



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

*2015 National Space & Missile Materials Symposium (NSMMS)  
Space Materials Experiments, Modeling & Simulation Session  
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# What is In-space Manufacturing?

- 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.

## TECHNOLOGIES

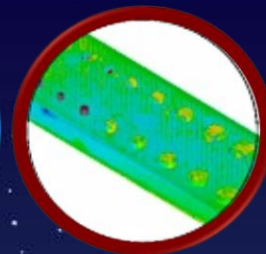


## SKILLS & PROCESSES

Design  
Optimize

Characterize

Certify



***On-demand Manufacturing Capability for  
Exploration Missions***



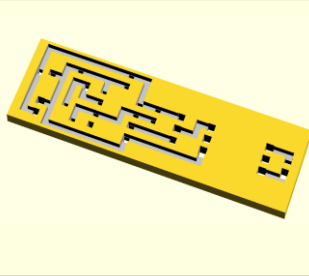
# More than just 3D Printing.... In-space Manufacturing Technology Development Areas

## RECYCLER



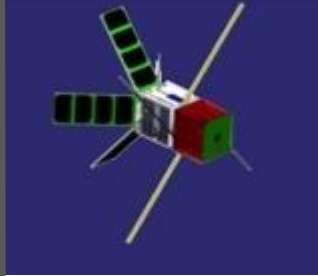
Recycling/Reclaiming 3D Printed Parts and/or packing materials into feedstock materials. This capability is crucial to sustainability in-space.

## PRINTED ELECTRONICS



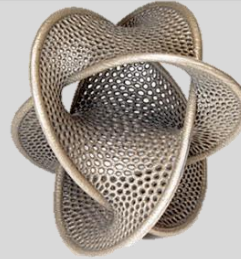
Leverage ground-based developments to enable in-space manufacturing of functional electronic components, sensors, and circuits. Image: *Courtesy of Dr. Jessica Koehne (NASA/ARC)*

## PRINTABLE SATELLITES



The combination of 3D Print coupled with Printable Electronics enables on-orbit capability to produce "on demand" satellites.

## MULTI MATERIAL 3D PRINTING



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*

## EXTERNAL STRUCTURES & REPAIRS



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

## ADDITIVE CONSTRUCTION



Contour Crafting Simulation Plan for Lunar Settlement Infrastructure Build-Up B. Khoshnevis, USC



