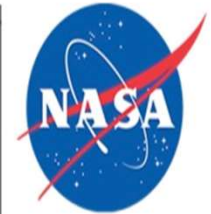


National Aeronautics and
Space Administration



**AIAA SPACE Conference
2018**

Tracie Prater, Ph.D.
ISM Technical Integration Lead

Niki Werkheiser
ISM Project Manager

Frank Ledbetter, Ph.D.
ISM Senior Technical Adviser

Kristin Morgan
ISM Multimaterial Fabrication
Laboratory Technical Lead

In-Space Manufacturing (ISM) at NASA Marshall Space Flight Center



**A Portfolio of Fabrication and
Recycling Technology Development
for the International Space Station**

MARSHALL
SPACE FLIGHT CENTER

What is In-Space Manufacturing?



In-space manufacturing refers to any manufacturing process which operates in the space environment

- On-demand, “just in time” manufacturing for space
 - Alternative to prepositioning of spares, launching parts and structures from earth
- Not limited to additive manufacturing



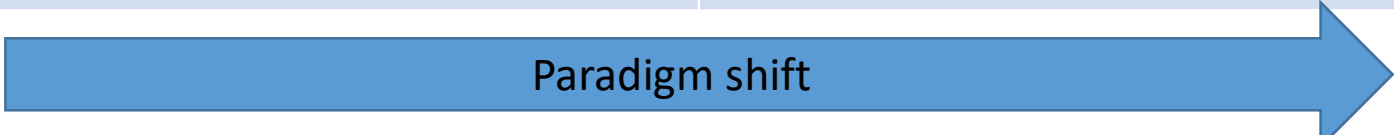
Tea.
Earl Grey.
Hot.



In-space manufacturing removes constraints



Constraint ¹	Constraint removed by ISM?
Structures must be designed for launch loads.	ISM enables structures which are optimized for operation in space, not for launch loads.
Structures must fit within launch vehicle payload fairings.	ISM enables structures whose size is limited only by the fabrication volume of the ISM capability.
Materials must be disposed of at the end of their lifecycle.	Materials can be recycled and used for further manufacturing.
All the spare parts and equipment needed for on-orbit servicing or repair and replacement activities must be prepositioned.	Spare parts can be made on-demand. ISM capabilities can enable on-orbit servicing and repair of equipment.
Component reliability and redundancy (R&R) largely driven by mission life/duration.	Redundancy is augmented by ISM capability to make components on demand. R&R requirements may be reduced in some instances when an ISM capability is present.



1. Table adapted from Moraguez, Matthew. "Technology Development Targets for In-Space Manufacturing." Master's thesis. MIT, 2018

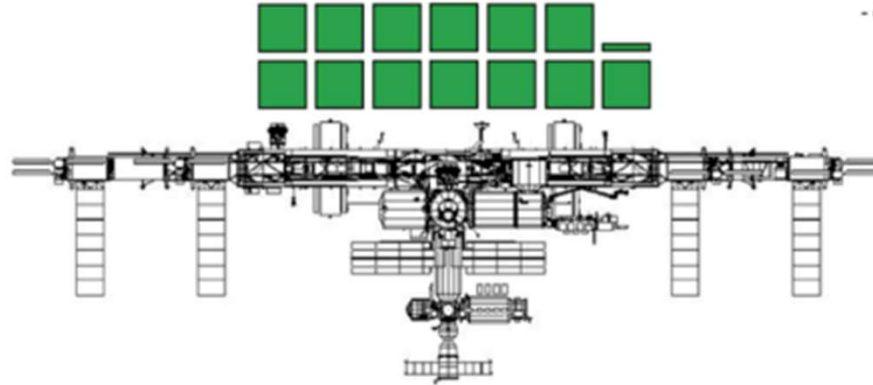
Why manufacture in space: The logistics quandary of long endurance spaceflight



Each square represents 1000 kg

Total Approx. Spares Mass Currently On-Orbit = 13,170 kg

Mass estimates are for mass of spare item only
- do not including any packaging or carrier mass

