapacitors with a specific capacitance of 150 F/g. These supercapacitors have completed a thousand charge and discharge cycles without any significant degradation in performance. The development of a printed array of mini-antennas to harvest power for electronic applications is a compelling technology also being developed by ISM through a university collaboration. This "rectenna" will harvest watts of electromagnetic radiation energy (Wi-Fi) through printed antennas on flexible substrates and utilize a rectifier circuit for power conversion.

Future development of printed electronics technologies will involve development of multi-material 3D printers to manufacture advanced sensors and devices on-demand as they are needed for ISS, Lunar Gateway, and future habitats on the Moon and Mars. Future phases of the Fabrication Laboratory activity are intended to include development of printed electronics capabilities. Parallel development of advanced functional materials for sensors and devices are also needed to fully realize the technology's potential in support of long duration spaceflight.

5. In-process sensing

Inspection of parts produced on-orbit and certification of them for use in an application or

environment remains a pre-eminent challenge. Currently part inspection techniques which can be implemented onboard ISS are limited to visual inspection and visual monitoring using cameras. Issues such as variations in surface finish, tolerances, distortions, residual stresses, voids, mechanical properties, etc. which are noted in AM processes on the ground are also likely to be present in the space environment. The ability to ensure production of parts with repeatable quality is critical for future ISM implementation and infusion of these technologies into sparing and repair for critical space systems. There are essentially two approaches to ensure consistency in the parts and the manufacturing process for ISM: a traditional qualification and certification approach (which may be difficult for ISM due to constraints on crew time and equipment size limitations) and online process control (i.e. process monitoring, where in situ monitoring of process signals provides information about the quality of the part produced by the process). Qualification and certification for ISM parts based on process monitoring require better machine and feedback control than is currently available in many off the shelf printers. While traditional approaches to qualification and certification are also being pursued in parallel, a more immediate solution for ISM verification and validation is based on in-process monitoring and control techniques. In 2018-2019, the ISM project had several parallel development efforts with small businesses on in-line monitoring for ISM.

- In Situ Monitoring and Process Control (AMARU). Made in Space (phase I SBIR). on development of new verification and validation methods for part fabricated via ISM. AMARU integrates advanced sensor technology with a real time data stream for part production analysis [20].
- In Situ Monitoring of In-Space Manufacturing with Multi-parameter imaging. LER Technologies (phase I SBIR). Development of multi-parameter imaging technique to detect flaws in real-time by evaluating dimensions deviation [21], microstructured defects, gaps between print lines, and surface finish, for each part layer.
- Acoustical Signature Analysis for In-Situ Monitoring and Quality Control for In-Space Additive Manufacturing. Metrolaser, Inc. (phase I SBIR). Development of a non-destructive evaluation method based on acoustic signatures. Combines laser Doppler vibrometry with vibrational resonance spectroscopy to collect acoustic signals from each layer during a build. Feasibility of system was demonstrated by experiment and computer simulation [22].
- Feedback sensors for closed-loop additive manufacturing. Cybernet Systems Corporation (phase I SBIR). Method to determine geometric differences between CAD model of part and printed geometry. IR cameras collect temperature data which is validated against thermal models. 3D data provides verification of part geometry after each layer. System is extensible to inform real-time correction of geometric variance [23].
- Automated in-process quality control of recycled filament production and FDM printers (phase I SBIR, continuing in a phase II effort). AM process monitoring and control systems for online quality control of feedstock production and printed parts. CRG's proposed approach applies sensors, hardware, and software algorithms to monitor and adjust feedstock production and printing processes in real time to support feedstock certification and improved print quality. Hardware and software developed on this program by CRG will be integrated into systems already being developed to support NASA's ISM efforts [24].

Accompanying inspection capabilities are also part of the Fabrication Laboratory effort. Companies developing integrated systems with a manufacturing process under the BAA (Techshot, Interlog) were additionally asked to also develop techniques to monitor the build in-process and detect anomalies in the printed part during manufacturing. As previously discussed, TUI is developing a post-process inspection system for dimensional verification. For critical parts, a nondestructive volumetric inspection capability (ex. computed tomography) will likely be required – this is a capability which does not yet exist on ISS.

