NASA's In-Space Manufacturing Project: Toward a Multimaterial Fabrication Laboratory for the International Space Station

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Human space exploration to date has been limited to low Earth orbit and the moon. The International Space Station (ISS) provides a unique opportunity for NASA to partner with private industry for development and demonstration of the technologies needed to support exploration initiatives. One challenge that is critical to sustainable and safer exploration is the ability to manufacture and recycle materials in space. This paper provides an overview of NASA's in-space manufacturing (ISM) project, its past and current activities, and how technologies under development will ultimately culminate in a multimaterial fabrication laboratory ("ISM FabLab") to be deployed on the International Space Station in the early 2020s. ISM is a critical capability for the long endurance missions NASA seeks to undertake in the coming decades. An unanticipated failure that can be adapted for in low earth orbit, through a resupply launch or a return to earth, may instead result in a loss of mission while in transit to Mars. To have a suite of functional ISM capabilities that are compatible with NASA's exploration timeline, ISM must be equipped with the resources necessary to develop these technologies and deploy them for testing prior to the scheduled de-orbit of ISS in 2024.

The paper provides a broad overview of ISM projects activities culminating with the Fabrication Laboratory for ISS. The FabLab will move NASA and private industry significantly closer to changing historical paradigms for human spaceflight where all materials used in space are launched from earth. While the current ISM FabLab will be tested on ISS, future systems are eventually intended for use in a deep space habitat or transit vehicle. The work of commercial companies funded under NASA's Small Business Innovative Research Program (SBIR) is also discussed, as these activities, from development of recyclable packaging for ISS to additive manufacturing capabilities for metals and electronics, could also potentially be infused into FabLab exploration capabilities as well.

Nomenclature

ALSS = Adaptive Laser Sintering System
AM = Additive Manufacturing
AMF = Additive Manufacturing Facility

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BAA = Broad Agency Announcement
COTS = Commerical Off the Shelf
CNC = Computer Numeric Control
CRISSP = Customizable Recyclable Packaging for ISS
FDM = Fused Deposition Modeling
HDPE = High Density Polyethylene
ISS = International Space Station
LDPE = Low density polyethylene
MAMBA = Metal Advanced Manufacturing Bot-Assisted Assembly
MSFC = Marshall Space Flight Center
PVC = Polyvinyl chloride
SBIR = Small Business Innovative Research
SIMPLE = Sintered Inductive Metal Printer with Laser Exposure
STEPS = Software and Tools for Electronics Printing in Space
UAM = Ultrasonic Additive Manufacturing

I. Introduction

NASA’s In-Space Manufacturing (ISM) project seeks to identify, design, and implement on-demand, sustainable manufacturing solutions for fabrication, maintenance, and repair for future exploration missions. The ability to produce parts and components on-demand during missions has the potential to significantly reduce mission logistics mass, increase reliability, and mitigate risk. Current logistics operations for low earth orbit (LEO) systems, such as the ISS, rely on regular resupply missions from Earth, as illustrated in Figure 1.[1] The ability to manufacture parts in space rather than launch them from Earth represents a fundamental shift in the current risk and logistics paradigm for human spaceflight, but one that is necessary to enable sustainable exploration missions. It is important to note that in-space manufacturing (ISM) refers to any manufacturing process that is operated in the space environment. ISM has already conducted manufacturing on-orbit using fused deposition modeling (FDM), a polymeric additive manufacturing process. In FDM, a thermoplastic polymer is heated to its glass transition temperature and extruded layer by layer to create a 3-dimensional object.