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

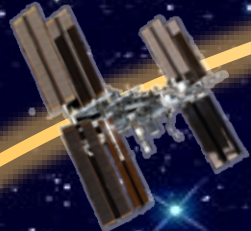
## PROVING GROUND

## EARTH INDEPENDENT

### 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

*International Space Station (ISS)*



*Commercial Cargo and Crew*

*Space Launch System*

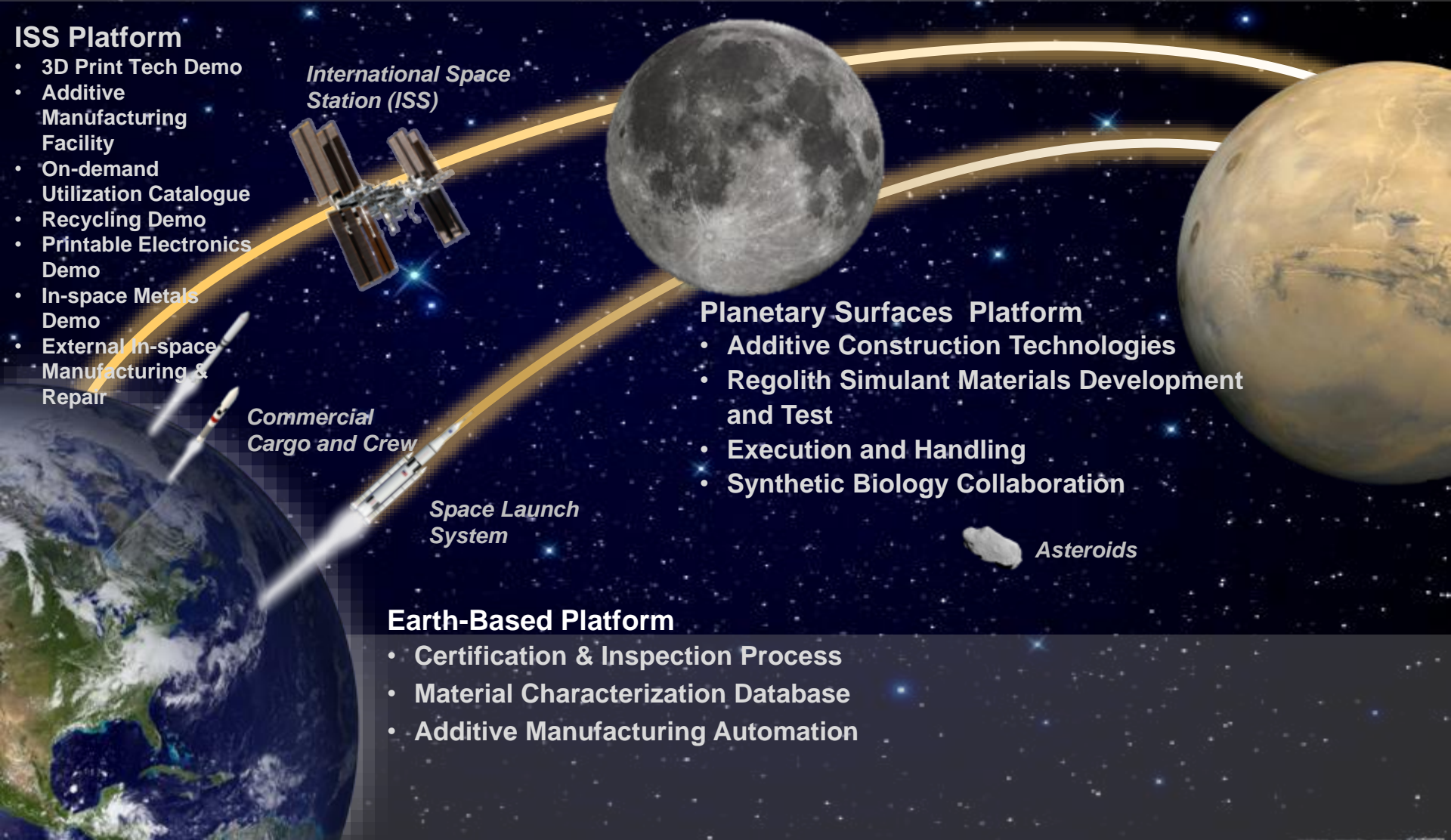
### Planetary Surfaces Platform

- Additive Construction Technologies
- Regolith Simulant Materials Development and Test
- Execution and Handling
- Synthetic Biology Collaboration

### Earth-Based Platform

- Certification & Inspection Process
- Material Characterization Database
- Additive Manufacturing Automation