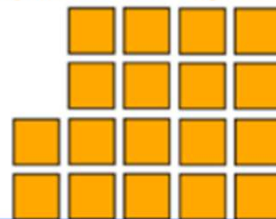


Predicted Annual Average Upmass 2012-2020

	Corrective Maintenance	= 1,260 kg
	Preventive Maint. / Consumables	= 1,930 kg
Total		= 3,190 kg

Expected Average Annual Failures* = 450 kg

Total Approx. Spares Mass Currently Stored On Ground = 17,990 kg



- Based on historical data, 95% of spares will never be used
- Impossible to know which spares will be needed
- Unanticipated system issues always appear, even after years of testing and operations

* - Based on predicted MTBFs

Image credit: Bill Cirillo (LaRC) and Andrew Owens (MIT)



Evolvable Path for In-Space Manufacturing



Ground & ISS Development & Demonstration | Exploration Implementation



3D Print Plastic Printing Demo

Material Characterization



Mat. Char. & Dev.	FabLab (Metals, Elec.)
Polymer Mfg.	Polymer Mfg. & Recycling
Additive Constr.	External Mfg.



Moon (Gateway)



Mars

to

Pre-2012

- Ground & Parabolic centric:
- Multiple FDM Zero-G parabolic flights
 - Trade/System Studies for Metals
 - Ground-based Printable Electronics/Spacecraft
 - Verification & Certification Processes under development
 - Materials Database
 - CubeSat Design & Development

2014

- ISS 3DP Tech Demo: First Plastic Printer on ISS
- NIAC Contour Crafting
- NIAC Printable Spacecraft
- Small Sat in a Day
- AF/NASA Space-based Additive NRC Study
- ISRU Phase II SBIRs
- Ionic Liquids
- Printable Electronics

2015-2024

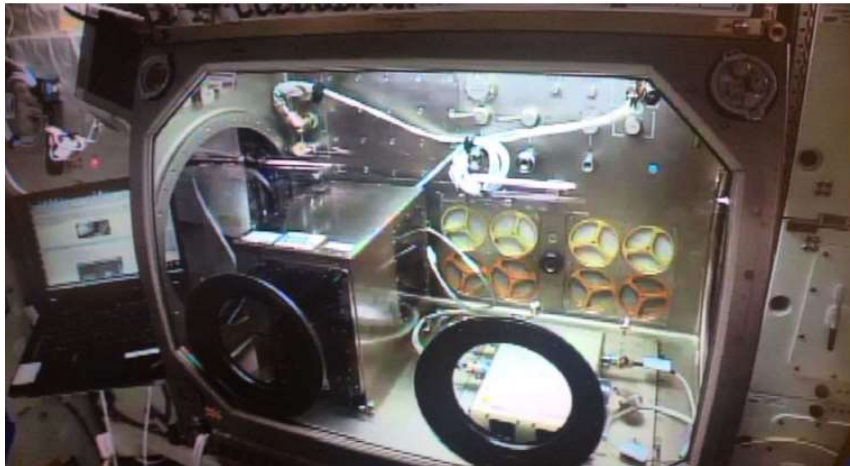
- 3DP Tech Demo
 - Add. Mfg. Facility (AMF)
 - ISM Certification Process Part Catalog
 - ISS & Exploration Material & Design Database
 - External Manufacturing Processes
 - Autonomous Processes
 - STEM (Future Eng.)
 - Additive Construction
- ISS: Multi-Material FabLab Rack Test Bed (Springboard for Deep Space Gateway)
- Integrated Facility Systems for stronger multi-use materials including metals & polymers, embedded electronics, autonomous inspection & part removal, etc.
- In-Space Recycler Tech Demo
- Hab/DSG Demos
- Reinforced polymers
 - Crew health monitoring
 - Components and supplies
 - Structural health monitoring (embedded and surface-printed electronics)

2025 and beyond

- Gateway, Lunar FabLabs
- Initial Robotic/Remote Missions
 - Provision feedstock (natural resources, synthetic biology)
 - Product: Ability to produce, repair, and recycle parts & structures on demand; i.e.. "living off the land"
 - Autonomous final milling
- Mars Preparation
- Transport vehicle and sites require FabLab capability (adapt for in-situ resource utilization)
 - Additive Construction & Repair of large structures
- Mars Multi-Material FabLab
- Provision & Utilize in situ resources for feedstock
 - FabLab: Provides on-demand manufacturing of structures, electronics & parts utilizing in-situ and ex situ (renewable) resources. Includes ability to inspect, recycle/reclaim, and post-process as needed autonomously to ultimately provide self-sustainment at remote destinations.