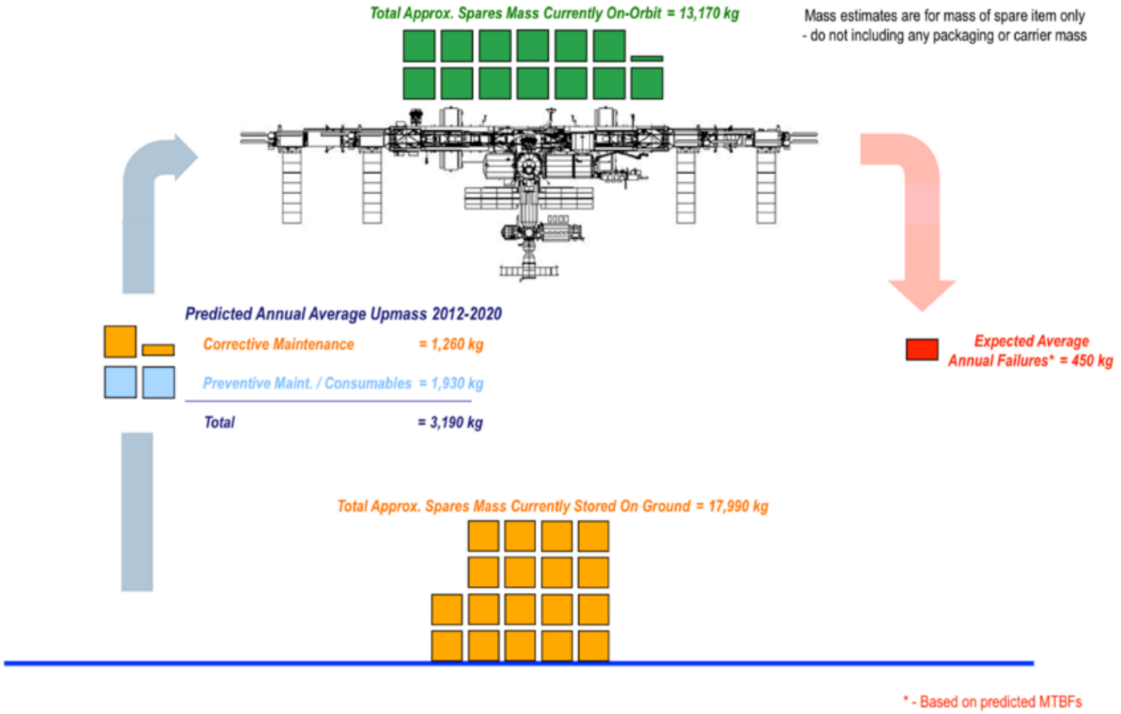


Figure 1. *ISS logistics model. Nearly 18000 kg of spares on the ground and an annual upmass of 3190 kg for corrective and preventive maintenance. Historically, 95% of spares will never be used. Image credit: Andrew Owens (MIT, NASA Space Technology Research Fellow) and Bill Cirillo (Langley Research Center).*

In 2014, NASA, in cooperation with Made in Space, Inc. under a small business innovative research (SBIR) contract, launched a 3D printer to the ISS with the goal of evaluating the effect of microgravity on the fused deposition modeling (FDM) process. The purpose of this technology demonstration was to prove out the manufacturing process for use on future exploration missions. This printer has completed two rounds of operations to date, the first in November-December 2014, and the second in June-July 2016. Analyses of phase I parts (mostly mechanical test coupons) have been published and analysis of phase II parts will be outbriefed as a NASA technical report in Fall 2017[2,3,4]. To date, analyses do not suggest that the FDM process is impacted in an engineering significant manner by microgravity[2,3,4]. Additional multiphysics modeling work on FDM from Ames Research Center conducted in support of the technology demonstration found no significant changes in road shape, filament temperature distribution, die swell of the filament after extrusion, or evolution of the temperature profile due to variation in the gravity parameter[5]. Building on the success of the first 3D printer in space, Made in Space developed a commercial facility, the Additive Manufacturing Facility (AMF). AMF is a user-based facility with a multimaterial polymeric printing capability (three thermoplastics -- ABS, Ultem 9085, and HDPE -- can be processed)[6]. NASA is undertaking additional materials characterization work using AMF. Several utilization parts for ISS have also been produced with AMF: a tow hitch to join two Synchronized Position Hold Engage and Reorient Experimental Satellite SPHERES satellites together during flight (Figure 2), a Radiation Exposure Monitor (REM) shield enclosure for the Bigelow Expandable Activity Module (BEAM), and an Oxygen Generation System (OGS) adapter that serves as a mount for a velocicalc probe to monitor airflow and hardware health[7].

Figure 2. *SPHERES Tow Hitch printed on ISS with AMF. SPHERES consists of 3 free-flying satellites on-board ISS. Tow hitch joins two of the SPHERES satellites together during flight. Printed 2/21/17.*

Beyond FDM, ISM is tasked with creating a more robust functional manufacturing capability to support exploration that incorporate additional processes and materials. While the design flexibility made possible by additive manufacturing (AM) and the form and mass of AM feedstock relative to bulk material makes AM attractive for ISM applications, AM processes represent only some of the desired capabilities under the larger ISM umbrella. ISM may also take the form of hybrid systems, which integrate additive and subtractive manufacturing processes into a single unit. Logistics analyses indicate that a robust suite of in-space manufacturing capabilities will[1]:

- Enable manufacturing of large scale structures in space that are not constrained by launch requirements (i.e. volume), avoiding the complexities of modular launch and assembly in space
- Decrease the mass of spares necessary for long endurance exploration missions (as stated in reference 1, the vast majority of spares will never be used)
- Use local resources and recycled materials for manufacturing, allowing dramatic reductions in initial mass requirements for buildup of infrastructure, particularly on planetary surfaces
- Provide a capability to adapt to unanticipated circumstances, enhancing crew safety
  - Manufacturing of a permanent solution in response to a failure or a palliative solution that mitigates impact of failures until a permanent solution can be found
  - Manufacturing of tools or crew aids on site (includes biomedical applications and specialized science equipment)

The FabLab is the key to demonstrating integration of a suite of manufacturing capabilities that will address the above needs in a single system.