6. Digital design database

To date, ISM has focused on development of manufacturing processes and supporting manufacturing technologies for testing in the sustained microgravity environment of ISS. The accompanying work of determining what parts may

be manufactured on long duration space missions (and using requirements for those parts to inform requirements for ISM platforms) is part of ISM's ongoing design database activity. The ISM project currently has a database of candidate parts for In-Space Manufacturing which originate from the following sources:

1) ISS databases cataloging part failures and problem reporting. When considering the information in these databases, ISM focused on identifying components from environmental control and life support systems which require regularly scheduled repair and replacement or have failed on ISS previously.

2) The ISS medical toolkit manifest, which catalogs medical items pertinent to emergent and non-emergent on-orbit medical scenarios. Historically the medical community has been an early adopter of additive manufacturing, as the technology provides unique opportunities for patient customization and can reduce logistics/lead times for medical consumables in operationally remote scenarios. The toolkit contains many medical devices of both polymer and metal materials which could in theory be manufactured on a space mission (assuming devices can be manufactured to medical standards and represent FDA-approved items).

3) The Intravehicular Activity (IVA) Government Furnished Equipment (GFE) Flight Crew Equipment (FCE) manifest, which catalogs tools, equipment and supplies needed for various ISS on-orbit scenarios. This manifest has yielded many items to date suitable for replacement via additive manufacturing technologies if lost or broken.

4) In the next year, the database will also expand to include heritage spacesuit components, with candidate parts identified based on historical documentation of spacesuit designs and continued conversations with the spacesuit design community.

The ISM project also has plans to expand the capability of the database and, in the future, implement a manufacturing execution capability so that a crew member could initiate manufacture of a part on an ISM manufacturing platform directly from the database interface. A related activity under a NASA Space Technology Research Fellowship uses candidate parts identified from ISS part databases to develop a systems modeling framework for assessing the utility of a manufacturing process in various mission scenarios [25]. This activity will also help to define requirements for future ISM manufacturing platforms by providing insight into the materials, build rates, reliability levels, and tolerances needed to realize the potential of a particular manufacturing technology for logistics reduction. The NSTRF and design database activities will provide a critical bridge between the "how we make it" and "what we make" aspects of the ISM project portfolio.

7. Computational modeling

Computational modeling work at NASA ARC has served as an invaluable complement to work on In-Space Manufacturing process development and testing of manufacturing systems on ISS. The NASA ARC physics-based modeling group has provided analysis and modeling support of In-Space Manufacturing since 2014. The ARC team has significant experience in modeling physics phenomena and materials in microgravity. Work includes:

• Development and validation of computational models to support understanding of processes in zero-G environments
• Elucidation of specific features of materials manufactured in micro-gravity that are distinct from earth-processed specimens
• Enabling of physics based analysis of the ISM payloads before launch
• Clarification of possible gaps in experimental performance.
• The support of verification and validation of parts manufactured in-space

To date, the ARC group has supported the In-Space Manufacturing demonstration of fused filament fabrication (3D Printing in Zero G technology demonstration mission), the in-space polymer recycling demonstration (Refabricator), and in-space metals manufacturing process development (the Multi-material Fabrication Laboratory, or "FabLab"). Computational models of FFF can predict the strength of the manufactured parts based on

process settings (elastic moduli, strength and toughness, anisotropy, plasticity). These models of FFF proved instrumental in assessing the flight and ground data sets from the 3D Printing in Zero G technology demonstration and suggested that microgravity does not have a significant impact on the printing of polymer parts. These models, which to date have been constructed for ABS and ULTEM 9085, can predict interfacial properties and translate between predictions at the microscale level to macroscale mechanical properties. Models in the multiscale approach extend from (1) quantum mechanical models of the monomers, (2) a fully atomistic model of the interface, (3) a microscopic continuous model of the filament interface, and (4) model of the bulk manufactured parts (Figure 17). Test data from materials produced with manufacturing capabilities on the ground and on ISS are used to validate and anchor predictions of these models.

