


An Overview of NASA's In-Space Manufacturing Project

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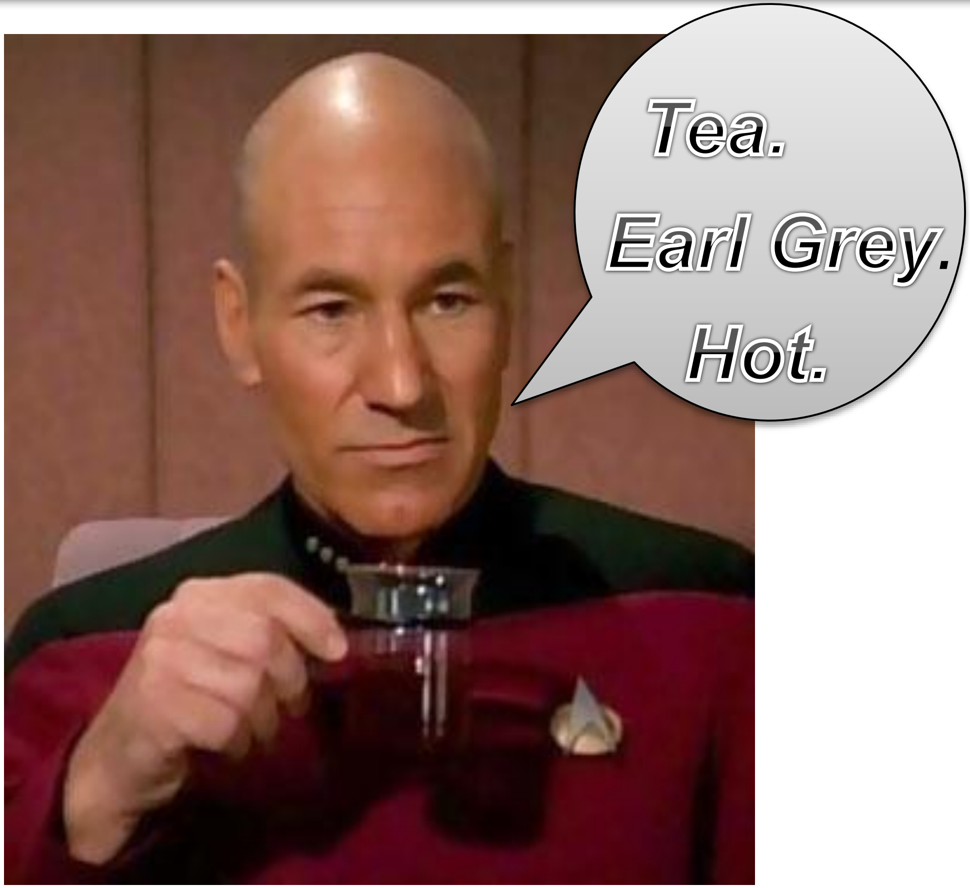
In-Space Manufacturing (ISM)



"If what you're doing is not seen by some people as science fiction, it's probably not transformative enough."

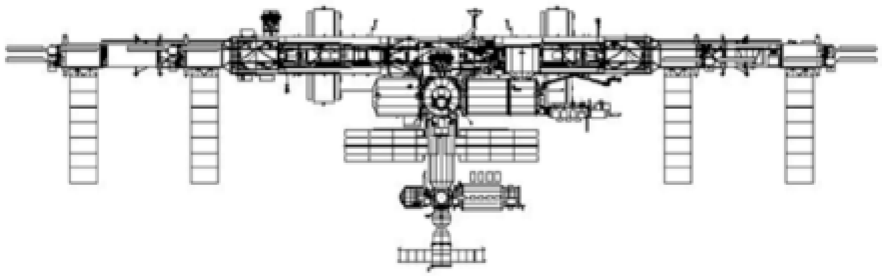
-Sergey Brin

The Current Paradigm: ISS Logistics Model

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



~3,000 kg Upmass per year

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

~18,000 kg on ground, ready to fly on demand

This is for a system with:

- **Regular resupply (~3 months)**
- **Quick abort capability**
- **Extensive ground support and redesign/re-fly capability**

- 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)

ISM Objective

The AES In-space Manufacturing (ISM) project serves as Agency resource for identifying, designing, & implementing on-demand, sustainable manufacturing solutions for fabrication, maintenance, & repair during Exploration missions.

ISM EXPLORATION APPLICATIONS

Unique Agency Expertise & Leveraging of Industry

ISM TECHNOLOGY DEVELOPMENT

ISM Parts/Systems Design Database & Test Articles

Answers WHAT we need to make

- Top-down, quantitative analyses of ISM benefits to crew time, cost, mass, & reliability (w/EMC).
- Provide expertise to NASA User community on AM design optimization & materials.
- Test high-impact parts/systems to inform Exploration technology requirements (bottoms-up).
- Develop In-space Parts Design Database, processes, & materials.

Part/System Requirements, Design, Materials & Processes

ISM

'One-stop shop' for AM design, materials, & technology expertise for NASA User Community.

AM EXPERTS / MATERIAL EXPERTS / DESIGNERS

Leverage industry to meet NASA needs (i.e. Agency knowledge-base for terrestrial technology).

In-space Manufacturing provides Exploration mission benefits to cost, mass, crew time & reliability

Proactive influence during Exploration design phase required for meaningful implementation

ISM Technology Development & Testing

Answers HOW we will make it

- Define NASA requirements for ISM Technologies based on ISS & EMC Applications identified (micro-g effects, performance, & operations)
- Collaborate and establish mechanisms to leverage industry to develop the technologies needed for NASA missions.
- Utilize ISS as test-bed for developing 'FabLab' to serve as springboard for cis-lunar 'proving ground' missions.

Multi-material 'FabLab' Test-bed

In-Space Manufacturing (ISM) Phased Technology Development Roadmap

Earth-based

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

Demos: Ground & ISS

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

Recycler
Mat. Char. ***Utilization Testing***
AMF

2015-2017

- ***3DP Tech Demo***
- ***Add. Mfctr. Facility (AMF)***
- ***ISM Certification Process Part Catalog***
- ***ISS & Exploration Material & Design Database***
- ***External Manufacturing***
- ***Autonomous Processes***
- ***Future Engineers***
- ***Additive Construction***

Metal Printing
FabLab ***Self-Repair/ Replicate***
External Mfg.