II. ISM's Evolving Capabilities

A current focus of ISM is evolving on-orbit manufacturing capabilities through payload demonstrations and ground-based work. This includes continuing to utilize current payloads while concurrently developing new technologies that could lead to flight demonstration missions through the SBIR program. The work discussed here seeks to expand the material envelope for in-space manufacturing to include aerospace grade materials (specifically metallics), develop recycling capabilities that will further reduce launch mass requirements, and provide manufacturing capabilities for families of parts (such as electronics) that have been identified as high value applications for in-space manufacturing from the perspectives of logistics and crew safety. All of the development efforts discussed here could potentially find a direct infusion point in the ISS Fabrication Laboratory (FabLab).

i) Payload operations and development

To date, the first 3D printer on-orbit has produced over 50 parts in the microgravity environment and these materials have undergone extensive testing and evaluation at NASA Marshall Space Flight Center. Made in Space's AMF has also been used to produce multiple functional parts for ISS applications[8]. The ISM program's second payload, an integrated 3D printing and recycling unit known as the ReFabricator developed by the small business Tethers Unlimited through the SBIR program, will be operational on station in the 2018 timeframe. The ReFabricator is an integrated 3D printer and recycler unit the enables self-sustained reprocessing of 3D printed parts back into filament feedstock for further printing. ReFabricator will demonstrate closure of the manufacturing loop for FDM and has implications for reclamation of waste material into useful feedstock both in-space and on-Earth[9]. Additionally, mechanical test coupons and filament segments returned from the payload will undergo mechanical testing and chemical evaluation to investigate the degradation of the Ultem 9085 feedstock over seven printing cycles in microgravity, provide an assessment of contamination in the manufactured feedstock with each cycle, and evaluate changes in the dimension and tolerance of the feedstock with additional processing. Ultimately results from the payload will provide information about the mechanical/chemical/dimensional integrity of the printing/recycling of Ultem 9085 in microgravity that will inform future ISM development efforts in sustainability and repurposing of mission recyclable materials.

ii) Ground-based work on development of metallic manufacturing capabilities for ISS

ISM also funds other ground-based work, conducted both in-house and through NASA's Small Business Innovative Research (SBIR) program, with the aim of developing technologies that can eventually be flown as standalone flight demos and/or infused into future ISM FabLab capabilities downstream. One key activity is expanding the classes of materials that can be processed with in-space manufacturing capabilities to include higher strength polymers and especially metallics. While attractive for spaceflight applications because of the design flexibility they impart and mass efficiencies, powder based additive manufacturing systems pose a significant challenge for crewed spaceflight operations in microgravity in terms of scaleability and powder management. Wire-based systems are more adaptable to microgravity, but may also be difficult to scale and often result in materials with poorer surface finishes and tolerances than powder bed processes. As a potential solution to this dilemma, hybrid manufacturing processes for ISS, which may integrate additive and subtractive processes within the same unit, are being explored through funded SBIR opportunities.

Made in Space's Vulcan unit, currently in a phase I NASA SBIR, integrates an FDM head derived from the additive manufacturing facility (AMF), a head for manufacturing of metals with a wire and arc metal deposition system, and a Computer Numerical Control (CNC) end-mill for finishing of near-net shape parts produced by the two additive manufacturing processes. At the end of the phase I project, Made in Space will have demonstrated capabilities for each of the constituent processes in Vulcan and provide a path forward for further scaling and integration of subsystems into a payload whose development would be the focus of a phase II effort[10].

Also under a phase I SBIR, Ultra Tech Machinery is working to scale the ultrasonic additive manufacturing (UAM) process and assess its feasibility for use on ISS. Developed by Fabrisonic and illustrated in Figure 3, the UAM process can print quality metal parts by using sound waves to consolidate layers of metal drawn from foil stock[11]. As a solid state welding process, UAM avoids the complexities of management of powder feedstocks or melting of materials in microgravity. In phase I, Ultratech is working to reduce the UAM process's footprint (i.e. power and volume requirements) by designing and implementing a higher frequency sonotrode. Scaling of the system also has implications for robotics and use of the process for freeform fabrication. Current UAM machines made by Ultratech are typically hybrid systems, so a potential flight unit developed as part of phase II would incorporate a CNC mill head to enable finish machining of metal parts in the same unit.

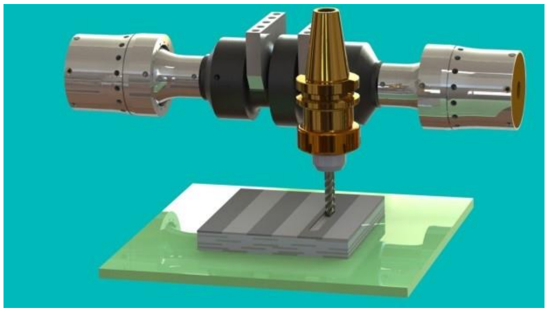


Figure 3. Illustration of the ultrasonic additive manufacturing process (image courtesy of Ultra Tech Machinery).

Tethers Unlimited is also funded under a phase I SBIR to develop the MAMBA (Metal Advanced Manufacturing Bot-Assisted Assembly) system, which uses an ingot-forming method to process virgin or scrap metal in to metal feedstock. Within the MAMBA unit, this bulk feedstock would be CNC milled to form a precision metal part. MAMBA builds on the recycling process developed for Tether's ReFabricator payload[12].

