

NASA's In-Space Manufacturing Project: Development of a Multimaterial, Multiprocess Fabrication Laboratory for the International Space Station

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Introduction:

NASA's long term goal is to send humans to Mars. Over the next two decades, NASA will work with private industry to develop and demonstrate the technologies and capabilities needed to support exploration of the red planet by humans and ensure their safe return to earth. To accomplish this goal, NASA is employing a capability driven approach to its human spaceflight strategy. This approach will develop a suite of evolving capabilities which provide specific functions to solve exploration challenges.

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 project, its past and current activities, and how technologies under development will ultimately culminate in a multimaterial, multiprocess fabrication laboratory ("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 may result in a loss of mission in transit to Mars. In order 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 will discuss the phased approach to FabLab development, desired capabilities, and requirements for the hardware. 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 FabLab will be tested on ISS, the system is ultimately intended for use in a deep space habitat or transit vehicle.

Mission of NASA's In-Space Manufacturing (ISM) Program:

NASA's in-space manufacturing 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. 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. 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:

- 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
- 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.

Evolving Capabilities:

In 2014, ISM, in partnership with Made in Space, launched the first 3D printer to ISS. To date, this printer has produced a total of 45 parts. Materials produced on orbit (ABS plastic) have undergone extensive testing and material evaluation. Results of analyses and follow-on studies have been published. Following the success of this payload, Made in Space was able to develop a more capable printer, the Additive Manufacturing Facility (AMF) through a partnership with the Center for the Advancement of Science in Space (CASIS). AMF has enhanced material capabilities and control systems. NASA is a customer for this facility and is using AMF to explore utilization scenarios for in-space manufacturing and conduct further material investigations. ISM's second payload, an integrated 3D printing and recycling unit developed by the small business Tethers Unlimited, will be operational on station in the 2018 timeframe. ReFabricator is an integrated 3D printer and recycler unit. ReFabricator can print a part from plastic feedstock filament, melt it, and re-extrude it as filament that can then be routed back to the printhead and used for further printing.

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 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 scalability 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. A payload capable of producing food and medical grade plastics (and accompanying sterilization procedures required for use of these materials) is also in development. Ground-based fundamental materials work on development of recyclable packaging materials and common use materials is also being pursued, activities which are critical to realizing the maximum benefits of ISM. Development of capabilities to additively manufacture electronics is also a core part of the ISM program. NASA MSFC has done significant ground based work on development of conductive dielectric inks and has tested additively manufactured antennas and ultra-capacitors. A recently purchased nScript machine is currently being used to support research and development work in this area. 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.

Verification and certification of parts produced on orbit is a pre-eminent challenge for ISM. 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 will likely leverage techniques developed through “for-space” (propulsion, for example) applications of additive manufacturing. A working document on verification and validation for parts produced using current ISM capabilities is 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. 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. 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.

The Multimaterial Fabrication Laboratory: A Phased Approach

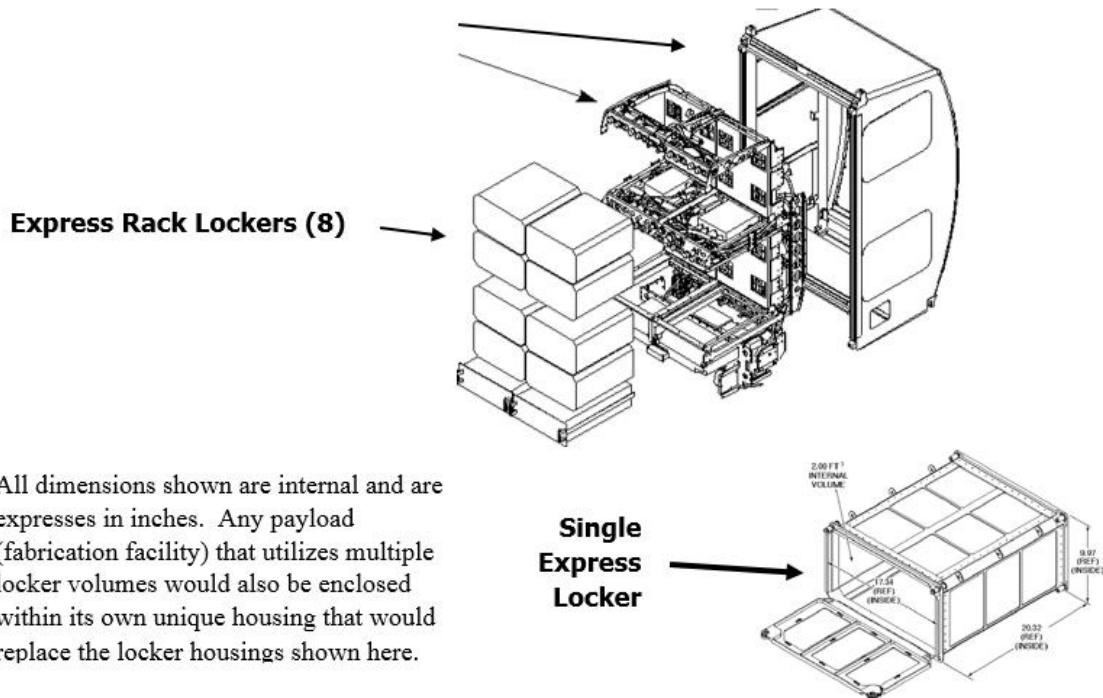
In 2017, the in-space manufacturing project will issue a broad area announcement (BAA) for a multimaterial, multiprocess fabrication laboratory for the International Space Station. The objective of the first phase (Phase A), is to demonstrate a scalable ground-based prototype of a Fab Lab system in order 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. As stated in this RFI, the desired capabilities for the FabLab are divided into minimum threshold capabilities (required) and objective target capabilities (desired). Desired system capabilities are summarized in Table 1. The ability to fabricate and/or repair complex electronics will be necessary for long duration missions and is viewed as key downstream FabLab capability. Ability to process feedstock prepared from in situ resources on a destination surface (such as processed lunar, asteroid, or martian regolith) is also desired. Volume constraints for the FabLab are expected to be bounded by the dimensions of the EXPRESS rack, equivalent to eight lockers (Figure). 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. These requirements were also defined in the RFI.

Table 1. Top level FabLab Requirements

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 <i>in-situ</i> , real-time monitoring for quality control and defect remediation capability.

** Astronaut time is extremely constrained. As a flight demonstration, the 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 required for any given nominal activity, with the end-goal being to apply the same rule to maintenance and off-nominal operations as well.*



All dimensions shown are internal and are expressed 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 1. FabLab’s eventual interface with the EXPRESS Rack defines constraints on volume, power, and mass of the system.

The presentation will discuss concepts for the FabLab, highlight constituent technologies, outline the development path of the FabLab to flight, and identify potential infusion points for the capabilities being developed in parallel through SBIRs and in-house work discussed in section. At the time of the presentation of this paper in September 2017, FabLab BAA phase A awards will have been selected.

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.

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 massless exploration and provide an adaptive, rapid response capability that reduces sparing requirements and enhances crew safety.