ISS serves as a Key Exploration Test-bed for the Required ISM Technology Maturation & Demonstrations

Fused Filament Fabrication (FFF) on ISS: The First Step



Tech demo printer installed in the Microgravity Science Glovebox (MSG)

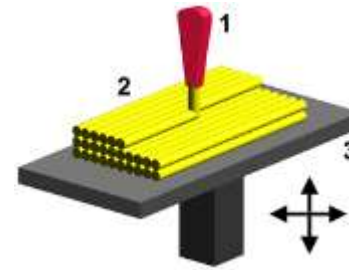
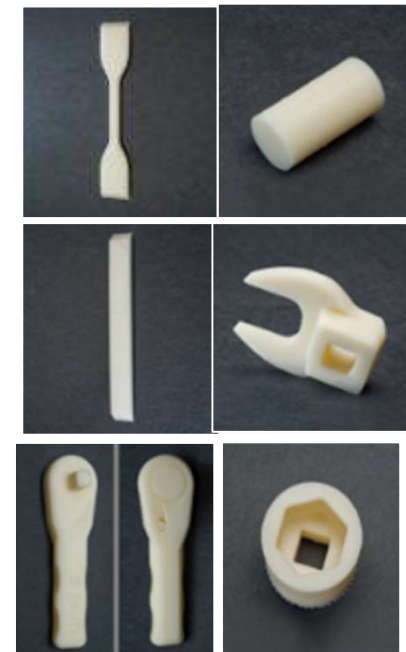


Illustration of the FFF (process

- Fused filament fabrication:
- 1) nozzle ejecting molten plastic,
 - 2) deposited material (modeled part),
 - 3) controlled movable table

3D Printing in Zero G Technology Demonstration Mission

- Operational on ISS in 2014
- Printer built and operated by Made in Space, Inc.
- Completed two rounds of operations
- Printed 55 specimens of Acrylonitriled Butadiene Styrene (ABS)
- No engineering significant effect of microgravity on material outcomes observed



Examples of specimens printed in phase I operations

Additive Manufacturing Facility (AMF)



Additive Manufacturing Facility (AMF)

- 2nd generation printer for ISS
- FFF system owned and operated by Made in Space, Inc.
- Can print in High Density Polyethylene (HDPE), Acrylonitrile Butadiene Styrene (ABS), and ULTEM 9085 (PEI/PC)
- To date, NASA has printed a number of functional parts for ISS with this capability
- NASA is currently executing a materials characterization plan to develop design values for ABS produced with AMF



The Made in Space Additive Manufacturing Facility (AMF)



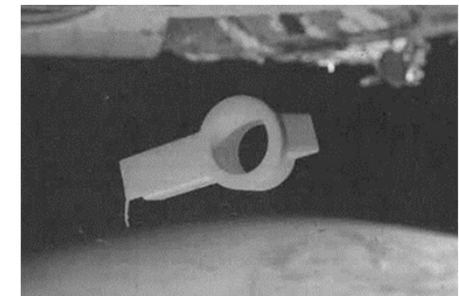
SPHERES Tow Hitch: SPHERES consists of 3 free-flying satellites on-board ISS. Tow hitch joins two of the SPHERES satellites together during flight. Printed 2/21/17.



REM Shield Enclosure: Enclosure for radiation monitors inside Bigelow Expandable Activity Module (BEAM). Printed 3/20/17 (1 of 3). Others printed 5-30 and 6-16. All are now installed on BEAM.



