The High Frontier: A New Age of Manufacturing in Space

Symposium on Space Innovations

Tracie Prater, Ph.D.

Materials and Processes Laboratory, NASA Marshall Space Flight Center

Niki Werkheiser, Project Manger, In-space manufacturing, NASA Marshall Space Flight Center

Kristin Morgan, Technical Lead for Multimaterial Fabrication Laboratory

.

Frank Ledbetter, Ph.D. senior technical advisor

National Aeronautics and Space Administration

NASA

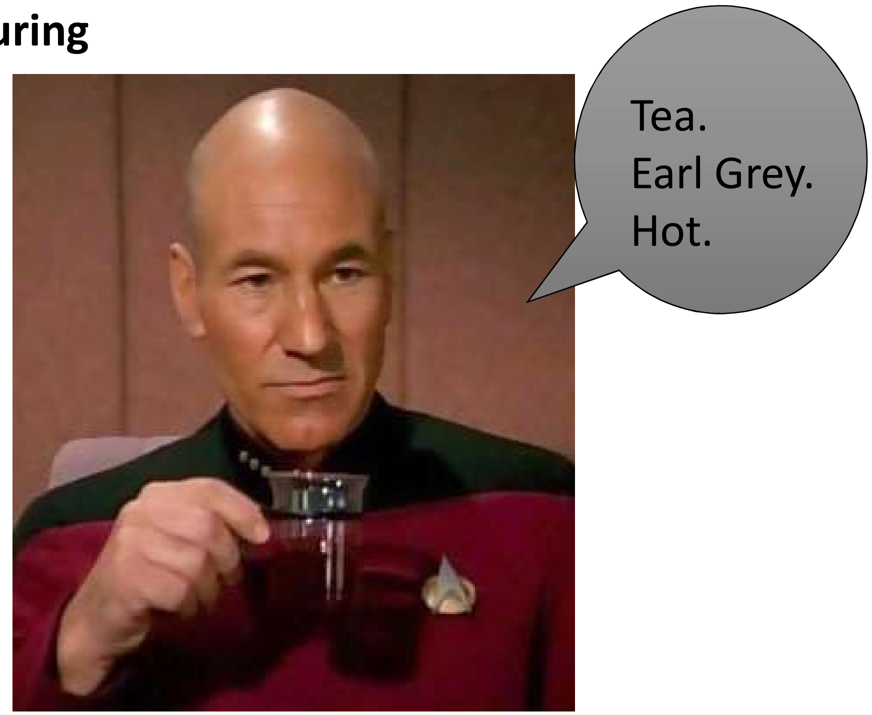
MARSHALL SPACE FLIGHT CENTER

Part 1: The In-Space Manufacturing Project

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**



In-space manufacturing removes constraints

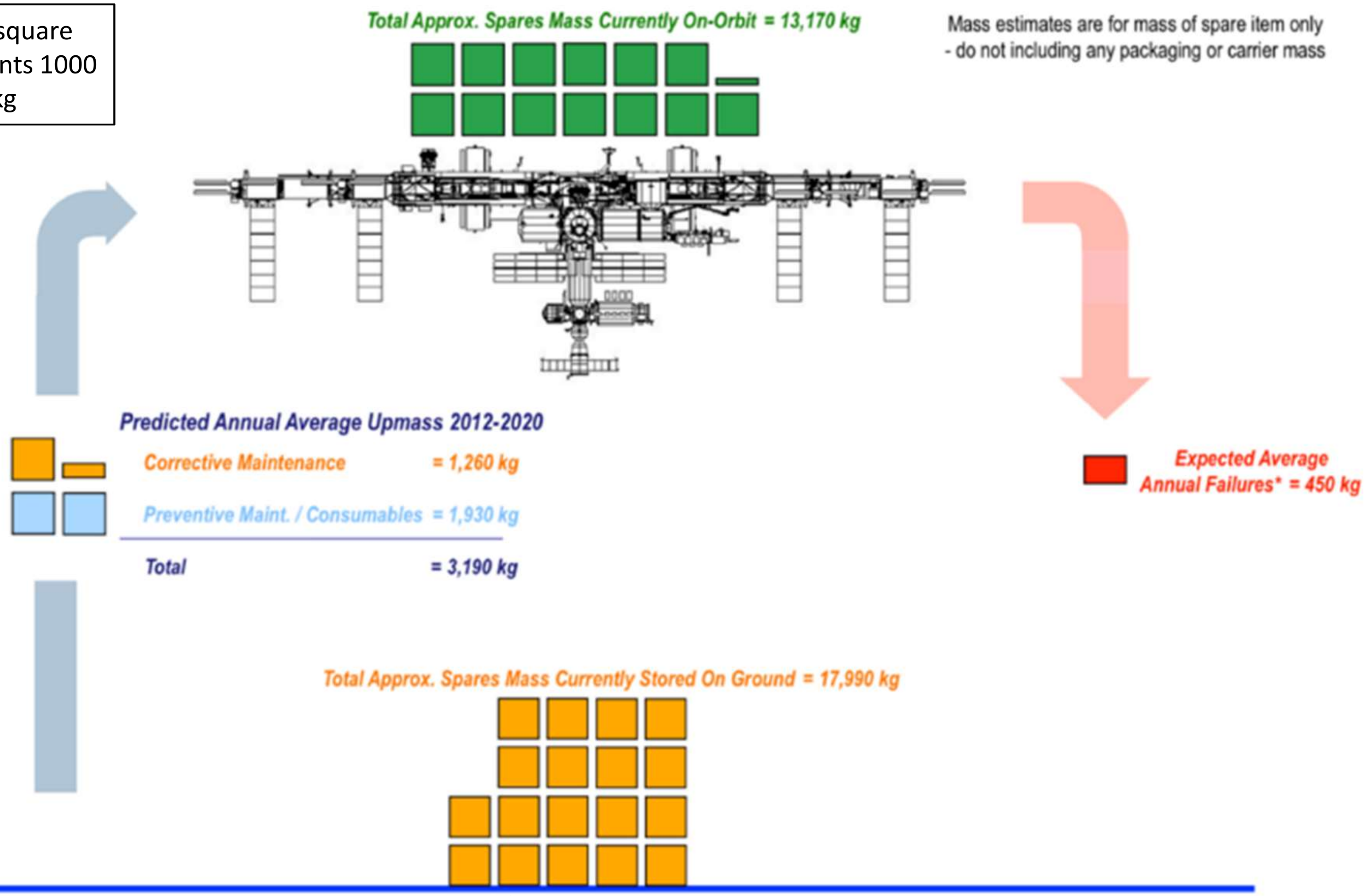
Constraint[1]	Constraint removed by ISM?
Structures must be designed for launch loads.	ISM enables structures which are optimized for operation in space, not for launch loads.
Structures must fit within launch vehicle payload fairings.	ISM enables structures whose size is limited only by the fabrication 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.

Paradigm shift

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



- 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

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

3D Print Plastic Printing Demo

Material Characterization

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

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

2015-2024

- 3DP Tech Demo
- Add. Mfg. Facility (AMF)
- ISM Certification Process Part Catalog
- ISS & Exploration Material & Design Database
- External Manufacturing
- Autonomous Processes
- STEM (Future Engs.)
- 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)

Exploration Implementation

Moon (Gateway) to Mars

2025 and beyond

Gateway, Lunar FabLabs

- Initial Robotic/Remote Missions
- Provision feedstock
- Evolve to utilizing in-situ materials (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

