NASA’s In-Space Manufacturing Initiative: Initial Results from International Space Station Technology Demonstration and Future Plans

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NASA Marshall Space Flight Center
“If what you’re doing is not seen by some people as science fiction, it’s probably not transformative enough.”
-Sergey Brin
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 Objective

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.

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.

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

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

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

Proactive influence during Exploration design phase required for meaningful implementation

Test-bed > Proving Ground > Earth Independent

Part/System Requirements, Design, Materials & Processes

Multi-material ‘FabLab’ Test-bed

3DP Demo

AMF

Recycler
In-Space Manufacturing (ISM)
Path to Exploration

Earth-Reliant

ISS Platform
- In-space Manufacturing Rack Demonstrating:
  - 3D Print Tech Demo (plastic)
  - Additive Manufacturing Facility
  - Recycling
  - On-demand Utilization Catalogue
  - Printable Electronics
  - In-space Metals
  - Syn Bio & ISRU
- External In-space Mfctr. & Repair Demo

Eart...
The 3D Print project delivered the first 3D printer on the ISS and investigated the effects of consistent microgravity on melt deposition additive manufacturing by printing parts in space.

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

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**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)
- **Est. Accuracy**: 95 %
- **Resolution**: .35 mm
- **Maximum Power**: 176W (draw from MSG)
- **Software**: MIS SliceR
- **Traverse**: Linear Guide Rail
- **Feedstock**: ABS Plastic

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**Potential Mission Accessories**

- **Caps**
- **Springs**
- **Containers**
- **Buckles**

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**Microgravity Science Glovebox (MSG)**
Phase I Operations Timeline

- Technology Demonstration Mission via a Small Business Innovation Research contract with Made in Space, Inc.
- Ground Control Samples were made in May 2014 on the flight unit in the MSG mock-up facility at MSFC
- The 3D Print Tech Demo launched to ISS on SpaceX-4 (September 2014)
- Installed in the Microgravity Science Glovebox on ISS in November 2014
- Flight Samples were made in November – December 2014
- Specimens underwent testing from May-September 2015
  - Small sample sizes make comparison between ground and flight specimens difficult
- Data from 3DP phase I out-briefed at a technical interchange meeting at NASA MSFC on Dec. 2-3, 2015
- Results will be published as a NASA technical publication in summer 2016
Phase I Prints

Completed Phase 1 Technology Demonstration Goals

- Demonstrated critical operational function of the printer
- Completed test plan for 42 ground control and flight specimens
- Identified influence factors that may explain differences between data sets

Phase II – Summer 2016
- Better statistical sampling
- Demonstrate critical maintenance functions of printer

Mechanical Property Test Articles

- Tensile
- Compression
- Flex

Functional Tools

- Crowfoot
- Ratchet
- Cubesat Clip
- Container
- Torque

Printer Performance Capability
Notes on Printer Operations

- Feedstock for ground and flight are the same material and originate from the same manufacturing lot, but are from different canisters.

- Flight feedstock 5-6 months older than ground feedstock at time of printing.

- Changes in build tray over course of prints:
  - Four separate build trays used for flight prints.

- Z-calibration distance (and tip to tray distance, which is determined by the z-calibration setting) was changed slightly during the course of flight prints based on visual feedback:
  - Z-Calibration was held constant for ground prints.
  - Tip to tray distance is not a directly measurable metric since 3DP unit does not have closed loop positional feedback.
# Testing of Phase I Prints

