In-space Manufacturing (ISM): 3D Printing in Space Technology Demonstration

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Objective: Develop and enable the manufacturing technologies and processes required to provide on-demand, sustainable operations for Exploration Missions (in-transit and on-surface). This includes development of the desired capabilities, as well as the required processes for the certification, characterization & verification that will enable these capabilities to become institutionalized via ground-based and ISS demonstrations.
More than just 3D Printing…. In-space Manufacturing Technology Development Areas

<table>
<thead>
<tr>
<th>RECYCLER</th>
<th>PRINTED ELECTRONICS</th>
<th>PRINTABLE SATELLITES</th>
<th>MULTI MATERIAL 3D PRINTING</th>
<th>EXTERNAL STRUCTURES &amp; REPAIRS</th>
<th>ADDITIVE CONSTRUCTION</th>
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<tbody>
<tr>
<td>Recycling/Reclaiming 3D Printed Parts and/or packing materials into feedstock materials. This capability is crucial to sustainability in-space.</td>
<td>Leverage ground-based developments to enable in-space manufacturing of functional electronic components, sensors, and circuits. Image: Courtesy of Dr. Jessica Koehne (NASA/ARC)</td>
<td>The combination of 3D Print coupled with Printable Electronics enables on-orbit capability to produce “on demand” satellites.</td>
<td>Additively manufacturing metallic parts in space is a desirable capability for large structures, high strength requirement components (greater than nonmetallics or composites can offer), and repairs. NASA is evaluating various technologies for such applications. Image: Manufacturing Establishment website</td>
<td>Astronauts will perform repairs on tools, components, and structures in space using structured light scanning to create digital model of damage and AM technologies such as 3D Print and metallic manufacturing technologies (e.g. E-beam welding, ultrasonic welding, EBF3) to perform the repair. Image: NASA</td>
<td>Contour Crafting Simulation Plan for Lunar Settlement Infrastructure Build-Up B. Khoshnevis, USC</td>
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Illustration of a lunar habitat, constructed using the Moon's soil and a 3D printer. Credit: Foster+Partners

Technologies Under Development for Sustainable Exploration Missions
In-space Manufacturing Path to Exploration

**EARTH RELIANT**
- ISS Platform
  - 3D Print Tech Demo
  - Additive Manufacturing Facility
  - On-demand Utilization Catalogue
  - Recycling Demo
  - Printable Electronics Demo
  - In-space Metals Demo
  - External In-space Manufacturing & Repair

**PROVING GROUND**
- International Space Station (ISS)
- Planetary Surfaces Platform
  - Additive Construction Technologies
  - Regolith Simulant Materials Development and Test
  - Execution and Handling
  - Synthetic Biology Collaboration

**EARTH INDEPENDENT**
- Asteroids
- Earth-Based Platform
  - Certification & Inspection Process
  - Material Characterization Database
  - Additive Manufacturing Automation
### In-space Manufacturing Phased Technology Development Roadmap

<table>
<thead>
<tr>
<th>Earth-based</th>
<th>International Space Station</th>
<th>Exploration</th>
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<tr>
<td>Pre-2012</td>
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<tr>
<td>3D Print Tech Demo</td>
<td>Plastic Printing Demo</td>
<td>Asteroids</td>
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<tr>
<td>• In-space: 3D Print Demo</td>
<td>• Recycler Small Sats</td>
<td>Lunar</td>
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<tr>
<td>• NIAC Contour Crafting</td>
<td>• Add Mfctr. Facility</td>
<td>Lagrange Point</td>
</tr>
<tr>
<td>• NIAC Printable Spacecraft</td>
<td>• Self-repair/replicate</td>
<td></td>
</tr>
<tr>
<td>• Small Sat in a Day</td>
<td>• External In-space Mfctr</td>
<td></td>
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<tr>
<td>• AF/NASA Space-based Additive</td>
<td>• Metal Printing</td>
<td></td>
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<tr>
<td>• Ground &amp; Parabolic centric</td>
<td>• Printable Electronics</td>
<td></td>
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<tr>
<td>• Verification &amp; Certification Processes under development</td>
<td>• 3D Print Tech Demo</td>
<td></td>
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<tr>
<td>• Materials Database</td>
<td>• Future Engineer Challenge</td>
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<tr>
<td>• Cubesat Design &amp; Development</td>
<td>• Utilization Catalogue</td>
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### 2014-2018

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<thead>
<tr>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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<tbody>
<tr>
<td>3D Print Tech Demo</td>
<td>Plastic Printing Demo</td>
<td>• Recycler Small Sats</td>
<td>• Add Mfctr. Facility</td>
<td>• Self-repair/replicate</td>
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<tr>
<td>• Future Engineer Challenge</td>
<td>• Utilization Catalogue</td>
<td>• ISM Verification &amp; Cert Process Development</td>
<td>• Add. Mfctr. Facility (AMF)</td>
<td>• External In-space 3D Printing</td>
</tr>
<tr>
<td>• In-space Recycler SBIR</td>
<td>• In-space Material Database</td>
<td>• Autonomic Processes</td>
<td>• Autonomous Processes</td>
<td>• Metals Demo Options</td>
</tr>
<tr>
<td>• Ionic Liquids</td>
<td>• External In-space 3D Printing</td>
<td>• Additive In-space Repair</td>
<td>• Additive In-space Repair</td>
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### 2020-25