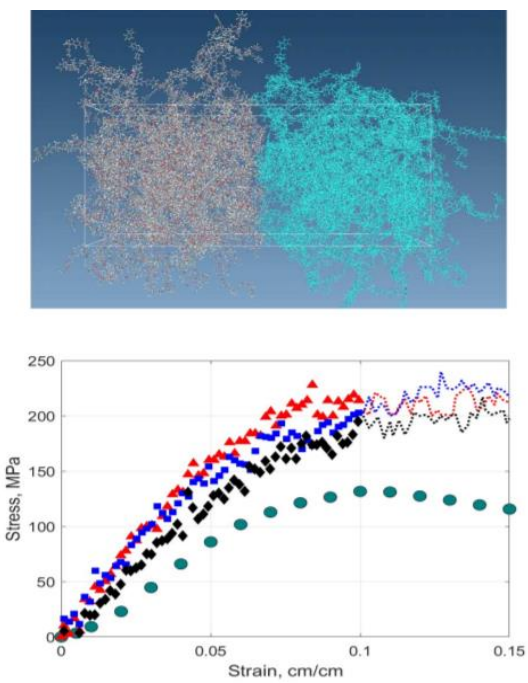


Fig. 17. Fully atomistic model of interface in ULTEM 9085 (polyetherimide/polycarbonate blend). Model (top) was used to predict the stress strain curves in the bottom plot.

8. Conclusions

The ISM project at NASA's Marshall Space Flight Center is a portfolio project with efforts broadly divided into six key areas:

- In-Space Manufacturing of polymers. ISM has used fused filament fabrication systems on ISS with the materials ABS and ULTEM 9085. This category includes ground-based development work on higher strength feedstock filaments compatible with FFF systems.
- In-space recycling includes the ability to recycle polymers into filament feedstock (ULTEM 9085 as a first demonstration with extensibility downstream to other thermoplastic materials and packaging materials). This aspect of the portfolio also features work on common use materials, defined as launch packaging materials which are intended to be reused and recycled on-orbit. The ISM project has also funded work on development of sterilization capabilities for parts which have close contact with crew in their intended use scenario (ex. biomedical devices, food utensils).
- ISM of metals. This work includes parallel development of multiple metallic processes for In-Space Manufacturing: ultrasonic additive manufacturing, bound metal deposition, and wire + arc. Ancillary development efforts include zero-G CNC milling, sintering, and robotic systems for movement of parts between subsystems for manufacturing and inspection.
- ISM of electronics. This includes development of inks for printed circuit applications, printed sensors for environmental monitoring, and flexible, wearable printed devices for crew health applications (ex. cortisol and hydration sensors). Process development is primarily conducted using the nScrypt multimaterial printing system.
- Design database: Development of a list of candidate parts for ISM, digitization of the database and creation of a digital thread for ISM, and activities which broadly use candidate parts to define requirements for future platforms and ISM capabilities.
- Computational modeling includes modeling of manufacturing processes in the space environment to predict differences in material outcomes which may be a result of lack of convection and/or microgravity effects.

Looking ahead to operation of ISM systems beyond ISS, we recognize increased levels of automation will be needed. The reliability of ISM platforms must also increase since systems will not be continuously tended. As ISM capabilities evolve to include metal manufacturing in an IVA environment, process controls and inspection capabilities must also mature in parallel to enable part certification for more critical structural applications. Another potential use for ISM platforms is to facilitate microgravity materials science and potentially improve computational models of manufacturing processes by isolating the variables of free convection and microgravity relative to earth-processed samples. The ISM project also provides technical management and subject matter expertise for Made in Space's Archinaut project (now in a phase II effort under a NASA Research Announcement) [26]. In this effort, Archinaut will demonstrate manufacturing of larger than payload faring structures in the space environment and robotically deploy solar arrays from a small satellite platform. ISM is a destination agnostic capability and the project remains focused on utilization of ISS to conduct technology development efforts. Processes and systems successfully demonstrated on ISS are broadly applicable to many mission scenarios, from lunar Gateway to Mars, in the space community's future.

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