Antenna Feed Horn: collaboration between NASA Chief Scientist & Chief Technologist for Space Communications and Navigation, ISM & Sciperio, Inc. Printed 3/9/17 and returned on SpaceX-10 3/20/17



OGS Adapter: adapter attaches over the OGS air outlet and fixtures the velocical probe in the optimal location to obtain a consistent and accurate reading of airflow through the port. 7/19/2016.

The ReFabricator: Closing the Manufacturing Loop



- Refabricator is an integrated 3D printer (FFF) and recycler for ULTEM 9085 (PEI/PC)
 - Phase III SBIR contract with Tethers Unlimited, Inc.
 - Recycles 3D printed plastic into filament feedstock through the Positrusion process
- Refabricator demonstrates feasibility of plastic recycling in a microgravity environment for long duration missions
 - Phase I of on-orbit operations consists of 7 printing and recycling cycles
 - Filament left on spool from each recycling cycle and 5 tensile specimens per cycle will be downmassed to earth for testing and evaluation
- Operational on ISS in late 2018



Sterilization of Recycled Polymer Materials



- ERASMUS from Tethers Unlimited (NASA SBIR Phase II) is a Medical-Grade and Food-Safe Plastic Recycling and Sanitization System
- ERASMUS will enable use of recycled materials for medical grade and food-safe applications on ISS
 - bacteria and viruses are more virulent in space and crew immune systems tend to be compromised
 - ERASMUS provides a dry heat sterilization process and UV sanitization routine which can be integrated with 3D printing and recycling systems

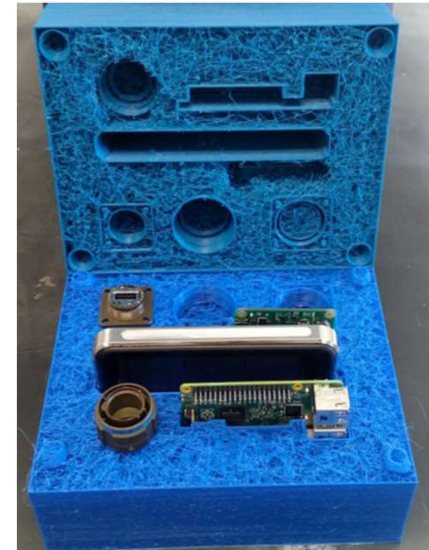


Examples of biomedical components and food utensils manufactured with ERASMUS. Image courtesy of TUI.

Recyclable Materials (Phase II SBIRs)



- Mature recyclable launch packaging material to enable sustainable manufacturing and reuse of otherwise nuisance materials on deep space missions
- Phase II-X: Customizable Recyclable International Space Station Packaging (CRISSP) from Tethers Unlimited
 - process for 3D printing of customized foam packaging
 - testing demonstrated that this packaging can provide vibration protection equivalent to or exceeding current materials used as ISS packaging
 - test samples were recycled into filament for 3D printing and degradation studies assessed reduction in material characteristics over multiple recycling cycles
 - CRISSP Phase II-X effort focuses on redesign and upgrade of TUI's ReFabricator system for multimaterial capabilities

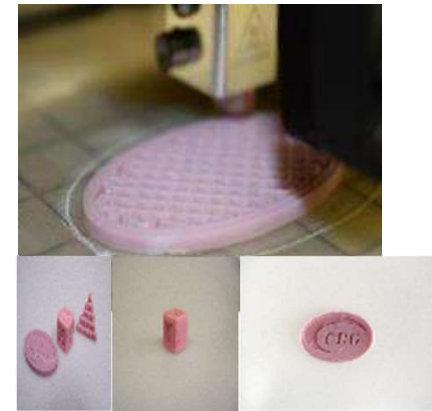


CRISSP (image from Tethers Unlimited)

Recyclable Materials (Phase II SBIRs)