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<tr>
<th>2020</th>
<th>2025</th>
<th>2030 - 40</th>
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<tr>
<td>Lunar, Lagrange Fab Labs</td>
<td>Planetary Surfaces Points Fab</td>
<td>Mars Multi-Material Fab Lab</td>
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<tr>
<td>• Initial Robotic/Remote Missions</td>
<td>• Transport vehicle and sites would need Fab capability</td>
<td>• Utilize in situ resources for feedstock</td>
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<tr>
<td>• Provision some feedstock</td>
<td>• Additive Construction</td>
<td>• Build various items from multiple types of materials (metal, plastic, composite, ceramic, etc.)</td>
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<tr>
<td>• Evolve to utilizing in situ materials (natural resources, synthetic biology)</td>
<td>• Product: Fab Lab providing self-sustainment at remote destination</td>
<td>• Product: Ability to produce multiple spares, parts, tools, etc. “living off the land”</td>
</tr>
<tr>
<td>• Product: Ability to produce multiple spares, parts, tools, etc. “living off the land”</td>
<td>• Autonomous final milling to specification</td>
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**ISS Technology Demonstrations are Key in ‘Bridging’ Technology Development to Full Implementation of this Critical Exploration Technology.**
ISM Step #1: First 3D Printer in Space!

- The 3D Print Tech Demo launched on SpaceX-4 (9/21/14) and was installed in the Microgravity Science Glovebox on ISS
- To date, it has printed 21 parts in space (14 unique designs); the printer functioned nominally.
- First part “emailed” to Space: 3D Print of a ratchet tool demonstrated on-demand capability by uplinking a part file that was not pre-loaded to the 3D Printer.
- The first flight samples were ‘unboxed’ at NASA MSFC in April 2015
- Results to be openly published Fall 2015

Images courtesy of NASA
3D Printer International Space Station Technology Demonstration Initial Samples

Mechanical Property Test Articles

- Tensile
- Compression
- Flex
- Torque

Functional Tools

- Crowfoot
- Ratchet
- Cubesat Clip
- Container

Printer Performance Capability

- Calibration
- Hole Resolution
- Feature Resolution
- Overhang
- Layer Quality
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:
- Will use laboratory scale accurate to 0.1 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

Average Sample Mass
- Geometric Accuracy
- Average Sample Volume

Average Sample Density
- Computed tomography
- Layer thickness / Bead Width

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
- Inter-laminar microstructure
- Areas of delamination
- Fracture surface of tensile samples

Data Obtained
- Thorough documentation of sample quality
- Archival Photographs

Average Sample Mass
- Geometric Accuracy
- Average Sample Volume

Average Sample Density
- Computed tomography
- Layer thickness / Bead Width

Mechanical Properties
- Comparison to ABS characterization data

Microstructure data
- Layer adhesion quality
In Space Manufacturing Elements

◆ AMF - Additive Manufacturing Facility (SBIR Phase II-Enhancement) with Made In Space
  - Commercial printer for use on ISS
    - Incorporates lessons learned from 3D Printer ISS Tech Demo
    - Expanded materials capabilities: ABS, ULTEM, PEEK
    - Increased build volume
  - Anticipated launch late CY2015

◆ In-space Recycler ISS Technology Demonstration Development (SBIR 2014)
  - Objective: Recycle 3D printed parts into feedstock to help close logistics loop.
  - Phase I recycler developments completed by Made In Space and Tethers Unlimited.
  - Phase II SBIR (2014) awarded to Tethers Unlimited.
  - Final deliverable will result in flight hardware for the In-space Recycler for proposed ISS Technology Demonstration in FY2017.

◆ Launch Packaging Recycling Phase I SBIR (2015)
  - Objective: Recycle launch packaging materials into feedstock to help close logistics loop
In-Space Manufacturing Elements

◆ **In-space Printable Electronics Technology Development**
  - Development of inks, multi-materials deposition equipment, and processes
  - Collaborating with Xerox Palo Alto Research Center (PARC) on Printable Electronics technologies developed at MSFC and Xerox PARC.
  - NASA Ames Research Center developing plasma jet printable electronics capability
  - Jet Propulsion Lab (JPL) has Advanced Concepts project to develop “printable spacecraft”
  - Printable Electronics Roadmap developed targeting ISS technology demonstrations including RF sensors/antennae, in-space printed solar panel, and printable cubesats