<table>
<thead>
<tr>
<th>Photographic and Visual Inspection</th>
<th>Data Obtained</th>
<th>CT Scanning / X-Ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspect samples for evidence of:</td>
<td>• Thorough documentation of sample quality</td>
<td>Inspect internal tomography of samples:</td>
</tr>
<tr>
<td>• Delamination between layers</td>
<td>• Archival Photographs</td>
<td>• Internal voids or pores</td>
</tr>
<tr>
<td>• Curling or deformation of samples</td>
<td></td>
<td>• Measure layer thickness / bead width</td>
</tr>
<tr>
<td>• Voids or pores</td>
<td></td>
<td>• Note any discrepancy in spacing between filament lines</td>
</tr>
<tr>
<td>• Sample removal damage</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mass Measurement</strong></td>
<td><strong>Average Sample Mass</strong></td>
<td></td>
</tr>
<tr>
<td>Measure mass of samples:</td>
<td>• Geometric Accuracy</td>
<td></td>
</tr>
<tr>
<td>• Laboratory scale accurate to 0.01 mg</td>
<td>• Average Sample Volume</td>
<td></td>
</tr>
<tr>
<td>• Note any discrepancy between flight and ground samples</td>
<td>• Internal structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Densification</td>
<td></td>
</tr>
<tr>
<td><strong>Structured Light Scanning</strong></td>
<td><strong>Average Sample Density</strong></td>
<td></td>
</tr>
<tr>
<td>Scan external geometry of samples:</td>
<td>• Mechanical Properties</td>
<td></td>
</tr>
<tr>
<td>• Accurate to ± 12.7 µm</td>
<td>• Comparison to ABS characterization data</td>
<td></td>
</tr>
<tr>
<td>• Compare scan data CAD model to original CAD model</td>
<td>• Microstructure data</td>
<td></td>
</tr>
<tr>
<td>• Measure volume from scan data</td>
<td>• Layer adhesion quality</td>
<td></td>
</tr>
<tr>
<td>• Measure feature dimensions:</td>
<td>• Microgravity effects on deposition</td>
<td></td>
</tr>
<tr>
<td>length, width, height, diameter, etc.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Mechanical (Destructive) Testing**

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

**Optical / SEM Microscopy**

Inspect for discrepancies between flight and ground samples:
- External anomalies noted in previous tests
- Microstructure
- Areas of delamination
- Fracture surface of tensile samples
3DP Phase I Key Observations: Material Properties

- **Density**
  - Flight specimens slightly more dense than ground specimens
  - Compression specimens show opposite trend
  - Gravimetric density strongly correlated with other mechanical properties

- **Tensile and Flexure**
  - Flight specimens stronger and stiffer than ground counterparts

- **Compression**
  - Flight specimens are weaker than ground specimens

### Mechanical Properties

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Percent Difference (WRT Ground)</th>
<th>Coefficient of Variation (Flight)</th>
<th>Coefficient of Variation (Ground)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate tensile strength (KSI)</td>
<td>17.1%</td>
<td>6.0%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Modulus of Elasticity (MSI)</td>
<td>15.4%</td>
<td>6.1%</td>
<td>2.7%</td>
</tr>
<tr>
<td>Fracture Elongation (%)</td>
<td>-30.4%</td>
<td>26.3%</td>
<td>9.9%</td>
</tr>
<tr>
<td>Compressive Strength (KSI)</td>
<td>-25.1%</td>
<td>3.1</td>
<td>5.0</td>
</tr>
<tr>
<td>Compressive Modulus (MSI)</td>
<td>-33.3%</td>
<td>9.4%</td>
<td>4.2%</td>
</tr>
<tr>
<td>Flexural Strength (PSI)</td>
<td>25.6%</td>
<td>9.3%</td>
<td>6.0%</td>
</tr>
<tr>
<td>Flexural Modulus (KSI)</td>
<td>22.0%</td>
<td>9.6%</td>
<td>3.9%</td>
</tr>
</tbody>
</table>

### Density

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Percent Difference (WRT Ground)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile</td>
<td>3.4%</td>
</tr>
<tr>
<td>Compression</td>
<td>-2.6%</td>
</tr>
<tr>
<td>Flexure</td>
<td>5.6%</td>
</tr>
</tbody>
</table>

Optical microscope image of tensile specimen
3DP Phase I Key Observations: XRay and CT

- CT scans show an abrupt step change in density about halfway through the thickness of many specimens
  - More pronounced densification in lower half of flight specimens
  - Differences in densities (measured as mean CT) between upper and lower half of specimens is not statistically significant
- Probable voids detected throughout flight and ground articles; no significant difference in number or size of voids between the flight and ground sets
3DP Phase I Key Observations: Structured Light Scanning

**Protrusions along bottom edges** indicate that extruder tip may have been too close to the print tray (more pronounced for flight prints).