- Phase II-X SBIR: Reversible Copolymer Materials for FDM 3-D Printing of Non-Standard Plastics from Cornerstone Research Group (CRG)
 - Under a phase II SBIR, CRG developed thermally-reversible polymer materials compatible with fused filament fabrication (FFF) systems
 - These materials are designed to be recycled, blended, and extruded.
 - Additives can also be combined with existing waste packaging, enabling reclamation of filament for additive manufacturing from packaging materials.
 - In the phase II-X effort, CRG will conduct further characterization of their thermally reversible material and scale the associated polymer resin production and packaging production processes
 - includes testing needed to certify this material for spaceflight applications



FDM prints using reclaimed anti-static bagging film with reversible cross-linking additive (image from Cornerstone Research Group)

Beyond Plastics: Hybrid Additive Manufacturing for Metals (Phase II SBIRs)



- Several projects under SBIR Phase II funding are developing metal manufacturing capabilities for in-space manufacturing and accompanying subtractive processes needed to provide a finished part
- Vulcan from Made in Space, Inc.
 - Weld-based additive manufacturing process for metal fabrication, a CNC mill for processing, and an automated capability for movement of the part between subsystems
 - Phase II work includes design, construction, and testing of an integrated, prototype unit to perform hybrid manufacturing functions



• Metal part produced with Vulcan manufacturing system. Image courtesy of MIS, Inc.

Beyond Plastics: Hybrid Additive Manufacturing for Metals (Phase II SBIRs)



- ISS Fabrication Laboratory using Ultrasonic Additive Manufacturing (UAM) Technology from UltraTech Machinery
 - Ultrasonic additive manufacturing process
 - solid-state process that occurs at room temperature
 - uses sound waves to remove the oxide layer between adjacent layers of metal foil, creating a metallurgical bond
 - UltraTech and subcontractor Fabrisonic, Inc. designed and tested a 30 kHz sonotrode which reduced process forces and enabled scaling of the process
 - Early tests of the prototype system produced quality material in 6016 T6 and 7075 T6 and enabled material production at significantly lower power and forces

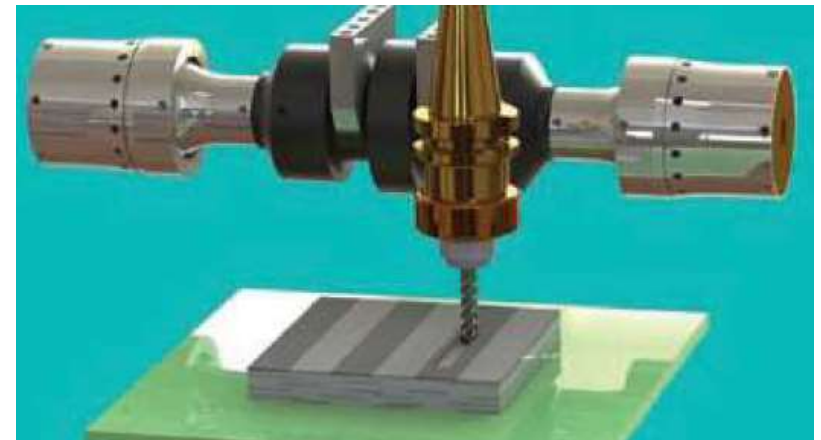
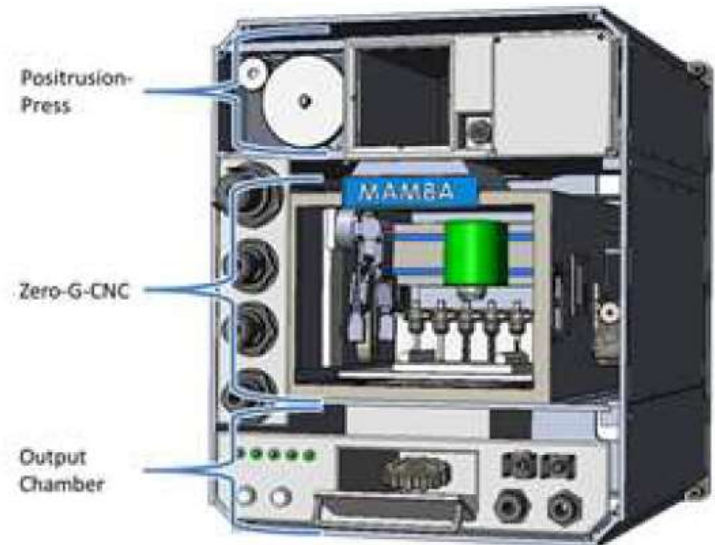