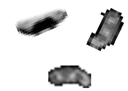
2018 - 2024

ISS: Multi-Material FabLab EXPRESS Rack Test Bed *(Key springboard for Exploration 'proving ground')*

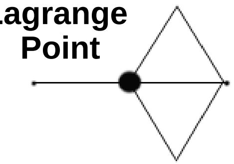
- **Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics, embedded electronics, autonomous inspection & part removal, etc.**
- **In-Space Recycler Tech Demo**
- **ACME Ground Demos**

Exploration Missions

Asteroids



Lagrange Point



Cis lunar

Mars

2025 - 2035+

Cislunar, Lagrange 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

Planetary Surfaces Points FabLab

- Transport vehicle and sites would need FabLab capability
- ***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 Critical Exploration Test-bed for the Required Technology Maturation & Demonstrations

In-Space Manufacturing (ISM) Portfolio

IN-SPACE POLYMERS

- ISS On-demand Mfg. w/polymers
- 3DP Tech Demo
- Additive Manufacturing Facility with Made in Space, Inc. (MIS)
- Material Characterization & Testing

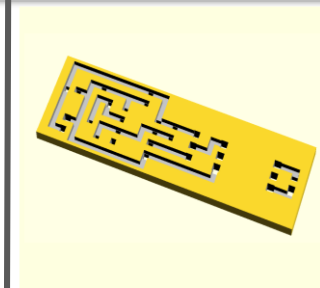
IN-SPACE RECYCLING

- Refabricator ISS Tech Demo with Tethers Unlimited, Inc. (TUI) for on-orbit 3D Printing & Recycling
- Multiple SBIRs underway on common-use materials & medical/food grade recycler

MULTI-MATERIAL FABLAB RACK

- Develop Multi-Material Fabrication Laboratory Rack as 'springboard' for Exploration missions
- In-Space Metals ISS Tech Demo
- nScrypt Multi-Material machine at MSFC for R&D

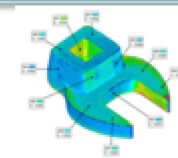
PRINTED ELECTRONICS



MSFC Conductive & Dielectric Inks patented

- Designed & Tested RFID Antenna, Tags and Ultra-capacitors
- 2017 ISM SBIR subtopic
- Collaboration w/ARC on plasma jet technology

IN-SPACE V&V PROCESS

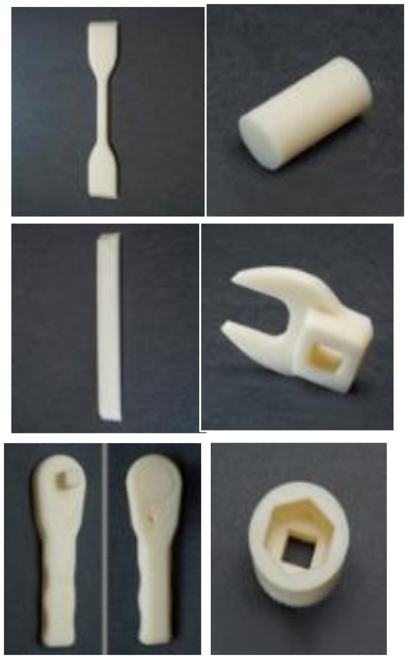


- Develop & Baseline on-orbit, in-process certification process based upon the DRAFT Engineering and Quality Standards for Additively Manufactured Space Flight Hardware

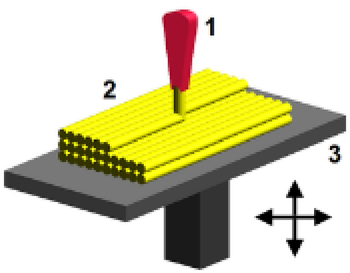
EXPLORATION DESIGN DATABASE & TESTING

- Develop design-level database for micro-g applications
- Includes materials characterization database in MAPTIS
- Design & test high-value components for ISS & Exploration (ground & ISS)

The First Step: The 3D Printing in Zero G Technology Demonstration Mission



The 3DP in Zero G tech demo delivered the first 3D printer on the ISS and investigated the effects of consistent microgravity on fused deposition modeling by printing 55 specimens to date in space.



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

Printer inside Microgravity Science Glovebox (MSG)

- **Phase I prints (Nov-Dec 2014)** consisted of mostly mechanical test coupons as well as some functional tools
- **Phase II specimens (June-July 2016)** provided additional mechanical test coupons to improve statistical sampling

3D Print Specifications	
Dimensions	33 cm x 30 cm x 36 cm
Print Volume	6 cm x 12 cm x 6 cm
Mass	20 kg (w/out packing material or spares)
Power	176 W
Feedstock	ABS Plastic

Testing of Phase I and Phase II Prints

Photographic and Visual Inspection

Inspect samples for evidence of:
- Delamination between layers
- Curling or deformation of samples
- Surface voids or pores
- Damge from specimen removal

Mass Measurement

Measure mass of samples:
- Laboratory scale accurate to 0.01 mg
- Mass measurement used in gravimetric density calculation (volume derived from structured light scanning)

Structured Light Scanning

Scan external geometry of samples:
- Accurate to ± 12.7 μm
- Compare scan data CAD model to original CAD model and other specimens of the same geometry
- Measure volume from scan data
- Measure feature dimensions

Data Obtained

- Thorough documentation of sample in as-built condition

Average Sample Mass

- Geometric Accuracy
- Average Sample Volume

Average Sample Density

- Internal structure and porosity
- Densification
- Evidence of printing errors

- Mechanical Properties: UTS, E, % elongation, UCS, G

- Microstructure data
- Layer adhesion quality
- Microgravity effects on deposition

CT Scanning / X-Ray

Inspect internal tomography of samples:
- Internal voids or pores
- Measure layer thickness / bead width
- Density measurement (mean CT)
- Note any misruns or evidence of printing errors

Mechanical (Destructive) Testing

Mechanical specimens only:
- ASTM D638: Tensile Test
- ASTM D790: Flexural Test*
- ASTM D695: Compression Test

Optical / SEM Microscopy

- External features (warping, voids, protrusions, deformations)
- Internal structure
  - Filament layup
  - Voids
  - Fracture surfaces
  - Delamination

*flexure specimens not part of phase II

Key Results: The 3D Printing in Zero G Technology Demonstration Mission (Phase I)

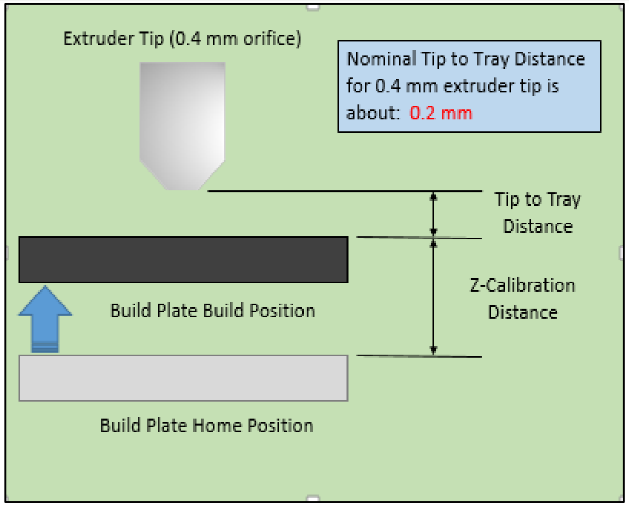
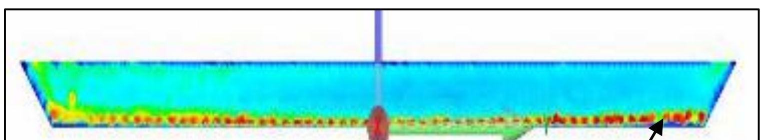