**Warping of Samples**
- may indicate inconsistent cooling of the specimen leading to internal stress build-up
- Damage sustained during specimen removal process

**Roundness of Circular Samples**
- Flight specimens *slightly* more out of round based on structured light scanning results

<table>
<thead>
<tr>
<th></th>
<th>Eccentricity</th>
<th>Elliptical Cross-Sectional Area (mm²)</th>
<th>Percent Error of Cross-Section WRT CAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight</td>
<td>0.14</td>
<td>121.7</td>
<td>4.11 %</td>
</tr>
<tr>
<td>Ground</td>
<td>0.12</td>
<td>123.0</td>
<td>2.96 %</td>
</tr>
</tbody>
</table>
3DP Phase I Key Observations: Optical Microscopy

- Break in tensile specimen (straight across)
- Break in tensile specimen aligned with filament (45°)
- Greater Densification of Bottom Layers (Flight tensile)
- Protrusions
- Warping
- Side Image Extruder Plate (Ground Specimen)
- Bottom Surface Crowfoot (Flight Specimen)
3DP Phase I Key Observations:
Scanning Electron Microscopy (SEM)

- Structural differences are seen within both ground and flight specimen groups
- Ground sample surfaces are generally more “open” than flight specimens

Ground tensile specimen surface
Flight tensile specimen surface

- Fracture surfaces for ground specimens have **open central fibers** and dense fiber agglomeration on sides
- Fracture surfaces for flight specimens have dense **fiber agglomeration on sides and bottom**

Ground tensile fracture surface
Flight tensile fracture surface
3DP Phase I Key Observations: Scanning Electron Microscopy (SEM)

- “Stuck parts” due to over-adhesion to build tray result in layer delamination upon removal

Flight tensile specimen F004  
Flight tensile specimen F018

- Fracture surfaces exhibit typical glassy brittle fracture
- Filament necking more prevalent in ground samples

Ground tensile  
G015  
G004
3DP Phase I Key Observations: Scanning Electron Microscopy (SEM)

<table>
<thead>
<tr>
<th>Raster orientation</th>
<th>Mean yield strength (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal (0)</td>
<td>3700</td>
</tr>
<tr>
<td>Diagonal (45)</td>
<td>2274</td>
</tr>
<tr>
<td>Transverse (90)</td>
<td>2081</td>
</tr>
<tr>
<td>Default (+/- 45)</td>
<td>2741</td>
</tr>
</tbody>
</table>

- Ground and flight specimens built with +/-45 orientation
- More filament bonding on bottom of flight specimens
- Potentially explains increased strength of flight specimens and reduced elongation

3DP Phase I Follow-On Work

**Ground Based Investigations**
- Study of effect of tip-to-tray distance on part quality and performance
  - Systematic variation of this distance using 3DP backup flight unit
  - Study envelopes commanded values for ground and flight prints
  - Test regime includes surface metrology, mass measurement, structured light scanning, XRay/CT, mechanical testing, and SEM
  - Complete by October 2016
- Printing with older feedstock
  - Assess hypothesis that flight feedstock being older at time of printing was a contributing variable to observed differences in mechanical properties
  - Study also uses 3DP flight backup unit

**Further Analysis of Phase I Specimens**
- Chemical composition analysis using Fourier Transform Infrared Spectroscopy
  - Demonstrated **no significant chemical differences between ground and flight prints** in terms of functional groups present and relative concentrations
- Scanning electron microscopy (SEM) of calibration coupons specimens (sparser fill) to better assess microgravity effects
- SEM of layer quality (square column) specimens

**On-Orbit Investigations**
- Better statistical sampling with specimens from Phase II operations
- Locked manufacturing process to enable assessment of microgravity effects on FDM process