Illustration of UAM process.
Image courtesy of UltraTech

Beyond Plastics: Hybrid Additive Manufacturing for Metals (Phase II SBIRs)



- Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA) from Tethers Unlimited combines three technologies to provide a precision metallics manufacturing capability for ISS
 - a press that processes virgin or scrap material into a metal ingot
 - a CNC mill designed to operate in microgravity
 - a robotic assistant to facilitate automated processing of material/parts through the subsystems
- MAMBA applies the same Positrusion process used to recycle plastics in the ReFabricator to aerospace grade metals.

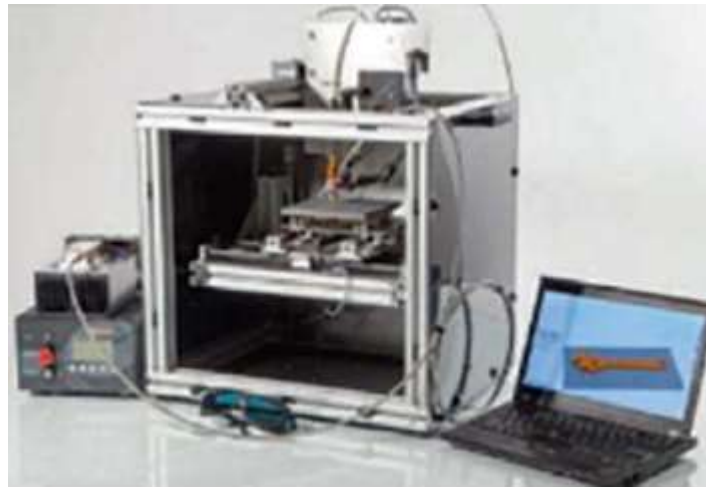


Schematic of MAMBA system.
Image courtesy of TUI

Additive Manufacturing of Metals For Space (Phase II-E SBIR)



- Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) from Techshot
 - 3D metal printer in which a ferromagnetic wire metal filament is heated to its Curie temperature through induction
 - Metal deposited on a build platform where a low power laser completes the melt

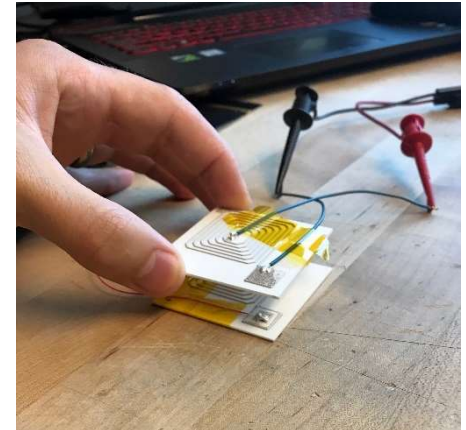


Sintered Inductive Metal Printer with Laser Exposure (SIMPLE).
Image courtesy of Techshot.

In-space manufacturing of electronics



- evaluating technologies to enable multi-material, on-demand digital manufacturing of components for sustainable exploration missions
 - In-house work uses nScript printer
 - 4 heads for dispensation of inks and FDM of polymers; also has pick and place capability
- Developed and demonstrated the functionality of a passive wireless humidity sensor intended for the in-line monitoring of systems.
 - Sensing material also developed in-house at MSFC
 - ECLSS and ISM are planning to perform ground development testing of sensors in the ECLSS environment which introduce the presence of CO, CH4, and H2
- Completed initial design concept of the first printable ECLSS pressure switch.
 - In additive design, switching is accomplished via a pressure sensitive material turning a transistor on when the system exceeds a certain pressure
- Work on miniaturization and adaptation of printable electronics for microgravity environment will continue through two contracts (phase I) awarded under SBIR subtopic In-Space Manufacturing of Electronics and Avionics
 - Techshot, Inc. (STEPS – Software and Tools for Electronics Printing in Space) – Phase I complete in Dec. 2017
 - Direct write and avionics printing capability for ISS
 - Optomec (miniaturization of patented Aerosol Jet technology) – Phase I complete in Dec. 2017