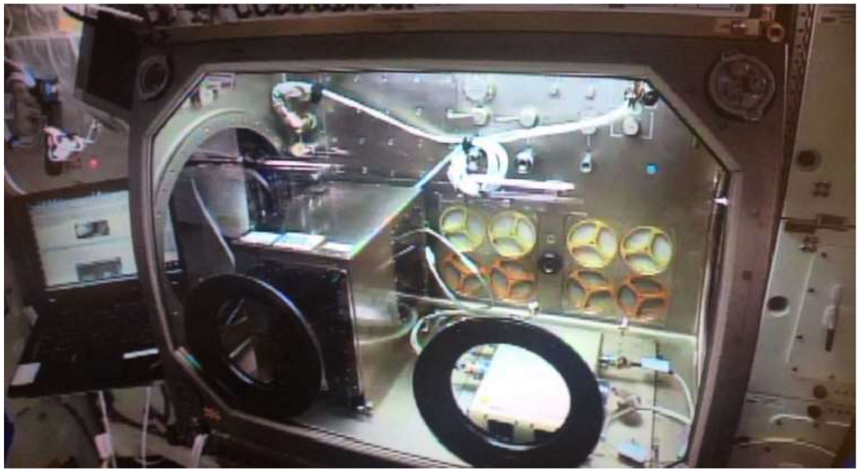
- Transport vehicle and sites require FabLab capability (adapt for in-situ resource utilization)
- Additive Construction & Repair of large structures

Mars Multi-Material FabLab

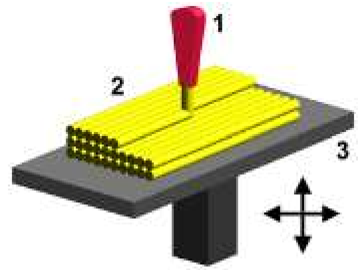
- Provision & Utilize in situ resources for feedstock
- FabLab: Provides on-demand manufacturing of structures, electronics & parts utilizing in-situ and ex situ (renewable) resources. Includes ability to inspect, recycle/reclaim, and post-process as needed autonomously to ultimately provide self-sustainment 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)

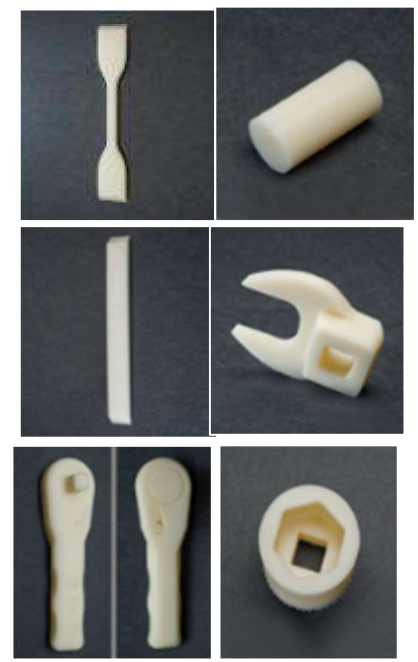


Fused filament fabrication:
1) nozzle ejecting molten plastic,
2) deposited material (modeled part),
3) controlled movable table

Illustration of the FFF (process

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 Acryonitriled 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)

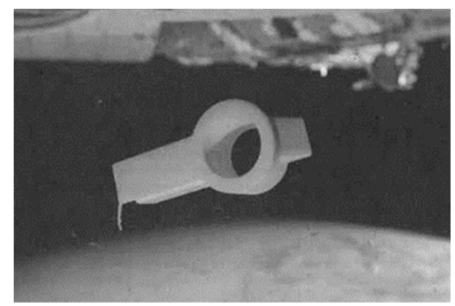
- 2nd generation printer for ISS
- FFF system owned and operated by Made in Space, Inc.
- Can print in High Density Polyethylene (HDPE), Acrylonitrile Butadiene Styrene (ABS), and ULTEM 9085 (PEI/PC)
- To date, NASA has printed a number of functional parts for ISS with this capability
- NASA is currently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

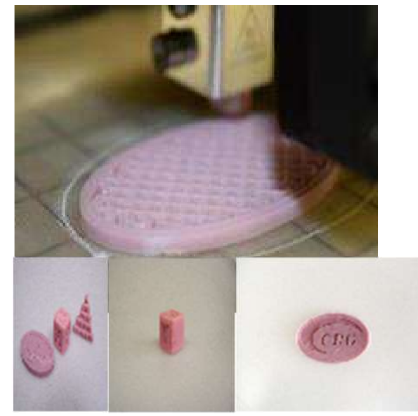
Recyclable Materials (Phase II SBIRs)