Illustration of z-calibration and tip to tray distances

Structured light scan of flight flexure specimen



colors indicate dimensional deviation from CAD model

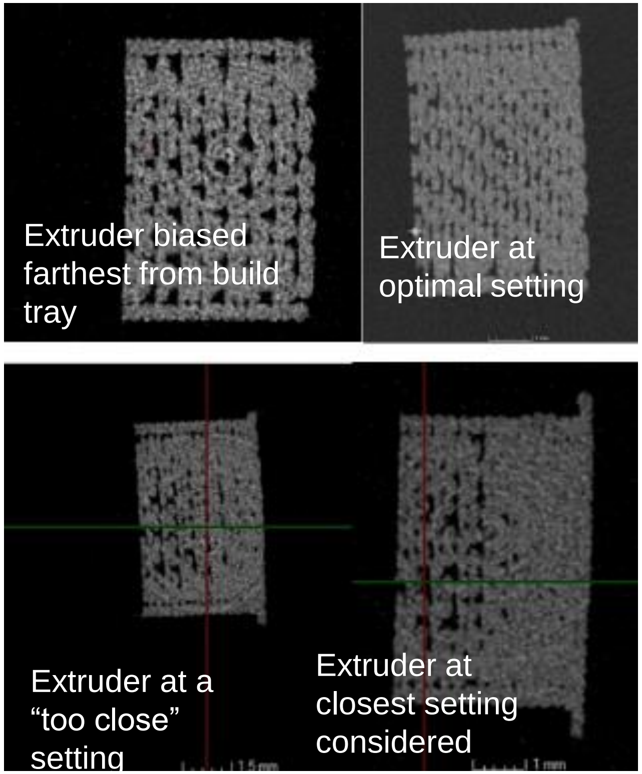
Red indicates slight protrusions of material

- Phase I flight and ground prints (ground prints were manufactured on the 3DP unit prior to its launch to ISS) showed some differences in densification, material properties and internal structure

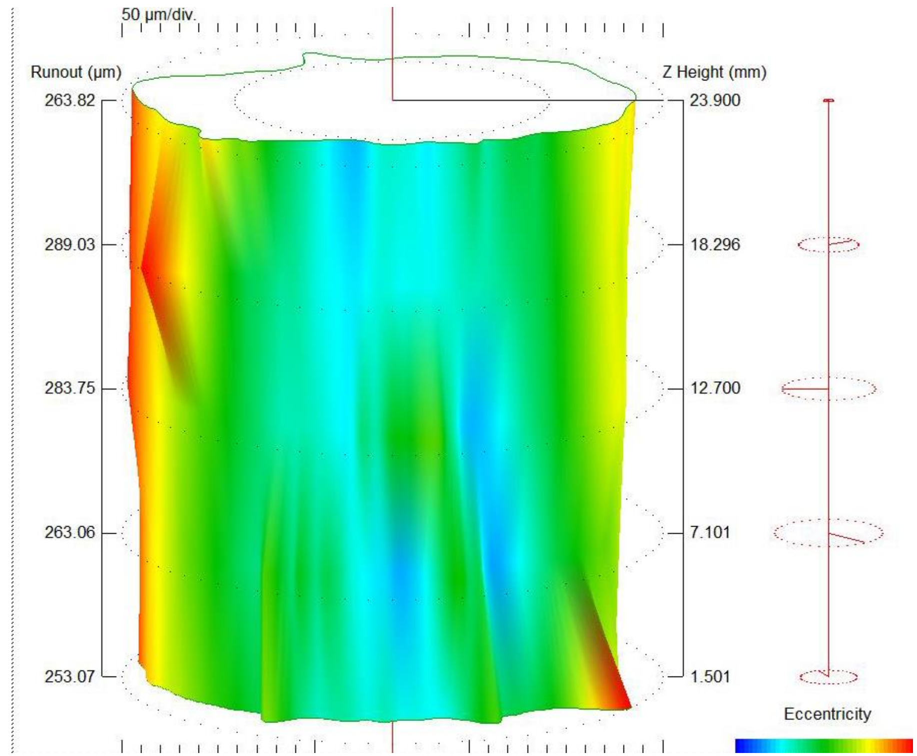
- Differences were determined, through SEM analysis, chemical analysis of the specimens, and a subsequent ground-based study using the identical flight back-up unit to be largely an artifact of differences in manufacturing process settings between ground and flight and also attributable to build to build variability. ***No engineering significant microgravity effect on the FDM process has been noted.***

- Complete results published as NASA Technical Report (July 2016) and in queue for publication in *Rapid Prototyping Journal* (late 2017)

Key Results: The 3D Printing in Zero G Technology Demonstration Mission (ground-based study)



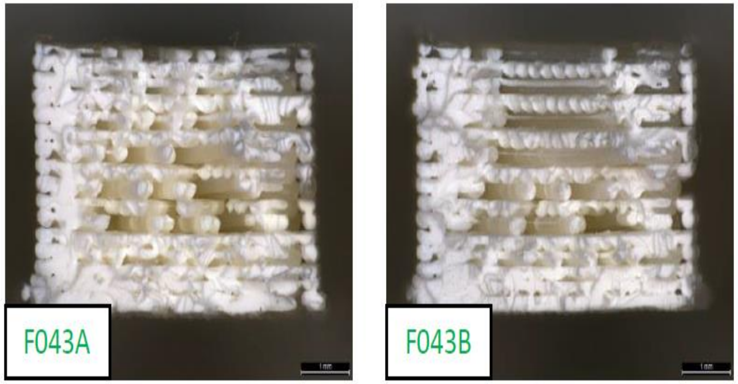
CT cross-section images show evolution of tensile specimen structure with decreasing extruder standoff distance (images from reference , a ground-based study using the flight-back up unit). Bottom half of the specimen becomes denser and protrusions form at base of specimen as extruder standoff distance is decreased.



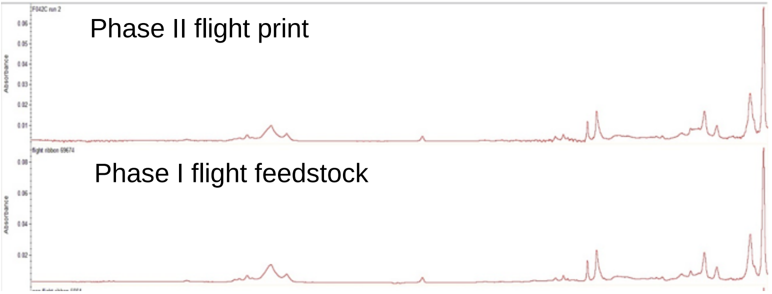
Results of cylinder mapping of compression cylinder from ground based study of extruder standoff distance using the flight backup unit. Off-nominal conditions for the extruder tip biased in either direction result in an increase in cylindricity. The greatest radial separation is observed for the closest extruder setting.