Techshot, Inc. also has a phase II SBIR for the Sintered Inductive Metal Printer with Laser Exposure (SIMPLE), which uses an additive manufacturing process with metal wire feedstock, inductive heating, and a low-powered laser to successively deposit and sinter metal layer by layer[13]. The test unit for SIMPLE developed under the phase I SBIR is pictured in Figure 4.

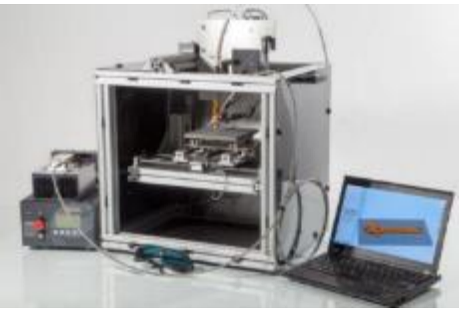


Figure 4. *SIMPLE (small metal 3D printer) developed by Techshot under an SBIR. Image courtesy of Techshot.*

Hybrid processes are advantageous for spaceflight operations because they allow parts to be fabricated and post-processed using the same hardware. Automated tool changeout, feedstock management, and movement of parts through the system will also limit the need for crew tending of manufacturing equipment. Use of metal feedstock in wire rather than powder form is safer (the ultrafine metal powders used in processes like selective laser melting are typically an explosion hazard) and pose a challenge for management in microgravity. The use of metallic manufacturing processes to recycle metal scrap parts and repurpose them into usable feedstock will be immensely beneficial for long duration, long endurance missions, as recycling capabilities minimize waste and decrease initial launch mass requirements for feedstock materials.

iii) Ground-based work on additive manufacturing of electronics for ISS

Given the historical incidence rates for failure of electronic components and subsystems on ISS[14], 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. Recently the Materials & Processes Laboratory and the Space Systems Department at NASA Marshall Space Flight Center have acquired an nScrypt printer as a platform primarily to explore the potential of additive electronics for future space mission applications. The nScrypt printer, a modular manufacturing capability with 4 heads for dispensation of inks and FDM of polymers, serves as a ground-based capability for development of the materials and processes needed for multimaterial additive manufacturing of electronics. The nScrypt machine can precisely print polymer based substrates, dispense electronic inks (resistive, dielectric, conductive, etc.) in desired patterns, pick and place electronic integrated circuits (ICs) into desired locations, and fiducially align layers. To date the machine has been used to conduct materials development activities (including development of processes for printing of metallic inks and optimization of polymer substrate printing) while concurrently exploring the use of this equipment to serve high value applications for ISS through a number of functional demonstration parts, including printed sensors.

One of the most novel uses of the nScrypt unit to date is in additive production of a wireless sensor archetype. Wireless sensors are frequently used to monitor physical and environmental conditions and provide information relating to the health of machines, structures, and processes. Wireless sensing networks represent an important focus area for space technology development, as these sensors are key to reducing mass associated with wiring, connectors, brackets and other mechanical parts. The nScrypt has been used to fabricate an inductively coupled RLC circuit which can be interrogated by a coupled antenna. This antenna is connected to an impedance analyzer to monitor changes in resistance, capacitance, and/or inductance. This sensor archetype is currently being investigated at MSFC for strain and humidity sensing applications on ISS, but could be expanded to temperature, light, and many other sensing applications provided a material sensitive to changes in these specific stimuli is developed. Specific sensors fabricated to date include a wireless humidity sensor printed with MSFC-developed silver and dielectric inks (pictured in Figure 5), a pressure sensor for us a structural health monitoring application for the Space Launch System, and a capacitive haptic sensor.

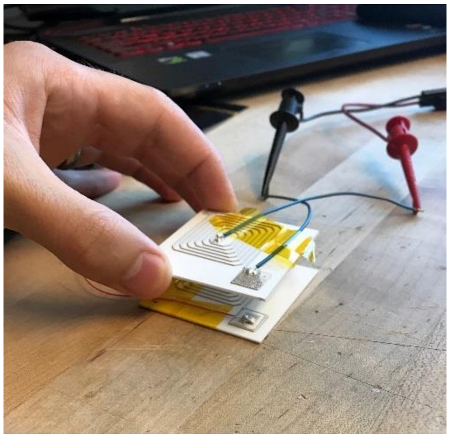


Figure 5. *Wireless humidity sensor developed at MSFC.*

Complementary work toward an additive electronics capability for ISS is also being conducted under the SBIR program. Techshot, Inc., in collaboration with nScrypt, is developing the Software and Tools for Electronics Printing in Space (STEPS) as part of a phase I SBIR. STEPS is a direct write and avionics printing capability for circuits, antennas, and circuit layouts. Eventually STEPS could evolve to produce complete circuit boards on-orbit. In another funded phase I SBIR, Optomec is adapting its patented Aerosol Jet technology for additive manufacturing of electronics for ISS. In the aersol jet process, an ink is atomized and dispensed through a jet stream that routes through the print head and exits through a converging nozzle which compresses the stream to a diameter on the order of microns and accelerates it to a high velocity. This effort focuses on development of an adaptive laser sintering system (ALSS). Localized laser sintering reduces sintering time and limits the exposure of the substrate to elevated temperatures. ALSS can also reduce the manufacturing footprint for additive electronics by integrating a postprocessing step in the same device.

