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

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

-Sergey Brin
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 Parts/Systems Design Database & Test Articles

- 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.

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

- 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.

ISM Objective

Unique Agency Expertise & Leveraging of Industry

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

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

Part/System Requirements, Design, Materials & Processes

Multi-material ‘FabLab’ Test-bed

AMF Recycler

3DP Demo

Test-bed > Proving Ground > Earth Independent

ISM EXPLORATION APPLICATIONS

ISM TECHNOLOGY DEVELOPMENT

Answers WHAT we need to make

- Answers HOW we will make it

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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

**PROVING GROUND**

**Earth-Based Platform**
- Define Capacity and Capability Requirements (work with EMC Systems on ECLSS, Structures, Logistics & Maintenance, etc.)
- Certification & Inspection Process
- Material Characterization Database (in-situ & ex-situ)
- Additive Manufacturing Systems Automation Development
- Ground-based Technology Maturation & Demonstrations (i.e. ACME-Project)
- Develop, Test, and Utilize Simulants & Binders for use as AM Feedstock

**EARTH INDEPENDENT**

**Planetary Surfaces Platform**
- Additive Construction, Repair & Recycle/Reclamation Technologies (both In-situ and Ex-situ)
- Provisioning of Regolith Simulant Materials for Feedstock Utilization
- Execution and Handling of Materials for Fabrication and/or Repair Purposes
- Synthetic Biology Collaboration

*Green text indicates ISM/ISRU collaboration*
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

**3D Print Specifications**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>33 cm x 30 cm x 36 cm</td>
</tr>
<tr>
<td>Print Volume</td>
<td>6 cm x 12 cm x 6 cm</td>
</tr>
<tr>
<td>Mass</td>
<td>20 kg (w/out packing material or spares)</td>
</tr>
<tr>
<td>Est. Accuracy</td>
<td>95 %</td>
</tr>
<tr>
<td>Resolution</td>
<td>.35 mm</td>
</tr>
<tr>
<td>Maximum Power</td>
<td>176W (draw from MSG)</td>
</tr>
<tr>
<td>Software</td>
<td>MIS SliceR</td>
</tr>
<tr>
<td>Traverse</td>
<td>Linear Guide Rail</td>
</tr>
<tr>
<td>Feedstock</td>
<td>ABS Plastic</td>
</tr>
</tbody>
</table>

**Potential Mission Accessories**

- Threads
- Springs
- Containers
- Buckles
- Caps
- Clamps

**Microgravity Science Glovebox (MSG)**

**THE FIRST 3D PRINTER IN SPACE**
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 - TBD
- Better statistical sampling
- Demonstrate critical maintenance functions of printer

Printer Performance Capability

Mechanical Property Test Articles

- Tensile
- Compression
- Flex

Functional Tools

- Crowfoot
- Ratchet
- Cubesat Clip
- Container
- Torque
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

Photographic and Visual Inspection
Inspect samples for evidence of:
• Delamination between layers
• Curling or deformation of samples
• Voids or pores
• Sample removal damage

Mass Measurement
Measure mass of samples:
• Laboratory scale accurate to 0.01 mg
• Note any discrepancy between flight and ground samples

Structured Light Scanning
Scan external geometry of samples:
• Accurate to ± 12.7 µm
• Compare scan data CAD model to original CAD model
• Measure volume from scan data
• Measure feature dimensions: length, width, height, diameter, etc.

Data Obtained
• Thorough documentation of sample quality
• Archival Photographs

CT Scanning / X-Ray
Inspect internal tomography of samples:
• Internal voids or pores
• Measure layer thickness / bead width
• Note any discrepancy in spacing between filament lines

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

Average Sample Mass

• Geometric Accuracy
• Average Sample Volume

Average Sample Density

• Internal structure
• Densification

Mechanical Properties
• Comparison to ABS characterization data

Microstructure data
• Layer adhesion quality
• Microgravity effects on deposition
• Comparison to ABS characterization data

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

Image from CT scan of flight tensile specimen

Lower density in upper section of part
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
- Side Image Extruder Plate (Ground Specimen)
- Warping
- 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

- 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
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
- Fiber necking more prevalent in ground samples

  Ground tensile G015  Ground tensile 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 fiber bonding on bottom of flight specimens
- Potentially explains increased strength of flight specimens and reduced elongation

Characteristic appearance of flight specimens:

- **0°**: Vertical alignment
- **+45°/-45°**: Diagonal pattern
- **45°**: Oblique alignment
- **90°**: Horizontal alignment
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
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.