Key Results: The 3D Printing in Zero G Technology Demonstration Mission (Phase II)

- For phase II operations, 25 specimens (tensile and compression) were built at an optimal extruder standoff distance.
- For the last 9 prints in the 34 specimen print matrix, extruder standoff distance was decreased intentionally to mimic the manufacturing process conditions for the phase I flight prints.
- Complete phase II data will be published on the NASA Technical Reports Server in late November 2017.
- Key findings:
    - All prints to date with 3DP appear to be part of the same family of data (result becomes apparent with greater statistical sampling made possible with phase II operations)
    - No substantive chemical changes in feedstock noted through FTIR analysis
    - No evidence of microgravity effects noted in SEM analysis, although there is some variation in internal material structure between builds and with changes in process settings



Densification of first layers observed at slightly closer extruder distance; also noted in phase I.



FTIR comparison of flight phase II print with feedstock from phase I

ISM Utilization and the Additive Manufacturing Facility (AMF): Functional Parts

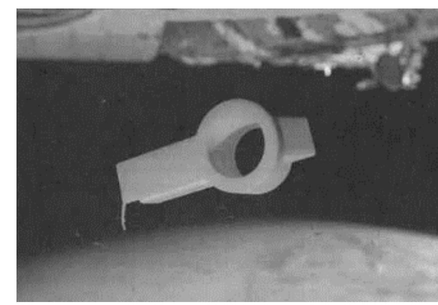
The Made in Space Additive Manufacturing Facility (AMF)

- Additive Manufacturing Facility (AMF) is the follow-on printer developed by Made in Space, Inc.
- AMF is a commercial, multi-user facility capable of printing ABS, ULTEM, and HDPE.
- To date, NASA has printed several functional parts for ISS using 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).

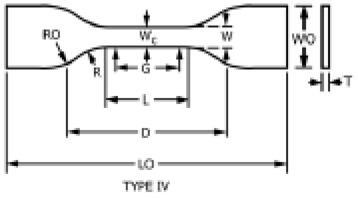
Antenna Feed Horn: collaboration between NASA Chief Scientist & Chief Technologist for Space Communications and Navigation, ISM & Sciperio, Inc. Printed 3/9/17 and returned on SpaceX-10 3/20/17.



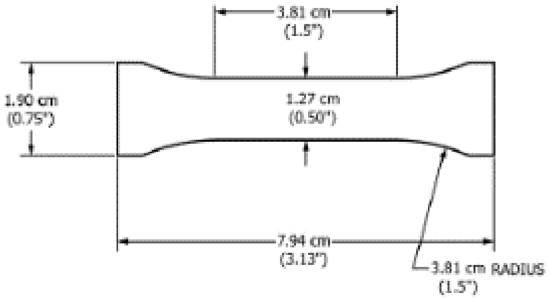
OGS Adapter: adapter attaches over the OGS air outlet and fixtures the velocicalc probe in the optimal location to obtain a consistent and accurate reading of airflow through the port. 7/19/2016.

ISM Utilization and the Additive Manufacturing Facility (AMF): Materials Characterization

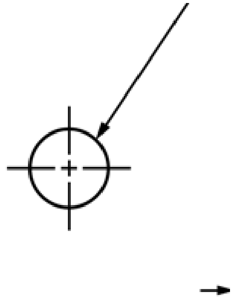
- To inform continued utilization of AMF by NASA, a materials characterization plan was developed and is now on contract with Made in Space
- Initial plan is to develop characteristic properties for ABS produced by AMF, but plan is extensible to other materials
- Testing methodology similar to composites. Test coupons are machined from printed panels (***4 mm thickness***).
- Panels printed at 0 (for tension and compression), 90, and +/-45 layup patterns.
- Ground panels have been delivered (made with a ground AMF unit equivalent to the flight unit) and are undergoing testing. Flight panels will follow in 2018.



Type IV tensile specimen from ASTM D638

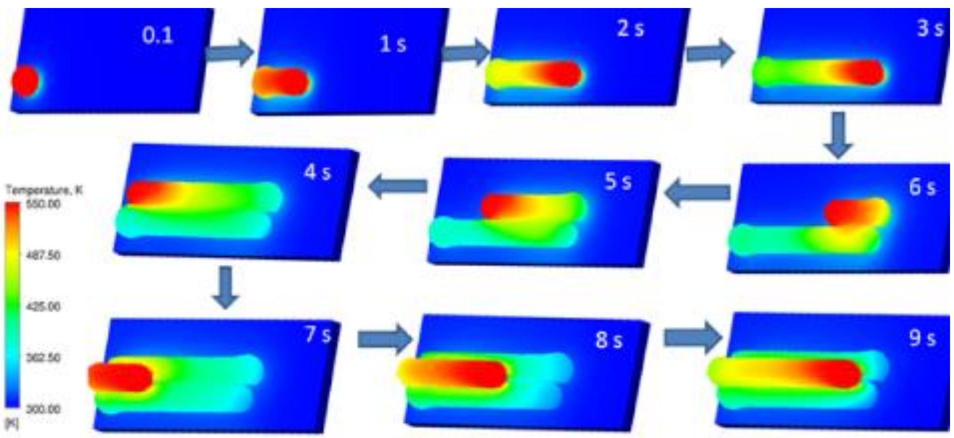


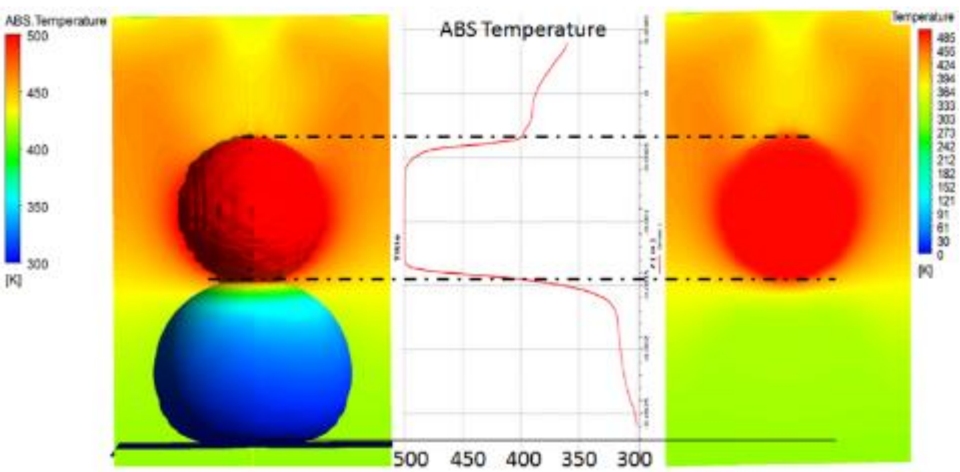
Thin-type compression specimen from ASTM D695. Requires support jig.



Flatwise tension from ASTM C297. Used to measure tensile strength in the through thickness of the specimen.