iv) Ground-based materials development work: recyclable materials

Logistics analyses have consistently indicated the dramatic impact of a recycling capability in reducing initial launch mass requirements for long duration missions. In addition to the ReFabricator payload which will enable reclamation and reuse of 3D printed Ultem for filament production and further fabrication activities, there is work underway through the NASA SBIR program to develop common use materials for launch packaging. Current packaging materials for ISS represent a broad spectrum of polymers: low density polyethylene (LDPE), high density polyethylene (HDPE), PET, Nylon, Polysulfone, vinyl, and polyvinyl chloride (PVC). The objective of this research is to design materials for packaging that are intended to be recycled and reused, therby transforming nuisance materials which would otherwise be downmassed as trash into an in situ resource to support further fabrication of packaging, tools, or devices. Materials developed under the SBIR and in-house work in this technology area are compatible with FDM and thus have a ready infusion point for the existing and future ISM ecosystem.

Cornerstone Research Group (CRG) is working under a phase II SBIR on development of reversible copolymer materials. The reversiable copolymer acts as a thermally-activated viscosity modifier impacting the melt properties of the material. These copolymer designs have strength and modulus values equal to or exceeding that of the base thermoplastic materials while maintaining a depressed viscosity that enhances their compability with the FDM process. To date CRG has explored both monolithic and blended materials for this application[15]. FDM prints with a material developed under this effort is shown in Figure 6.

Figure 6. *FDM prints using reclaimed anti-static bagging film with reversible cross-linking additive. Image from Cornerstone Research Group. Work conducted under an SBIR on development of recyclable packaging and common use materials for ISS.*

Tethers Unlimited is also developing their Customizable Recyclable ISS Packaging (CRISSP) system through a phase II SBIR. CRISSP is a recyclable foam packaging made from thermoplastic materials using FDM (Figure 7). A slicing engine can be used to create custom infill profiles for the foam to yield specific vibration characteristics or mechanical properties. Tethers has performed vibration analyses of the foam under launch loads and degradation studies (which measure the deterioration in chemical and mechanical properties with recycling) are also underway[16].

Figure 7. *CRISSP 3D-printed foam developed by Tethers Unlimited. Image courtesy of Tethers Unlimited.*

Through an internally funded innovative research project with NASA Ames Research Center and the Kennedy Space Center Vegetable Production System (VEGGIE) payload, the in-space manufacturing team explored the use of biologically derived thermoplastic feedstock filament to produce substrates for plant growth. The ultimate goal of such efforts would be to demonstrate an end to end process that uses raw plant mass (or compounds extracted from plant mass such as cellulose and lignin) alone or in combination with other materials/additives to produce filament feedstock which can subsequently be used in extrusion-based AM processes such as FDM. Initially several commercial off the shelf filaments originating from biologic materials were evaluated to produce plant substrates: Polylactic acid (PLA), Polyhydroxyalkanoates (PHA), PLA/PHA, and a potato starch derived filament. The activity also included optimization of the substrate lattice structure for nutrient absorption and water delivery. Wheat grass and radish seeds successfully germinated in the lattice structures with the addition of a moisture retainer starch polymer and either commercial off the shelf (COTS) microbial cellulose or microbial cellulose produced by the synthetic biology group at Ames Research Center (Figure 8). The next step for the work would be to mix microbial cellulose (produced at ARC) with pellets of biologically derived plastics to generate filament for 3D printing and investigate the potential production of lattice structures with cellulose already embedded in the growth block. PHA can also be made from microbes. The short duration project provided a cursory evaluation of the feasibility of using inedible plant mass or other biologically derived materials to make filament feedstock blends for 3D printing and is aligned with other activities on recycling and repurposing of materials[7].

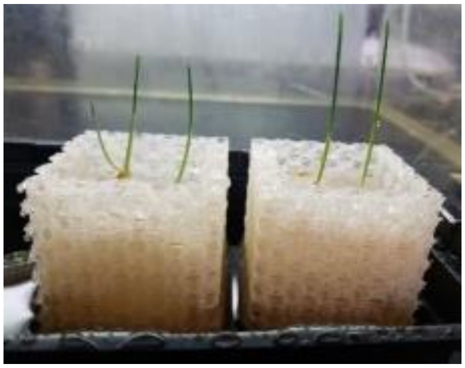


Figure 8. *Printing of plant substrates with biologically derived (COTS) filament. Germination of wheatgrass achieved with a retainer starch polymer and microbial-produced cellulose. Image credit Ames Research Center.*

v) Ground-based work on use of in-space manufacturing capabilities for biomedical applications

A manufacturing module for production of food and medical grade plastics, along with the accompanying sterilization procedures required for subsequent use of these materials, is also a desired capability for ISM. Human research data collected from long duration stays on ISS indicate that astronaut's immune systems are slightly compromised in microgravity. Biology experiments on ISS also show bacteria and viruses can become more virulent in the space environment. The combination of these factors makes maintaining a sterile environment and ensuring sterility of food and medical supplies a paramount concern for space missions. Funded under a phase II SBIR, Tethers Unlimited is working to develop ERASMUS, a dry heat sterilization system to enable reuse of consumables/supplies or consumables manufactured from recycled material[7]. Some examples of tools for manufacture and sterilization are shown in Figure 9.