- 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

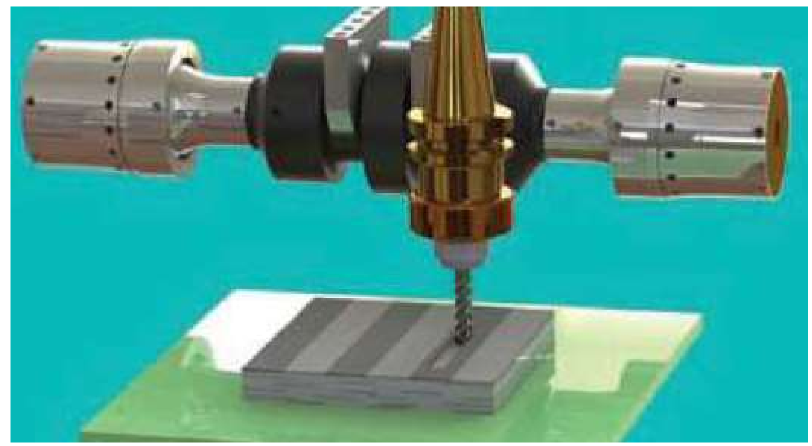
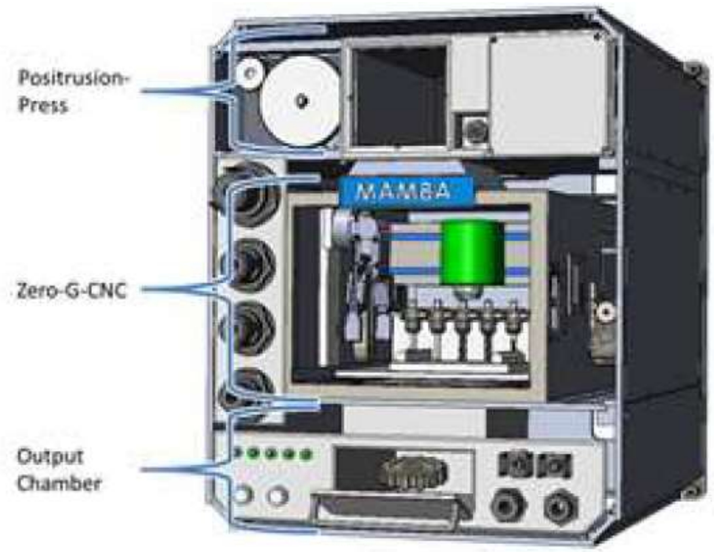


Illustration of UAM process.
Image courtesy of UltraTech

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

Other SBIR work

In-line inspection for manufacturing processes

- Verification and certification processes for ISM require better machine and feedback control than is currently available with off the shelf printers and other small manufacturing systems
- Focuses on development of in-line techniques for quality control applicable to ISM platforms

Phase I SBIRs awarded to Made in Space, Inc. (Mountain View, CA), Ler Technologies, Inc. (CA), Cybernet Systems Corporation (Ann Arbor, MI), MetroLaser, Inc (Laguna Hills, CA), and Cornerstone Research Group (Miamisburg, OH)

Development of higher strength feedstocks for in-space manufacturing

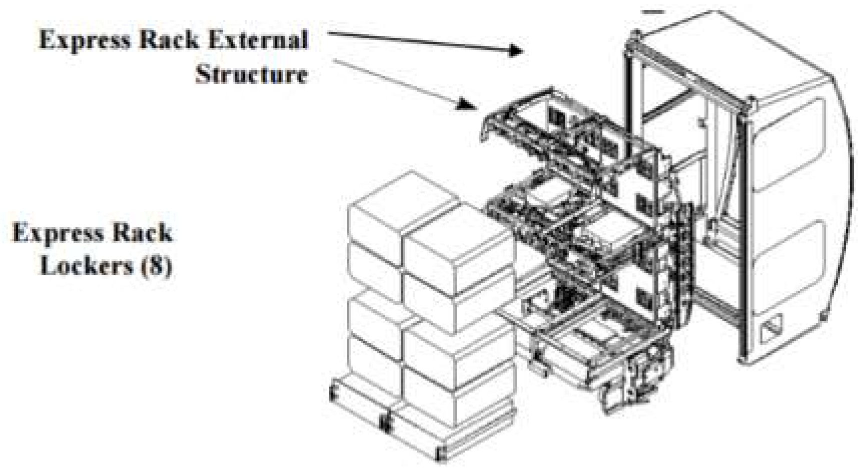
- Narrow the gap between the properties of materials produced using FDM techniques and metals
- Result in much higher strength plastics with isotropic properties and improved dimensional tolerances
- Homogenize material by reducing presence of pores