Printed wireless humidity sensor (wires attached for characterization purposes)



Printable ECLSS pressure switch

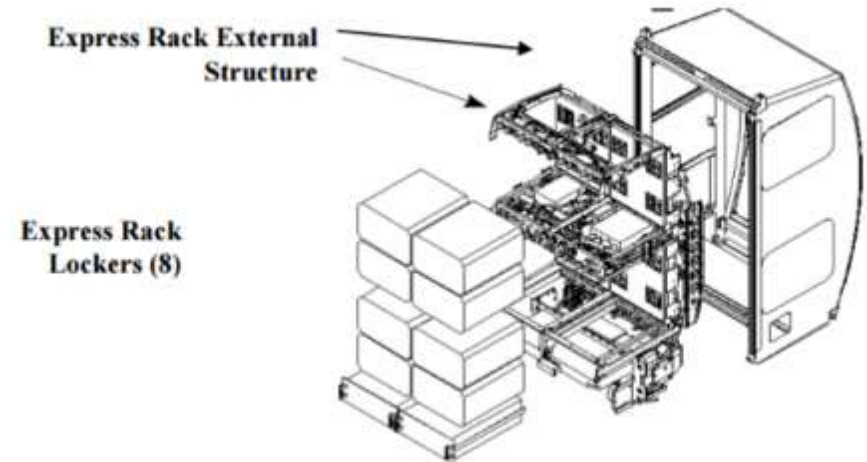


nScript multimaterial printer

Multimaterial Fabrication Laboratory for the International Space Station



- **Aligned with vision of in-space manufacturing project to develop and test on-demand, manufacturing capabilities for fabrication, repair and recycling during Exploration missions**
- **ISM offers:**
 - Efficiency gain and risk reduction for deep space exploration
 - “Pioneering” approach to maintenance, repair, and logistics will lead to sustainable, affordable supply chain model
- **In order to develop application-based capabilities for Exploration, ISM must leverage the significant and rapidly-evolving terrestrial technologies for on-demand manufacturing**
 - Requires innovative, agile collaboration with industry and academia
 - NASA-unique Investments to focus primarily on developing the skillsets and processes required and adapting the technologies to the microgravity environment and operations



Ultimately, an integrated “FabLab” facility with the capability to manufacture multi-material components (including metals and electronics), as well as automation of part inspection and removal will be necessary for sustainable exploration opportunities.



Multimaterial Fabrication Laboratory for the International Space Station

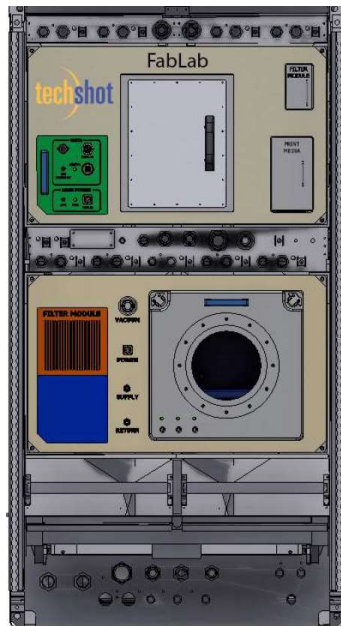


- Minimum capabilities for Fabrication Laboratory for ISS
 - On-demand manufacturing of metallics and other materials in the microgravity environment
 - Includes safety, waste management, and containment of debris
 - Ability to process a range of metals for in-space applications
 - Ability to operate in a reduced gravity environment
 - Minimum build envelope of 6"x6"x6"
 - High geometric part complexity and accuracy
 - Ability to fit within EXPRESS rack constraints (ex. power, mass, volume)
 - Earth-based remote commanding
 - Remote commanding for all nominal tasks, including part removal and handling
 - Post-processing requirement on crew for part readiness should be minimized
 - In-line remote/autonomous inspection and quality control
 - Incorporate inspection/verification capabilities to ensure quality control (assess tolerances, voids, etc.)
 - Metallurgical quality of finished part
 - Power consumption for FabLab is limited to 2000 W, payload mass limit is 576 lbm.