Figure 9. *Potential food and medical consumables for manufacture and sterilization using the Tethers ERASMUS system. Image credit Tethers Unlimited.*

An ISM-sponsored senior design project with Vanderbilt University evaluated the feasibility of printing a cast on-orbit as a response to a crew limb injury. The current ISS medical procedure for a broken limb is to apply a Structural Aluminum Malleable (SAM) splint. However, the medical industry has traditionally been an early adopter of additive manufacturing technologies and 3D printed lattice casts are now viewed as an alternative to plaster casts and traditional splints. Lattice casts are custom designed to fit the patient, waterproof, and provide greater comfort and freedom in movement[18]. Some research also suggests that lattice casts promote healing faster than traditional techniques[18,19]. The senior design group was able to use a scanner to gather specifications for a student's forearm, use a CAD software to generate a custom mesh specific to the scanned geometry, and print the cast in multiple, interlocking pieces (necessitated by the size constraints of the 3D printers on station). One piece of a two piece interlocking cast is shown in Figure 10. The lattice is created using the Meshmixer software and a female or male clip mechanism is imposed on the corresponding half in the CAD modeling software. The lattice and the clip mechanism are merged in CAD to create a single file for printing. Biomedical applications are seen as a high impact area for AM due to the increasing use of these technologies in the medical industry for customization of medical implants, equipment, and consumables. Given the logistical constraints of long duration spaceflight and unanticipated issues which may arise even with a healthy crew, ISM will continue to explore how our capabilities may evolve to best serve exploration medical capabilities.

Figure 10. *Process flow for generation of one piece of a two piece lattice cast.*

vi) Future ground-based activities

Future ground-based activities will focus on addressing known technology gaps and continuing to develop capabilities to enable production (and subsequent verification) of ISM-produced parts intended for critical applications in space systems. Such scenarios may include palliative repair and on-demand production of spares. Verification and certification of parts produced on orbit is a pre-eminent challenge for ISM, as part inspection techniques that can be implemented onboard ISS are limited by constraints on crew time, crew skill sets, and power and volume of equipment. Online quality control is critical to ISM in lieu of availability of ground-based techniques and skilled personnel for material evaluation. Implementation of real-time multimodal data acquisition for process sensing, feedback, and closed loop control based on process signals for ISM may leverage techniques developed through "for-space" (propulsion) applications of additive manufacturing. Ultimately however, an in situ process monitoring system that is specific to ISM platforms, and meets the constraints of ISS in terms of personnel skill sets, A working document on verification and validation for parts produced using current ISM capabilities is also in development.

Logistics analyses for ISS conducted in support of the ISM program have pinpointed areas where ISM capabilities stand to be most impactful from the perspective of enhancing crew safety and reducing the mass of available spares required for long duration, long endurance mission[1,13]. High value application areas for ISM include valves, seals and O-rings, filters, electronics, and chemically active components (sorbents, desiccants, catalysts, and resins). Continued exploration of design and production of these high impact parts (such as those from environmental control and life support systems) using current and near-term capabilities is an ongoing activity. The ISM team recently completed an assessment of next generation ECLSS designs to identify components that could be designed for maintainability and potential replacement using ISM capabilities. Manufacturability investigations focused on historical part failures for ISS are key to informing requirements development for the multimaterial fabrication laboratory discussed in the next section.

III. The Multimaterial In-Space Manufaturing Fabrication Laboratory: A Phased Approach to Development of an Exploration System

In 2017, the in-space manufacturing project issued a Broad Area Announcement (BAA) for a multimaterial, multiprocess fabrication laboratory for the International Space Station[20]. The objective of the first phase (Phase A), is to demonstrate a scalable ground-based prototype of a Fab Lab system in order for NASA to better assess and facilitate development of the technologies to a flight opportunity. The objective of phase B is to further mature the highest potential technologies developed identified in phase A to a pre-flight deliverable. Phase C will be a flight demonstration on the ISS to demonstrate the feasibility of this ISM system, to fully the categorize the risk to crew, and to develop, refine and create standards for the manufacturing processes and properties of materials produced in a controlled microgravity environment, as well as demonstrate the ability to fabricate integrated circuits. A phased approach provides natural pivot points, enabling the ISM program to maintain a flexible path approach and revector FabLab capabilities to the highest potential technologies developed under the opportunity. It is anticipated that development of the desired capabilities within a singular facility will require the integration of multiple enabling technologies. Thus, partnering between industries with complementary technologies, as well as with academic research units, is expected to be necessary to develop the FabLab within the targeted time frame.