Phase I SBIRs awarded to Geocomposites (Metaire, LA), Actuated Medical, Inc. (Bellefonte, PA), and Intelligent Optical Systems (CA)

Other work under XHab (university design projects) with University of Connecticut and South Dakota State University

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



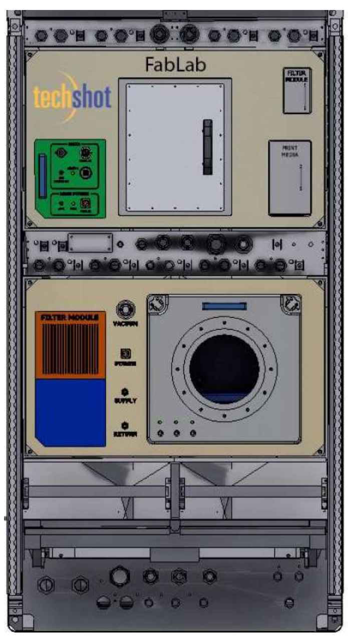
Ultimately, an integrated "FabLab" facility with the capability to manufacture multi-material components (including metals and electronics), as well as automation of part inspection and removal will be necessary for sustainable exploration opportunities.

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

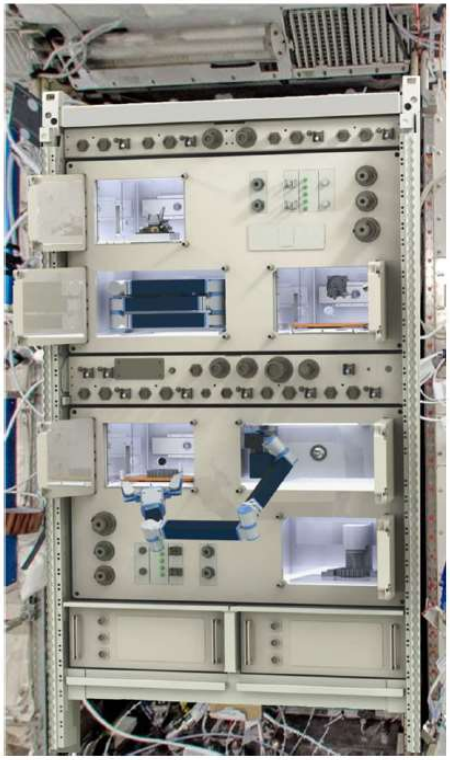
- Phase A awards for the NEXT-STEP Broad Agency Announcement (BAA) went to:
  - Tethers Unlimited of Bothell, Washington
  - Techshot, Inc. of Greenville, Indiana
  - Interlog Corporation of Anaheim, California
- 18 month period of performance to develop a ground-based prototype system
  - Includes materials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

Summary

- In-space manufacturing
  - 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

Part II: NASA's Centennial Challenges Program 3D-Printed Habitat Challenge

Planetary Surface Construction: Centennial Challenges 3D-Printed Habitat Challenge

- Advance the automated manufacturing and materials technologies needed for fabrication of habitats on a planetary surface using indigenous materials and mission recyclables

- Terrestrially, these technologies stand to revolutionize the construction industry by automating labor intensive processes and enabling rapid fabrication of large scale structures
    - World's population will increase from 6.6 billion to 12.9 billion by 2100
    - Requires aggressive construction practices to satisfy increased demand for housing

Potential of 3D Printing Technologies for Space and Earth

- Autonomous systems can fabricate infrastructure (potentially from indigenous materials) on precursor missions
  - Can serve as a key enabling technology for exploration by reducing logistics (i.e. launch mass) and eliminating the need for crew tending of manufacturing systems
- Also has potential to address housing needs in light of unprecedented population growth
  - Disaster response
  - Military field operations

Artist's rendering of a manufacturing operation on a planetary surface.
Image credit: Contour Crafting.