Modeling work on FDM (NASA Ames Research Center)





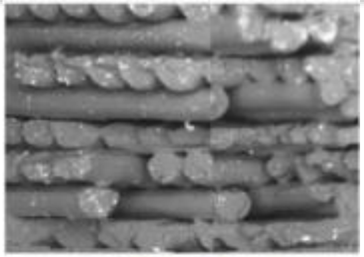
Slide credit: Dr. Dogan Timucin, Ames Research Center

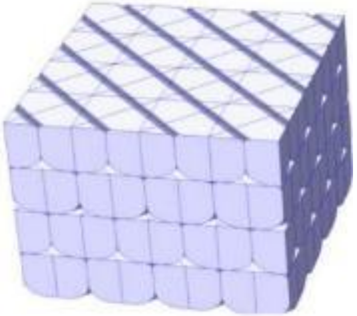
- Objective is to model FDM process in space (initially for ABS) and predict structural properties of the manufactured parts
- Use physics based analysis of FDM to determine what physics phenomena may be distinct in space-based manufacturing
- Developed FE model in ANSYS CFX for coupled fluid flow and heat conduction problem associated with filament extrusion and deposition
  - Uses ABS parameters available in the literature
- Performed qualitative analysis of inter-diffusion between two molten roads based on polymer reputation theory for long-chain molecules
- Concluded that the reputation time is much smaller than the time to cool down to glass transition temperature
  - Filaments can be assumed perfectly welded
- ***No significant changes in road shape, filament temperature distribution, die swell, or evolution of temperature profile noted in modeling and simulation due to variation in gravity parameter***

Modeling work on FDM (NASA Ames Research Center)

Structural Modeling of Macroscopic FDM parts

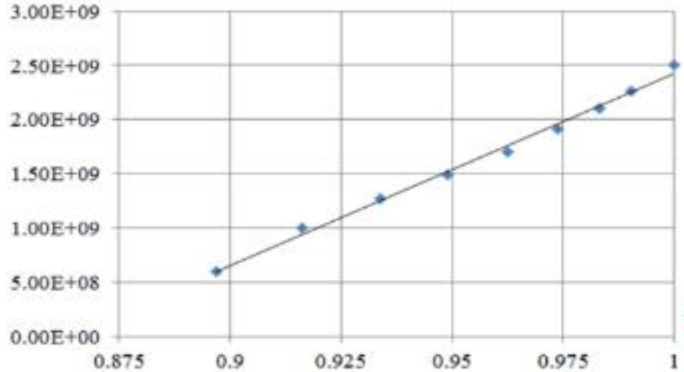
- Modeled FDM parts as a composite cellular structure with known microstructure (as determined from the deposition process model)
- Effective structural parameters of the part were studied analytically based on classical homogenization and laminate theories
- Developed a finite-element model in ABAQUS to estimate the elastic moduli of representative volume elements or unit cells in order to verify analytical models
- Moduli were simulated for different layups, raster orientations, air gap distribution as a function of volume void fraction
- The part strength was estimated using the Tsai-Wu failure criterion

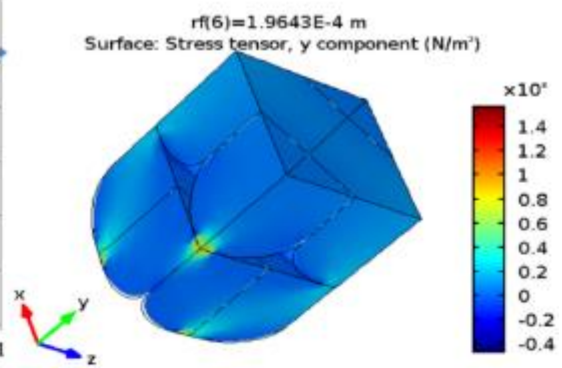




representative volume element

elastic modulus as a function of void fraction



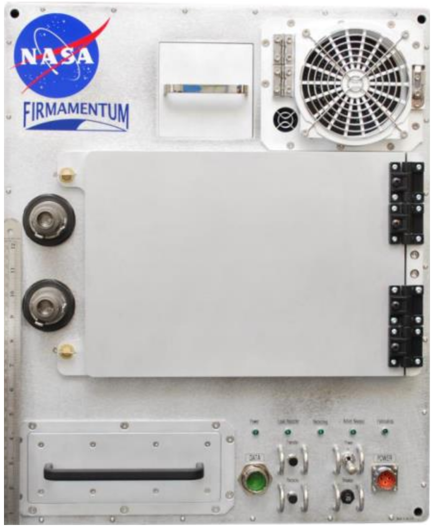


unit cell FE simulation

Slide credit: Dr. Dogan Timucin, Ames Research Center

ReFabricator from Tethers Unlimited, Inc.: Closing the Manufacturing Loop

- Technology Demonstration Mission payload conducted under a phase III SBIR with Tethers Unlimited, Inc.
- Refabricator demonstrates feasibility of plastic recycling in a microgravity environment for long duration missions
- Refabricator is an integrated 3D printer (FDM) and recycler
  - Recycles 3D printed plastic into filament feedstock through the Positrusion process
- Environmental testing of engineering test unit completed at MSFC in April
  - Payload CDR completed in mid-June
  - Operational on ISS in 2018



Refabricator ETU

Toward an In-Space Metal Manufacturing Capability

- Made in Space Vulcan unit (phase I SBIR)
  - Integrates FDM head derived from the additive manufacturing facility (AMF), wire and arc metal deposition system, and a CNC end-mill for part finishing

- Ultra Tech Ultrasonic Additive Manufacturing (UAM) system (phase I SBIR)
  - UAM prints parts by using sound waves to consolidate layers of metal drawn from foil feedstock (similar to ultrasonic welding)
  - Solid state process that avoids complexities of management of powder feedstock
  - Work is to reduce the UAM process's footprint by designing and implementing a higher frequency sonotrode
  - Scaling of system also has implications for robotics and freeform fabrication

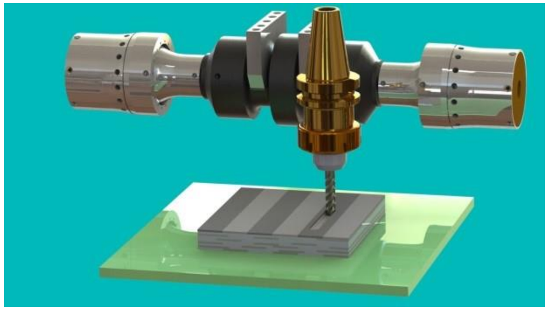
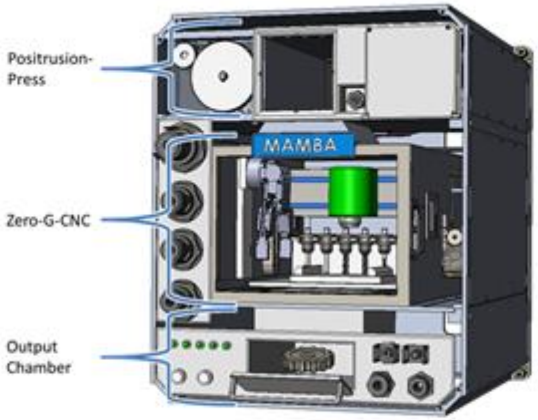


Illustration of UAM process
(image courtesy of Ultra Tech)