**SEM Image**
- Deformed ABS Filament with microcracks
3DP Phase I Lessons Learned

• Need to understand cooling rate and strength relationships
• Adhere to established manufacturing protocols
  • Develop a locked and qualified manufacturing process that will enable true comparison of ground and flight prints for phase II operations
  • Fabricate samples with the same processing parameters
• Fully characterize the samples prior to mechanical testing
• Utilize raw data from mechanical testing
• Video record sample during mechanical testing
• Consider use of noncontact measurement techniques (digital image correlation) to understand elongation behavior
  • Mechanical/elastic in nature
3DP Phase I Executive Summary

- The Phase I parts (first 21 parts printed) underwent testing and evaluation at the Materials and Processes Laboratory at NASA Marshall Space Flight Center and were compared with “ground truth” samples printed prior to printer’s launch to ISS.
  - Phase I report will be published as NASA technical publication in summer 2016.
- Considerable structural variance within and between ground and flight specimens precludes ascertaining any obvious microgravity influence on FDM process.
- Differences noted in testing between the ground and flight specimens could not be linked to microgravity as a processing variable.
  - More definitive assessment will be made with SEM analysis of sparser fill calibration specimens.
  - “Build” structural variance accounts for difference in measured tensile properties.
- Based on the Phase I results, the ISM team developed a go forward plan which includes: (1) Clear objectives defined for Phase II on-orbit prints and (2) Additional ground-based characterization work in order to address variables related to the 3DP data set.
- Complementary microstructural and macrostructural modeling work of FDM at Ames Research Center underway.
  - ISM team providing data for model validation.
In-Space Manufacturing (ISM)
Phased Technology Development Roadmap

<table>
<thead>
<tr>
<th>Earth-based</th>
<th>Demos: Ground &amp; ISS</th>
<th>Exploration (Proving Ground to Earth Independence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-2012</td>
<td>Plastic Printing Demo</td>
<td>Asteroids/Cis-Lunar</td>
</tr>
<tr>
<td>2014</td>
<td>In-space Recycler Utilization Testing AMF</td>
<td>Lagrange Point</td>
</tr>
<tr>
<td>2015-2017</td>
<td>Metal Printing Fab Lab Self-repair/replicate</td>
<td>Lunar, Lagrange FabLabs</td>
</tr>
<tr>
<td>2018-2024</td>
<td>ISS: Multi-material “Fab Lab” Rack Test Bed (Key springboard for Exploration ‘proving ground’)</td>
<td>Planetary Surfaces Points Fab</td>
</tr>
<tr>
<td></td>
<td>3D Print Demo Add. Mfctr. Facility (AMF)</td>
<td>Initial Robotic/Remote Missions</td>
</tr>
<tr>
<td></td>
<td>In-space Recycler ISS Demo ISM Cert Process Part Catalogue</td>
<td>Provision feedstock</td>
</tr>
<tr>
<td></td>
<td>ISM &amp; Exploration Material &amp; Design Database</td>
<td>Evolve to utilizing in situ materials (natural resources, synthetic biology)</td>
</tr>
<tr>
<td></td>
<td>External In-space Mfctr. (STMD) Autonomous Processes</td>
<td>Product: Ability to produce, repair, and recycle parts &amp; structures on demand; i.e. “living off the land”</td>
</tr>
<tr>
<td></td>
<td>Future Engineer STEM Challenge Additive Construction by Mobile</td>
<td>Autonomos final milling to specfication</td>
</tr>
<tr>
<td></td>
<td>ACME Ground Demos</td>
<td>Planetary Multi-Material Fab Lab</td>
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</tbody>
</table>

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
- Plastic Printing Demo
- In-space Recycler Utilization Testing AMF
- Metal Printing Fab Lab Self-repair/replicate
- ISS: Multi-material “Fab Lab” Rack Test Bed (Key springboard for Exploration ‘proving ground’)