Structured Light Scan Data of Crowfoot Tool 3D Printed on ISS

Optical Microscopy of Ground Control Ratchet Tool Head

Optical Microscopy of Break in Tensile Test Flight Specimen
# In-Space Manufacturing (ISM)
## Phased Technology Development Roadmap

### Earth-based

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<tr>
<td>Ground &amp; Parabolic centric:</td>
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<tr>
<td>• Multiple FDM Zero-G parabolic flights</td>
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<tr>
<td>• Trade/System Studies for Metals</td>
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<tr>
<td>• Ground-based Printable Electronics/Spacecraft</td>
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<tr>
<td>• Verification &amp; Certification Processes under development</td>
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<tr>
<td>• Materials Database</td>
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<tr>
<td>• Cubesat Design &amp; Development</td>
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<tr>
<td>3D Print Tech Demo</td>
<td>Plastic Printing Demo</td>
<td>Recycler Utilization Testing AMF</td>
<td>Metal Printing Fab Lab Self-repair/replicate</td>
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<td>• In-space:3D Print: First Plastic Printer on ISS Tech Demo</td>
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<td>• NIAC Contour Crafting</td>
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<td>• NIAC Printable Spacecraft</td>
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<td>• Small Sat in a Day</td>
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<td>• AF/NASA Space-based Additive NRC Study</td>
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<td>• ISRU Phase II SBIRs</td>
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<tr>
<td>• Ionic Liquids</td>
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<td></td>
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<td>• 3D Print Demo</td>
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<td></td>
<td>• Add. Mfctr. Facility (AMF)</td>
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<td></td>
<td>• In-space Recycler ISS Demo</td>
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<td></td>
<td>• ISM Cert Process Part Catalogue</td>
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<tr>
<td></td>
<td>• ISS &amp; Exploration Material &amp; Design Database</td>
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<tr>
<td></td>
<td>• External In-space Mfctr. (w/DARPA &amp; STMD)</td>
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<tr>
<td></td>
<td>• Autonomous Processes</td>
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<td></td>
<td>• Future Engineer STEM Challenge</td>
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<td></td>
<td>• ACME</td>
<td></td>
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<tr>
<td></td>
<td>• ISS: Multi-material “Fab Lab” Rack Test Bed (Key springboard for Exploration ‘proving ground’)</td>
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<tr>
<td></td>
<td>• Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals &amp; various plastics, embedded electronics, autonomous inspection &amp; part removal, etc.</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>• ACME Ground Demos</td>
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</table>

### Demos: Ground & ISS

- Plastic Printing Demo
- Recycler Utilization Testing AMF
- Metal Printing Fab Lab Self-repair/replicate

### Exploration (Proving Ground to Earth Independent)

<table>
<thead>
<tr>
<th>2025-35</th>
<th>2035+</th>
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<tr>
<td>Lunar, Lagrange FabLabs</td>
<td>Planetary Surfaces Points Fab</td>
</tr>
<tr>
<td>Initial Robotic/Remote Missions</td>
<td>Transport vehicle and sites would need Fab capability</td>
</tr>
<tr>
<td>Provision feedstock</td>
<td>Additive Construction &amp; Repair of large structures</td>
</tr>
<tr>
<td>Evolve to utilizing in situ materials (natural resources, synthetic biology)</td>
<td>Product: Ability to produce, repair, and recycle parts &amp; structures on demand; i.e. “living off the land”</td>
</tr>
<tr>
<td>Materials Database</td>
<td>Autonomous final milling to specification</td>
</tr>
<tr>
<td>Cubesat Design &amp; Development</td>
<td>Mars Multi-Material Fab Lab</td>
</tr>
</tbody>
</table>

*Green text indicates ISM/ISRU collaboration.*

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

• Niki Werkheiser, In-Space Manufacturing Project Manager
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• Dr. Frank Ledbetter, Senior Technical Advisor for In-Space Manufacturing
• Personnel who worked on testing of phase I prints:
  • Dr. Terry Rolin
  • Dr. Ron Beshears
  • Steven Phillips
  • Catherine Bell
  • Dr. Richard Grugel
  • Erick Ordonez
  • Lewis “Chip” Moore
Questions
Backup Slides
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 Nscript 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

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

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

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

“Design Consultation” with FE Winner, R.J. Hillan, NASA ISM team members, and MIS Design Lead, Mike Snyder
12/4/15

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

NASA Systems Eng. Excellence Award for 3D Print Demo