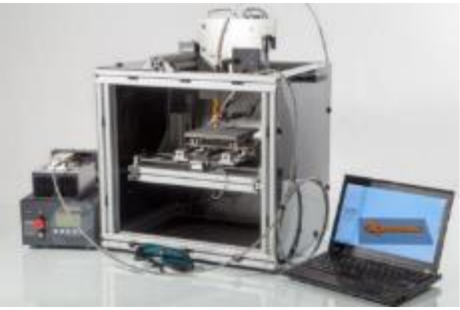
Toward a In-Space Metal Manufacturing Capability

- Tethers Unlimited MAMBA (Metal Advanced Manufacturing Bot-Assisted Assembly)
    - Phase I SBIR
    - Ingot-forming method to process virgin or scrap metal
    - Bulk feedstock is CNC-milled
    - Builds on recycling process developed through ReFabricator payload

- Techshot, Inc. SIMPLE (Sintered Inductive Metal Printer with Laser Exposure)
    - Phase II SBIR
    - AM process with metal wire feedstock, inductive heating, and a low-powered laser
    - Compatible with ferromagnetic materials currently
    - Test unit for SIMPLE developed under phase I SBIR; phase II seeks to develop prototype flight unit



Tethers Unlimited MAMBA concept. Image courtesy of Tethers Unlimited.



Techshot's SIMPLE, a small metal printer developed under a Phase I SBIR. Image courtesy of Techshot.

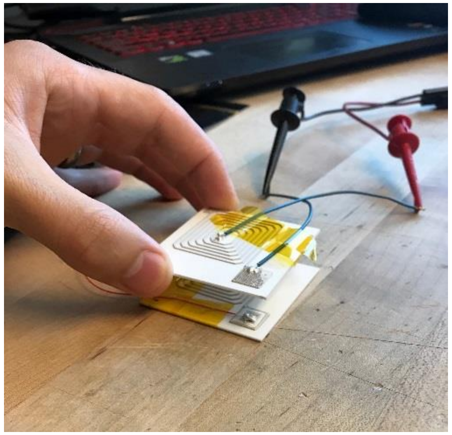
Ground-based work on additive electronics

- evaluating technologies to enable multi-material, on-demand digital manufacturing of components for sustainable exploration missions
  - In-house work uses nScrypt printer
    - 4 heads for dispensation of inks and FDM of polymers; also has pick and place capability

- Development of additively manufactured wireless sensor archetype (MSFC)
  - Printed RLC circuit with coupled antenna
  - Capacitive sensing element in circuit is pressure, temperature, or otherwise environmentally sensitive material
  - Sensing material also developed in-house at MSFC

- Design of pressure switch for urine processor assembly (UPA)
  - 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)
    - Direct write and avionics printing capability for ISS
  - Optomec working on miniaturization of patented Aerosol Jet technology



Printed wireless humidity sensor (wires attached for characterization purposes)

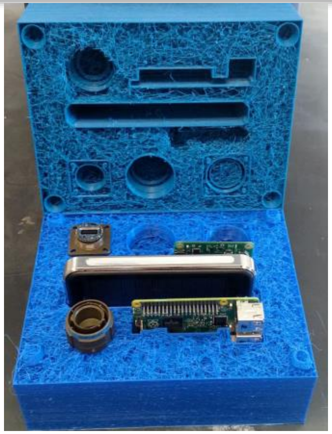
nScrypt multimaterial printer

Materials Development: Recyclable materials

- Logistics analyses show the dramatic impact of a recycling capability for reducing initial launch mass requirements for long duration missions
  - Current packaging materials for ISS represent a broad spectrum of polymers: LDPE, HDPE, PET, Nylon, PVC

- Tethers CRISSP (Customizable Recyclable ISS Packaging) seeks to develop common use materials (which are designed to be recycled and repurposed) for launch packaging
  - Work under phase II SBIR
  - Recyclable foam packaging made from thermoplastic materials using FDM
  - Can create custom infill profiles for the foam to yield specific vibration characteristics or mechanical properties

- Cornerstone Research Group (CRG) is working under a phase II SBIR on development of reversible copolymer materials
  - Reversible copolymer acts as a thermally activated viscosity modifier impacting the melt properties of the material
  - Designs have strength and modulus values comparable to or exceeding base thermoplastic materials while maintaining depressed viscosity that makes them compatible with FDM



CRISSP (image from Tethers Unlimited)

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

Use Scenarios for ISS Fabrication Capabilities: Biomedical applications

- ERASMUS form Tethers Unlimited
  - Manufacturing modulus for production of medical grade plastics, along with the accompanying sterilization procedures required for subsequent use of these materials
  - Bacteria and viruses can become more virulent in the space environment and crew's immune systems may be compromised
  - Enables reuse of consumables/supplies or consumables manufactured from recycyled material

- Senior design project on medical capabilities and ISM
  - Medical industry has traditionally been an early adopter of AM
  - Lattice casts are custom designed to fit the patient, waterproof, and provide greater comfort and freedom in movement
  - Scan of limb can be imported into CAD software and custom mesh/lattice generated
  - Printed in multiple interlocking segments due to printer volume constraints

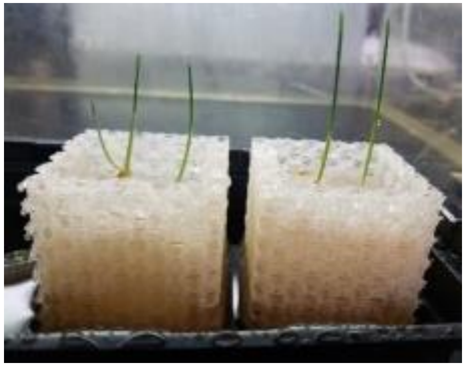
- Given logistical constraints of long duration spaceflight on consumables and unanticipated issues which may arrive even with a healthy crew, ISM will continue to explore evolving capabilities to best serve exploration medicine

Potential food and medical consumables for manufacture and sterilization using the Tethers Unlimited ERASMUS system

One piece of a two piece lattice cast (senior design project)

3D Printing with Biologically Derived Materials

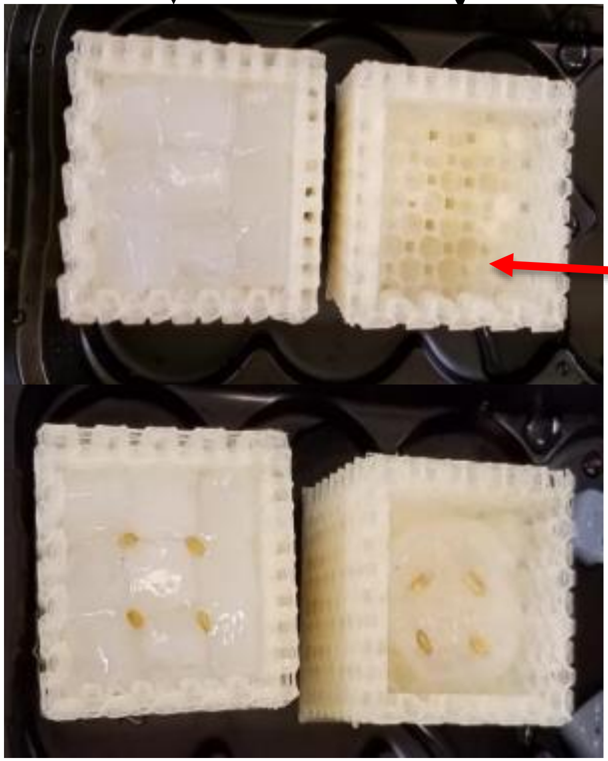
- Use biologically derived filament materials and/or materials from inedible plant mass to create 3D printed substrate blocks for plant growth
- Collaborative activity between VEGGIE project/payload at Kennedy Space Center, Synthetic Biology team at Ames Research Center, and In-space Manufacturing team at NASA Marshall