Overview of the 3D Printed Habitat Competition

Advance additive construction technology to create sustainable housing solutions for earth and beyond

Autonomous, Sustainable Additive Manufacturing of Habitats		
Phase 1	**Phase 2**	**Phase 3**
Design: Develop state-of-the-art architectural concepts that take advantage of the unique capabilities offered by 3D printing.	**Structural Member:** Demonstrate an additive manufacturing **material** system to create structural components using terrestrial/space based materials and recyclables.	**On-Site Habitat:** Building on material technology progress from Phase 2, demonstrate an automated 3D Print System to **build a full-scale habitat**.
Prize Purse Awarded: $0.04M	**Prize Purse:** $1.1M	**Prize Purse:** $2.0M

Phase I as an architectural concept competition. Picture on the left is the Mars Ice House, winner of the Phase I competition from Space Exploration Architecture and Clouds AO.

Phase II Competition, Level 1

Specimen 1

- Truncated cone with a tolerance of + 7 mm
- Extruded material must maintain the printed height to within 15% for a minimum of 5 minutes

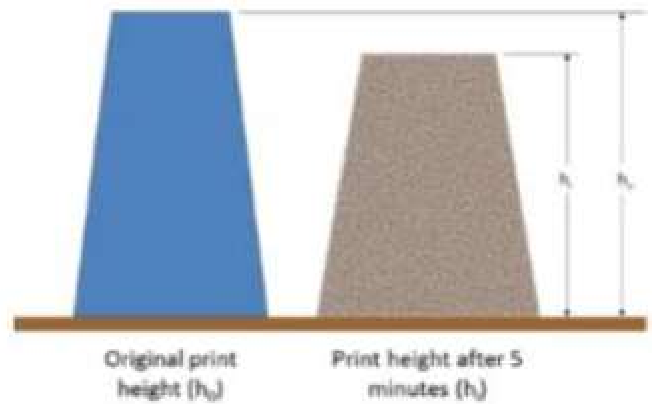
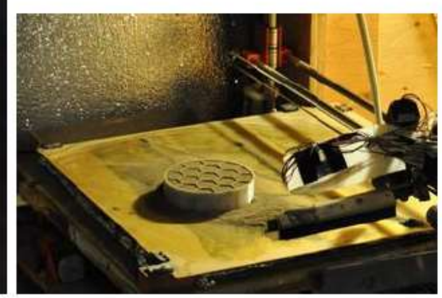


Diagram of slump test

Specimen 2

- Compression specimen (300 mm height and 150 mm diameter) tested per ASTM C39
- Minimum compressive load 450 kg

Winning level 1 entry from Foster + Partners and Branch Technology



Second place: University of Alaska Fairbanks

Phase II Competition, Level 2

Specimen

- Beam 60 cm length x 200 mm height x 100 mm wide cross-section
- Tested per ASTM C78
- Tolerance for specimen width and height was + 7mm
- Tolerance for length was +/-7 mm
- 1st place: MoonX(Seoul, South Korea)
- 2nd place: Oregon State University
- 3rd place: Foster+Partnersand Branch Technology
- 4th place: University of Alaska, Fairbanks
- 5th place: CTL Group
- 6th place: ROBOCON (Singapore)

Second-place team Form Forge of Oregon State University, Corvallis, printed this beam for the phase II, level 2 challenge. Image courtesy Form Forge.