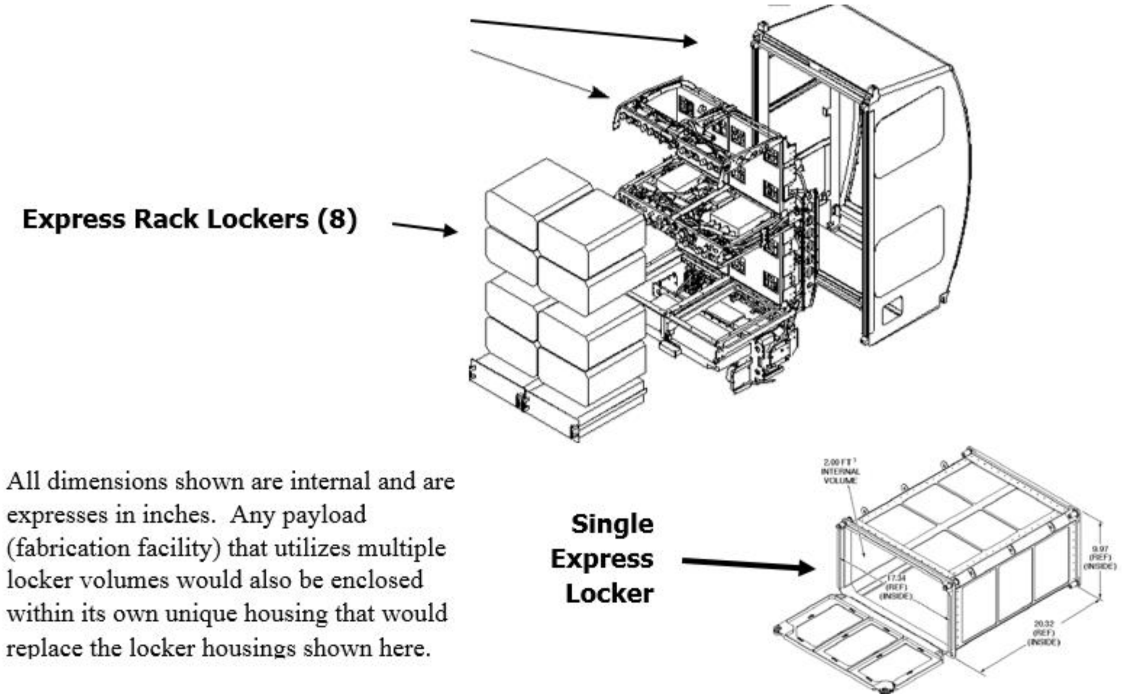
The 2017 BAA will request proposals for the phase A ground based demonstration with a measureable ability to mature into a flight demonstration on the ISS within three years. In 2016, NASA issued a request for information to inform development for requirements for FabLab. The desired capabilities for the FabLab are divided into minimum threshold capabilities (required) and objective target capabilities (desired). Desired system capabilities (taken from the BAA) are summarized in Table 1. Volume constraints for the FabLab are expected to be bounded by the dimensions of the EXPRESS rack, equivalent to eight lockers (Figure 11). The EXPRESS rack provides 16 cubic feet of payload volume. The power budget, also driven by operation in the EXPRESS rack, is 2000 W. Mass of the payload should be less than 576 lbm for a total rack, 288 lbm for a half rack, etc.

Table 1. Top level FabLab Requirements

Threshold	**Objective**

Threshold	Objective
The system should have the ability for on-demand manufacturing of multi-material components including metallics and polymers as a minimum.	Multi-material capability including various aerospace-grade metallic, polymer, and/or conductive inks significantly increase the merit of the proposal.
The minimum build envelope shall be 6” x 6” x 6”.	As large of a build-volume and/or assembly capability as possible within the Express Rack volume constraints listed in Section 3.
The system should include the capability for earth-based remote commanding for all nominal tasks.	Remote commanding and/or autonomous capability for all tasks (nominal and off-nominal.
The system should incorporate remote, ground-based commanding for part handling and removal in order to greatly reduce dependence on astronaut time.*	The system should incorporate autonomous part handling and removal in order to greatly reduce dependence on astronaut time.*
The system should incorporate in-line monitoring of quality control and post-build dimensional verification.	The system should incorporate *in-situ*, real-time monitoring for quality control and defect remediation capability.

***** *Astronaut time is extremely constrained. As a flight demonstration, the ISM FabLab would be remotely commanded and operated from the ground, with the ultimate goal being to introduce as much eventual autonomy as possible. As a minimum, there should be no greater than 15 minutes of astronaut time*



All dimensions shown are internal and are expresses in inches. Any payload (fabrication facility) that utilizes multiple locker volumes would also be enclosed within its own unique housing that would replace the locker housings shown here.

Figure

Figure 11. *FabLab’s eventual interface with the EXPRESS Rack defines constraints on volume, power, and mass of the system.*

The core of the FabLab solicitation is an expansion of the material envelope for in-space manufacturing capabilities. As such, the ability of proposed engineering solutions to fabricate a range of materials including metallics will be a preeminent evaluation criteria. The ability to fabricate quality aerospace grade materials in a controlled and repeatable manner on orbit will help accelerate the acceptance of ISM as a tool and institutionalize the capability among the design and logistics communities. It is generally recognized that unanticipated failures for ISS still occur even after nearly 17 years of continuous operations and that, by virtue of the law of cumulative probability, incidences of failure will only increase with extended missions that travel farther than LEO. FabLab will provide an important capability for addressing the inherent uncertainty in system performance and serve as an additional safety measure that can also potentially transform logistics and launch mass requirements.