COTS microbial cellulose

ARC microbial cellulose

Microbial cellulose used as seed germinating platform

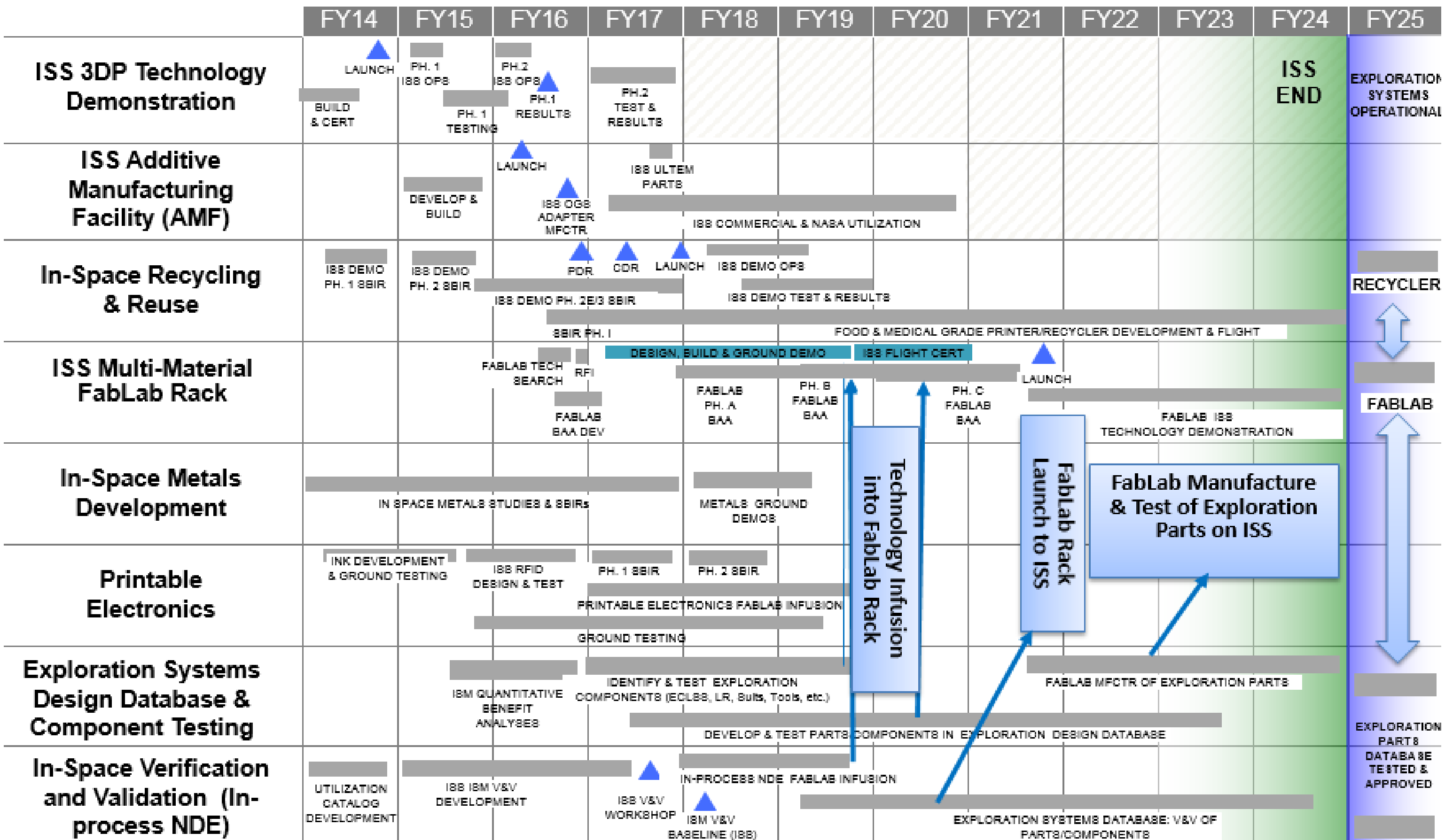


Moisture Retainer
-Starch polymer

3D Printed plant growth blocks from MSFC (PLA/PHA)

Seeds allowed to germinate for 3 days

ISM Technology Development Road Map



NASA is working with industry and academia to adapt rapidly evolving terrestrial manufacturing, repair, and recycling technologies for in-space applications.

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Fabrication Laboratory Overview

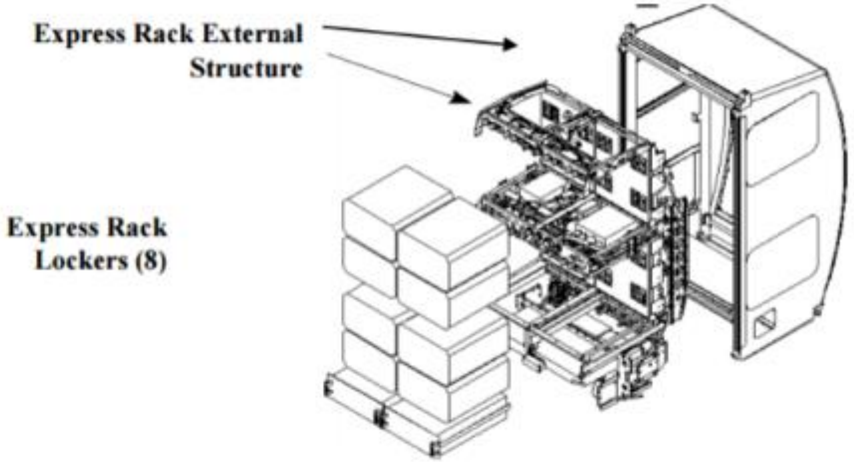
- **Aligned with vision of in-space manufacturing project to develop and test on-demand, manufacturing capabilities for fabrication, repair and recycling during Exploration missions**
- **ISM offers:**
  - Dramatic paradigm shift in development and creation of space architectures
  - Efficiency gain 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**

The Multimaterial Fabrication Laboratory for ISS (“FabLab”)