3D printed beam entry (post flexural testing) from Foster + Partners and Branch Technology

Phase II Competition, Level 3

- Head to head competition at Caterpillar's Edwards Demonstration Facility in Peoria, Illinois
    - 7 teams invited to Level 3 competition based on successful completion of Level 1 and Level 2
- 3 teams competed from August 23-August 26, 2017
    - Foster+Partners and Branch Technology (1st place)
    - Penn State (2nd place)
    - MoonX (3rd place, international team not eligible for prize money)

Penn State

MoonX

Branch Technology and Foster + Partners

Phase III, Virtual Construction Competition

$200,000 Prize Purse Overall. Teams must use Building Information Modeling (BIM) software.

- **Virtual Construction, Level 1**
  - minimum of 60% of the information required for construction of the pressure retaining and load bearing portion of the habitat
  - MEP and ECLSS design (LOD 100)
  - Structure and Pressure Retaining Walls/Components (LOD 300)

- **Virtual Construction, Level 2**
  - 100% of information required for construction
  - MEP an ECLSS design (LOD 200)
  - Structure and Pressure Retaining Walls/Components (LOD 400)

MEP: Mechanical/Electrical/Plumbing
ECLSS: Environmental Control and Life Support Systems
LOD: Level of Design

Evaluation criteria: LOD, system information, layout/efficiency, aesthetics, constructability, and BIM use functionality

Phase III, Virtual Construction Level 1 Results

1st place, Team Zopherus

Lander structure encloses the printer, providing a pressurized, thermally controlled print environment for processing of the extracted materials (ice, Calcium Oxide, and Martian aggregate) into feedstock and fabrication of the first habitat module.

2nd place, AI Space Factory

Vertically oriented cylinder made of PLA reinforced with basalt fiber. The cylindrical geometry was chosen to
maximize the ratio of usable living space to surface area and reduce structural stresses. A double shell structure allows for expansion and contraction of material with the thermal swings the structure will experience on the Martian surface.

Phase III, Virtual Construction Level 1 Results

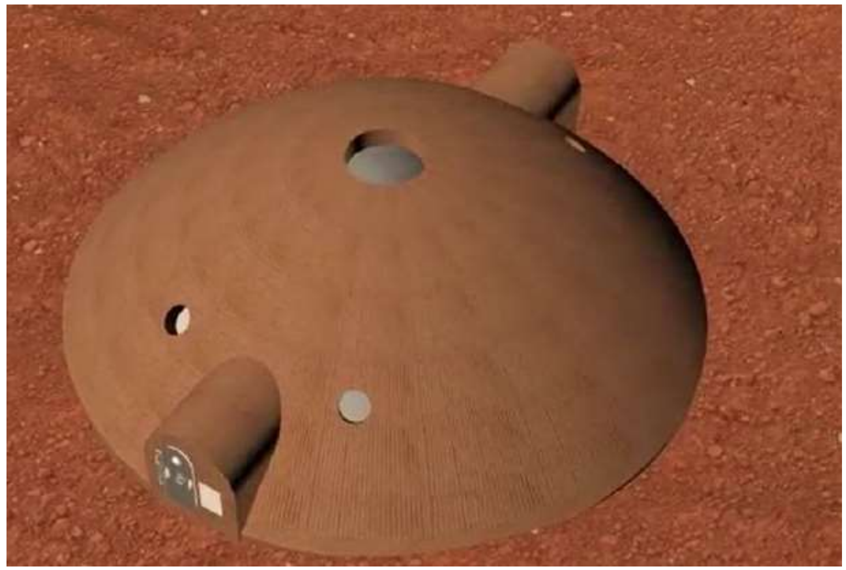
3rd place, Kahn-Yates

The habitat consists of an inner and outer polymer shell which sandwiches a sulfur concrete. The sandwich layer is omitted in certain locations to provide natural light.

4th place, SEArch+/ApisCor

Materials and thicknesses selected specifically to provide radiation shielding. The habitat is flanked by overlapping shells and oriented at 30 degrees above the horizon; these features allow for the entrance of natural light without compromising radiative protection.