The FabLab must also provide a system for raw feedstock form and handling. Material use should be maximized to the extent possible with a given system. Containment methods for particulate-based systems (i.e. those using feedstock in powder form) or systems that generate chip debris must also be sufficiently addressed.

FabLab systems must also meet the aforementioned overarching ISS requirements and demonstrate that the manufacturing process is robust to changes in the gravity vector. Other figures of merit for evaluation include the geometric accuracy and complexity of the parts that can be produced. An example of a complex part intended to demonstrate the capabilities of a candidate manufacturing process (feature resolution, tolerances and dimensional accuracy, etc.) is shown in Figure 12. Given constraints on crew time and the limitations in crew skill sets to perform dedicated manufacturing operations, remote commanding is also viewed as a critical capability. Postprocessing requirements and the ability to integrate postprocessing into the FabLab itself is also a consideration. Hybrid systems, can reduce the challenges associated with postprocessing. A verification and validation capability for the FabLab platform is also desired. For example, the system may be able to detect voids in situ or inspect finished parts for dimensional accuracy.

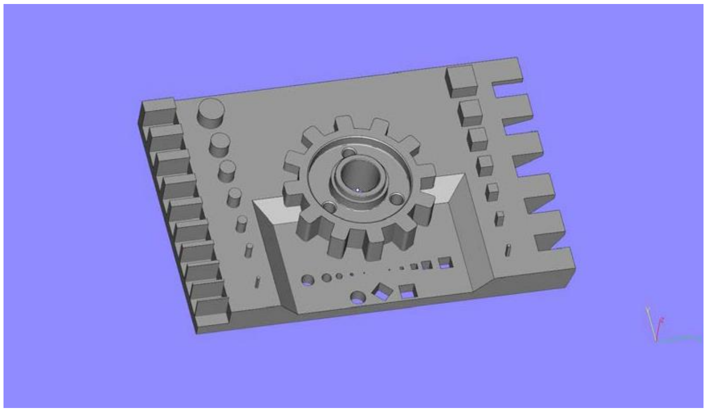


Figure 12. Example range coupon taken from the BAA[20].

The FabLab solicitation closed in late August 2017 and awards are anticipated in the late Fall timeframe. Phase A is an 18-month period of performance with deliverables of an operational bench-top/lab-level prototype and a PDR package. Phase B is also 12-18 months with deliverables of an engineering test unit (ETU) prototype, characterization of test articles, and a CDR package. Phase C is an 18 month period of performance concluding with delivery of a flight certified ISM technology demonstration system for ISS. The FabLab is intended to be deployed on ISS in the 2021 timeframe.

IV. Summary

Successful implementation of ISM requires accelerating integration of current and near-term ISM capabilities into the design of advanced space exploration systems for deep space habitats and other “proving ground” missions. ISM should not be viewed as a “bonus” for existing space systems, but a tremendous opportunity to transform logistics, reduce system operational risk for next generation exploration habitats, and enable entirely new systems and mission concepts. While ISM’s overarching current goal is development of the Fabrication Laboratory for International Space Station, there are multiple projects underway under the ISM project umbrella that also potentially infuse into future ISM exploration systems. Among these are:

- continued payload operations and materials characterization of specimens manufactured in microgravity

- development and operation (in the 2018 timeframe) of a recycling payload for ISS by Tethers Unlimited, which represents the first closure of the manufacturing loop for in-space manufacturing
- development of hybrid manufacturing (additive and subtractive) ground demonstration units with potential extensibility to on-orbit manufacturing
- materials development work to enable maximum reuse of spaceflight materials (includes fundamental materials work on development of recyclable packaging materials, common use materials, and biologic feedstocks)
- in-house and SBIR activities related to additive manufacturing of electronics (miniaturization of systems, development of conductive dielectric inks and metal inks, fabrication and testing of additively manufactured antennas, ultra-capacitors, and wireless sensors using the nScrypt)
- continued exploration of ISM capabilities to support crew health and safety

The additive manufacturing space is a highly disruptive area and ISM seeks to leverage innovations in the broader field to accelerate payload development and advance the state of the art for space-based manufacturing capabilities. To achieve its goals of providing a rapid, on-demand suite of manufacturing capabilities to support long endurance exploration missions in the 2025+ timeframe, ISM seeks to develop a Fabrication Laboratory (FabLab), targeted for implementation on ISS in the early 2020s. As discussed in this paper, the FabLab will provide a robust, multi-material on-demand manufacturing capability for human space exploration. Since further iterations of FabLab will be integrated in deep space habitats or transit vehicles in a functional support capacity, it is critical that ISS be used as a near-term test bed for this capability. The FabLab serves as a bridge between ISM's current capabilities (primarily 3D printing and recycling of polymers) and realization of a robust on-orbit manufacturing capability to support maintenance and repair of space systems. The FabLab will bring us one small step closer to Earth independent exploration and provide an adaptive, rapid response capability that reduces sparing requirements and enhances crew safety.

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