Typical EXPRESS Rack structure



Power consumption for entire rack is limited to 2000 W

Payload mass limit for rack is less than 576 lbm

- NASA is seeking proposals to provide a feasible design and demonstration of a first-generation In-space Manufacturing Fabrication Laboratory for demonstration on the ISS
- Minimum target capabilities include:
  - Manufacturing of metallic components
  - Meet ISS EXPRESS Rack constraints for power and volume
  - Limit crew time
  - Incorporate remote and autonomous verification and validation of parts
- Proposal window now closed
- Federal Business Opportunities link to solicitation (closed): www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=8a6ebb526d8bf8fb9c6361cb8b50c1f8

The Multimaterial Fabrication Laboratory for ISS

- BAA for multimaterial, multiprocess fabrication laboratory for the International Space Station
- Phased approach
  - Phase A – scaleable ground-based prototype
  - Phase B – mature technologies to pre-flight deliverable
  - Phase C – flight demonstration to ISS

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 required for any given nominal activity, with the end-goal being to apply the same rule to maintenance and off-nominal operations as well.*

Student Projects

- Future Engineers, collaboration between NASA and American Society of Mechanical Engineers challenges K-12 students to design space hardware that can be 3D printed: www.futureengineers.org
  - Think Outside the Box Challenge (ended October 2016)
  - Mars Medical Challenge (ended March 2017)
  - Two for the Crew Challenge (currently open)

- Senior design projects
  - Material property database and design of a 3D printed camera mount for Robonaut (2015-2016)
  - Design of a 3D printed parametric tool kit and dynamic user interface for crew use (2016-2017)
  - Feasibility study of 3D printing of lattice casts (alternative to SAM splint procedure and traditional casts) – (2016-2017)
  - Crew health and safety toolkit (2017-2018)
  - 3D printed plant substrates (2017-2018)

- NASA XHab university projects
  - Student teams apply NASA systems engineering practices to develop hardware
  - 2016-2017 projects with University of Connecticut and University of Maryland

Vanderbilt University Senior Design Pictured: 3D printed lattice cast segment

University of Connecticut XHab: Design of an integrated recycler and printer for ISS

University of Maryland: 3D Printing of Spacesuit components (pictured: 3-element wedge for elbow)

In-Space Manufacturing Photo Album (2017)

ISM Booth at the ISS POIWG Trade Fair in Huntsville, AL 4/26/17

Vanderbilt University ISM Senior Design Project Team at Design Day April 2017

1st Place FPS Team Texas State FPS Competition 4/10/17

TUI CEO and Refabricator PM with Congresswoman Suzan DelBene (center) at the 2017 NASA Technology Day on the Hill 6/15/17

The Refabricator NASA/TUI Team at MSFC for Engineering Unit Testing (4/27/17)

Collaborators

- Niki Werkheiser, In-Space Manufacturing Project Manager
- Dr. Raymond “Corky” Clinton, Deputy Manager, NASA MSFC Science and Technology Office
- Zach Jones, Manufacturing Engineer for ISM
- Dr. Frank Ledbetter, Senior Technical Advisor for In-Space Manufacturing
- Dr. Dogan Timucin and Dr. Kevin Wheeler, Ames Research Center
- Personnel who worked on testing and analysis of materials:
  - Dr. Terry Rolin (CT)
  - Dr. Ron Beshears (CT)
  - Ellen Rabenberg (SEM)
  - Cameron Bosley (mechanical test)
  - Dr. Richard Grugel (SEM)
  - Tim Huff (FTIR)
  - Lewis “Chip” Moore (surface metrology)

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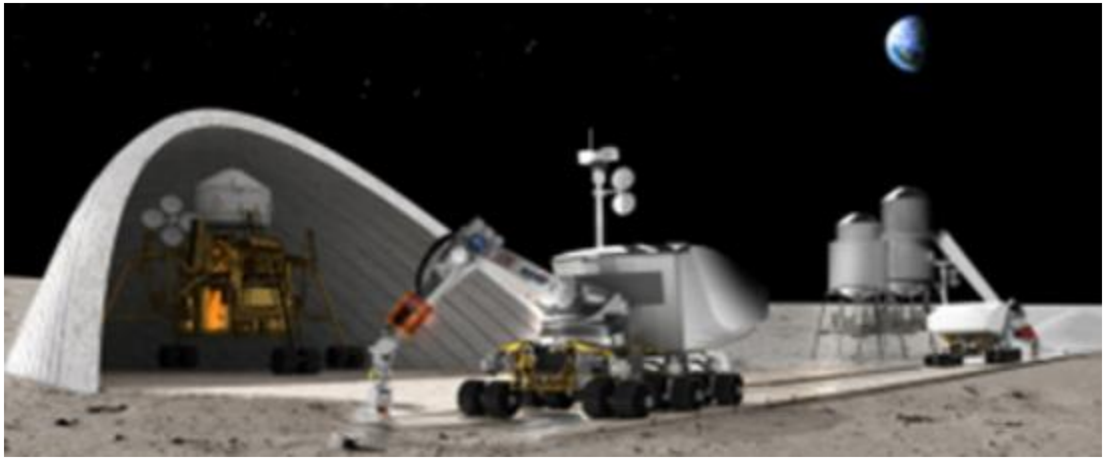
2. Prater, T.J., Bean, Q.A., Werkheiser, N., et al. "Summary Report on Results of the 3D Printing in Zero G Technology Demonstration Mission, Volume 1." NASA/TP-2016-219101 NASA Technical Reports Server. http://ntrs.nasa.gov/search.jsp?R=20160008972
3. Prater, T.J., Bean, Q.A., Werkheiser, N., et al. "Analysis of specimens from phase I of the 3D Printing in Zero G Technology demonstration mission." *Rapid Prototyping Journal* (in queue for publication)
4. Prater, T.J., Bean, Q.A., Werkheiser, N., et al. "A Ground Based Study on Extruder Standoff Distance for the 3D Printing in Zero G Technology Demonstration Mission." (in queue for publication on NASA Technical Reports Server in June 2017)
5. Prater, T.J., Bean, Q.A., Werkheiser, N., et al. "NASA's In-Space Manufacturing Initiative: Initial Results from the International Space Station Technology Demonstration Mission and Future Plans." *Proceedings of the 2016 National Space and Missile and Materials Symposium.*
6. In-Space Manufacturing (ISM) Multi-Material Fabrication Laboratory (FabLab). Solicitation Number: NNHZCQ001K-ISM-FabLab. https://www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=8a6ebb526d8bf8fb9c6361cb8b50c1f8

Extra slides: Centennial Challenge on 3D Printing of Habitats

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 manufacturing operations on a planetary surface

Centennial Challenge: 3D Printed Habitat

Objective: Advance additive construction technology needed 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. **Prize Purse Awarded:** $0.04M	**Structural Member:** Demonstrate an additive manufacturing **material** system to create structural components using terrestrial/space based materials and recyclables. **Prize Purse:** $1.1M	**On-Site Habitat:** Building on material technology progress from Phase 2, demonstrate an automated 3D Print System to **build a full-scale habitat**.

Mars Ice House, winner of the Phase I competition from Space Exploration Architecture and Clouds AO

Phase II Competition: Level 3 Results

1st place, $250,000: Branch Technology and Foster + Partners

2nd place, $150,000: Penn State University