Phase III, Virtual Construction Level 1 Results



5th place, Northwestern University

Rovers additively manufacture a foundation and deploy an inflatable shell. The rovers print the habitat's outer shell, which overlays the inflatable. The layout is a hub and spoke design, with a central multi-use space surrounded by sectioned spaces programmed to support various mission functions (crew quarters, lab space, kitchen/dining, etc.) In this concept, a series of modular habitats are connected by a network of tunnels.

Phase III, Construction Level 1 Results

Team SEArch+/Apis Cor of New York won first place in this level of NASA’s 3D-Printed Habitat Challenge. The team is pictured above dropping a shotput on their foundation to simulate a meteor strike.

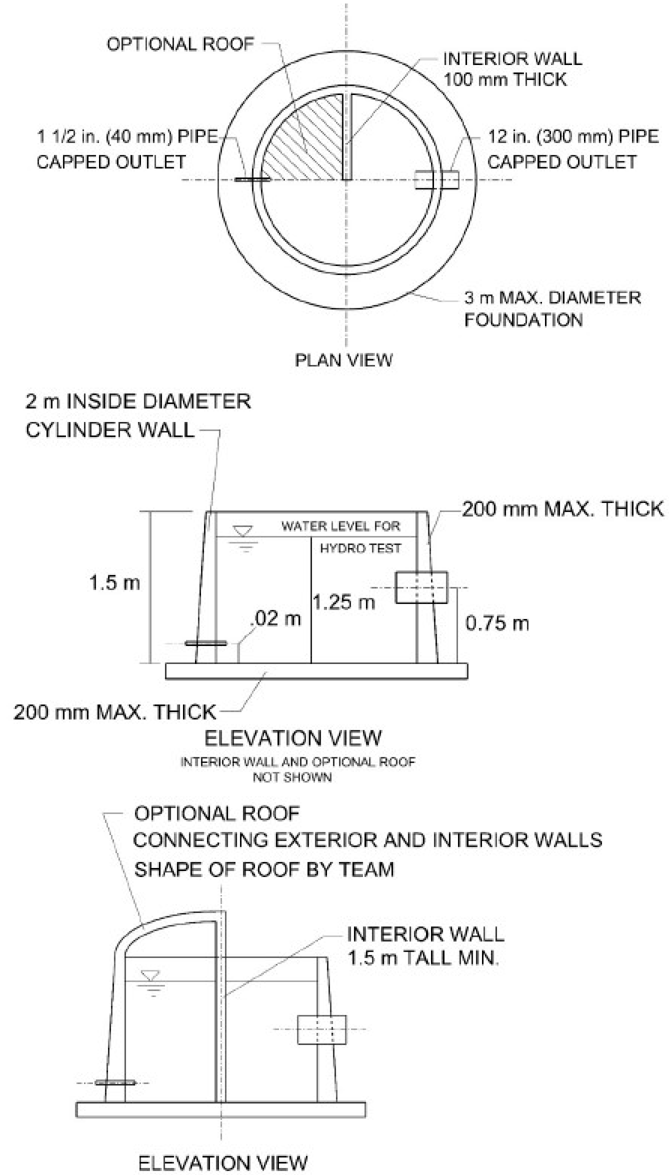
Penn State won second place in this level of NASA’s 3D-Printed Habitat Challenge. Pictured above is a shotput drop on the foundation to assess its impact resistance.

Phase III, Construction Level 1 Results

FormForge|Austin Industries|WPM of
Austin, Texas, won third place in this level.

Phase III, Construction Level 2: Hydrostatic Test

3D-printed habitat element for hydrostatic test



Phase III Construction, Level 3

- Head to head competition from April 29-May 4, 2019 at Caterpillar's Edward Demonstration Facility in Peoria, Illinois
- Up to 8 teams will be invited to compete
- The 1/3 scale model of the habitat must be printed in a 4.5 meter by 4.5 meter area at the head to head competition.
- Total time allocated to printing activities is 30 hours
- A BIM model with structural and pressure retaining elements at LOD 400 which corresponds to the structure that will be printed at the event is required

Final Thought

Manufacturing is destination independent – we'll need these capabilities wherever we choose to go!