Multimaterial Fabrication Laboratory for the International Space Station



- Phase A awards for the NEXT-STEP Broad Agency Announcement (BAA) went to:
 - Tethers Unlimited of Bothell, Washington
 - Techshot, Inc. of Greenville, Indiana
 - Interlog Corporation of Anaheim, California
- 18 month period of performance to develop a ground-based prototype system
 - Includes materials characterization and demonstration of inspection capabilities

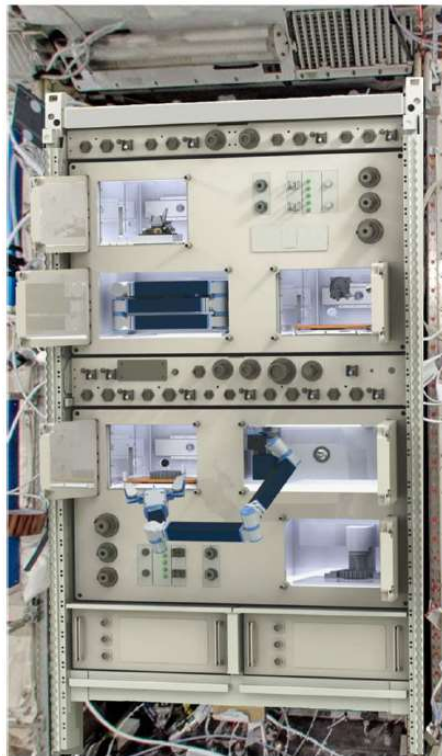


Techshot FabLab will be compatible with the space station's EXPRESS Rack. Remotely controlled operations from Earth will manufacture multi-material components, including metals, ceramics, plastics and electronics.

Multimaterial Fabrication Laboratory for the International Space Station



- Tethers Unlimited, Inc. (TUI) Empyrean FabLab increases astronaut efficiency by providing autonomous processing and verification and validation services in a system designed for microgravity operation.
 - focus on a suite of support technologies for microgravity-enabled multi-material manufacturing, including robotic handling, quality control, autonomy, and teleoperation capabilities.



TUI Empyrean Fab Lab (image courtesy of TUI).
Partners include IERUS technologies and
BluHaptics.

Multimaterial Fabrication Laboratory for the International Space Station



- Interlog Corporation (Interlog) will develop the Microgravity Multiple Materials Additive Manufacturing (M3AM) technology to provide on-demand manufacturing solutions for fabrication, maintenance, and repair on space missions.
- M3AM is capable of manufacturing various aerospace-grade metallic parts such as Aluminum, Titanium, Nickel, and other metallics. M3AM can also bond dissimilar materials (e.g., metals, glass epoxy, flexible ceramics).
- M3AM is enabled by Interlog's proprietary manufacturing technique that additively constructs a part via a focused bonding-energy mechanism.
- M3AM seeks to offer multi-material AM on a single platform, autonomous operation, dissimilar material bonding for electronics and PCB (Printed Circuit Board) fabrication as additional features, autonomous part removal, and multiple material feeding mechanisms.



M3AM Interlog's engineers, Veronica Swanson (left) and Andy Peng (right), are performing a proof of concept test with a newly-developed prototype for multiple materials additive manufacturing in a single platform. Image courtesy of Interlog.



Closing thoughts



- Key challenges to ISM implementation are socialization of capabilities with the design community and integration of ISM into exploration systems currently under development.
- ISM is a critical capability for the long endurance missions NASA seeks to undertake in the coming decades and also an important aspect of low earth orbit commercialization initiatives.
- ISM will continue to create and leverage partnerships with industry, small business, and academia to conduct technology development.
- The use of ISS as a proving ground for manufacturing systems will pave the way for the transition to earth-independent exploration class missions in the post-ISS era.