Exploration (Proving Ground to Earth Independence)
- Asteroids
- Cis-Lunar
- Lagrange Point
- Lunar, Lagrange FabLabs
- Planetary Surfaces Points Fab
- Mars Multi-Material Fab Lab

ISS Serves as a Key Exploration test-bed for the Required Technology Maturation & Demonstrations

2014
- Plastic Printing Demo
- In-space Recycler Utilization Testing AMF

2015-2017
- Metal Printing Fab Lab Self-repair/replicate
- ISS: Multi-material “Fab Lab” Rack Test Bed (Key springboard for Exploration ‘proving ground’)

2025-35
- Lunar, Lagrange FabLabs
- Planetary Surfaces Points Fab

2035+
- Mars Multi-Material Fab Lab
- 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.
Collaborators

• Niki Werkheiser, In-Space Manufacturing Project Manager
• Dr. Raymond “Corky” Clinton, Deputy Manager, NASA MSFC Science and Technology Office
• Quincy Bean, Technology Discipline Lead Engineer for In-Space Manufacturing
• Steve Newton, In-Space Manufacturing Deputy Project Manager
• Dr. Frank Ledbetter, Senior Technical Advisor for In-Space Manufacturing
• Personnel who worked on testing and analysis of phase I prints:
  • Dr. Terry Rolin
  • Dr. Ron Beshears
  • Steven Phillips
  • Catherine Bell
  • Dr. Richard Grugel
  • Erick Ordonez
  • Lewis “Chip” Moore
Questions
Additional ISM Activities

• Interface with and design of components for ISS stakeholders
  • Oxygen Generation Assembly Adapter allows ISS crew to obtain consistent and accurate airflow velocity measurements for Environmental Control and Life Support Systems (ECLSS) hardware
  • Air Nozzle Adapter (will be used to inflate refillable stowage bags for ISS demo test) for use on ISS
  • Robonaut camera calibration mount (senior design project with Vanderbilt University)
  • OGA and air nozzle will be printed with Additive Manufacturing Facility (AMF)
• Defined phase II prints based on phase I results
  • Streamlined process for operations to conserve crew time
  • TBD as to when phase II prints will occur
• Made in Space Additive Manufacturing Facility (AMF) commercial printer is now on ISS
  • Multi-user facility
  • NASA prints will take place this summer
Additional ISM Activities

- Tethers Unlimited (TUI) developing an in-space recycler and printer for recycling of printed parts into feedstock
- NASA Science Technology Mission Directorate (STMD) External In-space Manufacturing Tipping Point Project with Made in Space, Inc. entitled “Versatile In-Space Robotic Precision Manufacturing and Assembly System”
- Additive Construction by Mobile Emplacement (ACME)
  - project is in conjunction with the Army Corps of Engineers and is co-led by MSFC and KSC
  - Development of additive construction technologies for use with in-situ resources
- Procurement of Nscrypt machine
  - Multimaterial 3D printer
  - printable electronics capability
- Ongoing development work toward ISS “FabLab”
  - Trade studies of manufacturing processes for in-space applications
  - Logistics analyses
  - Material characterization activities to understand machine and material capabilities and inform requirements development
ISM Education & Public Outreach ‘Scrapbook’
(Oct, 2015 – April, 2016)

Future Engineers listed as ‘Breakthrough Award’ in Nov. Issue of Popular Mechanics

FE Junior Division Winner, Emily T., with her winning design, the Flower Tea Cage

NASA Systems Eng. Excellence Award for 3D Print Demo

Media Event with ISM and Former ISS Commander Butch Wilmore 11/16/15

Featuring R.J. Hillan, NASA ISM team members, and MIS Design Lead, Mike Snyder 12/4/15

3D Print included as Top 15 ISS events for the ISS 15th Anniversary Infographic Released 11/2/15

National FE Challenge Teen Winner, Ryan B., at California Science Center with Astronaut Leland Melvin 10/27/15

November 2, 2000
15th ANNIVERSARY
Human Habitation

PopulAer
MECHANICS

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