◆ **In-space Multi-Material Manufacturing Technology Development**
  - In-space Adaptive Manufacturing (ISAM) project with Dynetics utilizing the Hyperbaric Pressure Laser Chemical Vapor Deposition (HP-LCVD)
  - HP-LCVD technology holds promise for a novel solution to manufacturing with multiple materials (including metallics) in microgravity.
  - Phase I deliverable is spring similar to design utilized on ISS
Additive Construction by Mobile Emplacement (ACME)

- Joint initiative with the U. S. Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL) Automated Construction of Expeditionary Structures (ACES) Project
- Objective: Develop a capability to print custom-designed expeditionary structures on-demand, in the field, using locally available materials and minimum number of personnel.
- Goal: Produce half-scale and full-scale structures with integrated additive construction system at a lab or planetary analog site

- Funded by NASA/GCDP and U.S. Army Corps of Engineers (USACE)
- Partnerships between MSFC, KSC, Contour Crafting Corporation (CCC), and the Pacific International Space Center for Exploration Systems (PISCES)
Leveraging External Platforms for Technology and Skillset Development

**National Future Engineers STEM Program:** National challenge conducted jointly by NASA and American Society of Mechanical Engineers (ASME)

- Competition was held in two divisions, Junior (K-12) and Teen (13-18)
- First Challenge was to design a tool that astronauts could use on ISS. Teen winner’s part will be printed on ISS later this year.
- The Space Container Challenge was announced on 5/12/15 and closes 8/2/15. [www.futureengineers.org](http://www.futureengineers.org)
- Discussions underway for a joint NASA/IndyCar Challenge

**NASA GrabCAD Handrail Clamp Assembly Challenge**

- GrabCAD has a community of nearly 2 million designers
- Challenge was to design a 3D Printed version of the Handrail Clamp Assembly commonly used on ISS
- Nearly 500 entries in three weeks
- Five winners were selected
In-space Manufacturing Summary

In order to provide meaningful impacts to Exploration Technology needs, the ISM Initiative Must Influence Exploration Systems Design Now.

- **In-space Manufacturing offers:**
  - Dramatic paradigm shift in the development and creation of space architectures
  - Efficiency gain and risk reduction for low Earth orbit and 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 in time to support NASA budget and schedule, ISM must be able to leverage the significant commercial developments.**
  - Requires innovative, agile collaborative mechanisms (contracts, challenges, SBIR’s, etc.)
  - NASA-unique Investments to focus primarily on adapting the technologies & processes to the microgravity environment.

- **We must do the foundational work – it is the critical path for taking these technologies from lab curiosities to institutionalized capabilities.**
  - Characterize, Certify, Institutionalize, Design for AM

- **Ideally, ISS US Lab rack or partial rack space should be identified for In-space Manufacturing utilization in order to continue technology development of a suite of capabilities required for exploration missions, as well as commercialization on ISS.**
BACKUP
**Visual and photographic Inspection**

- Identification and documentation of anomalies, damage (e.g., print tray removal damage)
- Identification and documentation of any visual differences between flight and ground samples (initial identification of microgravity effects)
- Attention will be given to any signs of delamination between layers, curling of the sample, surface quality, damage, voids or pores, and any other visually noticeable defect.

**Mass Measurement / Density Calculation**

- Mass measurement using a calibrated laboratory scale accurate to 0.1mg repeated five times for a mean mass
- Density calculation requires the volume determined by structured light scanning
  - Provides information on void space or expansion of the material created during the printing process
  - Flight samples will be compared with their respective ground samples to assess any differences
Structured Light Scanning
- ATOS Compact Scan Structured Light Scanner
- Blue light grid projected on the surface
- Stereo-images captured
- Image processing provides
  - A CAD model of the printed part
  - A comparison of the printed part and the original CAD file from which the part was printed
  - A statistically valid determination of the volume of the sample

Computed Tomography (CT) Scanning/X-Ray
- Phoenix Nanome|x 160
- X-ray scans
- Provides 2D and 3D models of the internal structures that could affect mechanical properties
  - Internal voids
  - De-lamination of the ABS layers
- Resolution as low as 8-10 microns is possible
3D Printing ISS Tech Demo Sample Testing Techniques

Mechanical (Destructive) Testing

- ASTM Standards Applied on Mechanical Samples only
- D638 for tensile testing
  - Tensile strength, tensile modulus, and fracture elongation
- D790 for flexure testing
  - Flexural stress and flexural modulus
- D695 for compression testing
  - Compressive stress and compressive modulus

Optical and Scanning Electron Microscopy

- Detail the surface microstructures of the layers
- Detail the surface of the flight prints damaged by over-adhesion to the build tray; it is hoped this will identify the root cause of seemingly increased adhesion of part to tray
- Inter-laminar regions will be investigated; flight and ground samples will be compared
- Defects or anomalies noted by the initial inspection will examined, as well as the fracture surfaces from the mechanical tests