*Asteroids*





# In-space Manufacturing Phased Technology Development Roadmap

Earth-based	International Space Station					Exploration			
	<p>3D Print Tech Demo</p>						<p>Lunar</p>	<p>Mars</p>	
Pre-2012	2014	2015	2016	2017	2018	2020-25	2025	2030 - 40	
<p><i>Ground &amp; Parabolic centric:</i></p> <ul style="list-style-type: none"> <li>Multiple FDM Zero-G parabolic flights</li> <li>Trade/System Studies for Metals</li> <li>Ground-based Printable Electronics/Spacecraft</li> <li>Verification &amp; Certification Processes under development</li> <li>Materials Database</li> <li>Cubesat Design &amp; Development</li> </ul>	<ul style="list-style-type: none"> <li><b>In-space:3D Print: First Plastic Printer on ISS Tech Demo</b></li> <li><b>NIAC Contour Crafting</b></li> <li><b>NIAC Printable Spacecraft</b></li> <li><b>Small Sat in a Day</b></li> <li><b>AF/NASA Space-based Additive NRC Study</b></li> <li><b>ISRU Phase II SBIRs</b></li> <li><b>Ionic Liquids</b></li> <li><b>Printable Electronics</b></li> </ul>	<ul style="list-style-type: none"> <li><b>3D Print Tech Demo</b></li> <li><b>Future Engineer Challenge</b></li> <li><b>Utilization Catalogue</b></li> <li><b>ISM Verification &amp; Cert Process Development</b></li> <li><b>Add. Mfctr. Facility (AMF)</b></li> <li><b>In-space Recycler SBIR</b></li> <li><b>In-space Material Database</b></li> <li><b>External In-space 3D Printing</b></li> <li><b>Autonomous Processes</b></li> <li><b>Additive In-space Repair</b></li> </ul>		<p><b>ISS:</b> <i>Utilization/Facility Focus</i></p> <ul style="list-style-type: none"> <li>In-space Recycler Demo</li> <li>Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals &amp; various plastics</li> <li>Printable Electronics Tech Demo</li> <li>Synthetic Biology Demo</li> <li>Metal Demo Options</li> </ul>	<p><i>Lunar, Lagrange FabLabs</i></p> <ul style="list-style-type: none"> <li>Initial Robotic/Remote Missions</li> <li>Provision some feedstock</li> <li>Evolve to utilizing in situ materials (natural resources, synthetic biology)</li> <li>Product: Ability to produce multiple spares, parts, tools, etc. "living off the land"</li> <li>Autonomous final milling to specification</li> </ul>	<p><i>Planetary Surfaces Points Fab</i></p> <ul style="list-style-type: none"> <li>Transport vehicle and sites would need Fab capability</li> <li>Additive Construction</li> </ul>	<p><i>Mars Multi-Material Fab Lab</i></p> <ul style="list-style-type: none"> <li>Utilize in situ resources for feedstock</li> <li>Build various items from multiple types of materials (metal, plastic, composite, ceramic, etc.)</li> <li>Product: Fab Lab providing self-sustainment at remote destination</li> </ul>		

**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!



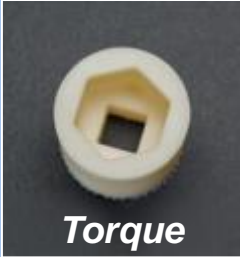
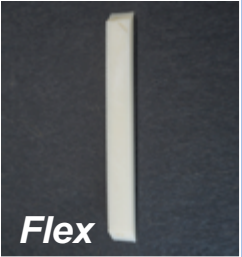
- The 3D Print Tech Demo launched on SpaceX-4 (9/21/14) and was installed in the Microgravity Science Glovebox on ISS
- To date, it has printed 21 parts in space (14 unique designs); the printer functioned nominally.
- First part “emailed” to Space: 3D Print of a ratchet tool demonstrated on-demand capability 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



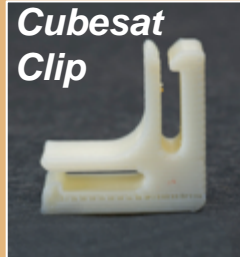
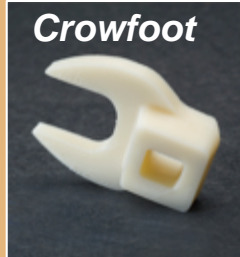


# 3D Printer International Space Station Technology Demonstration Initial Samples

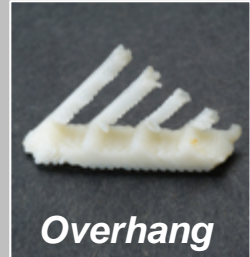
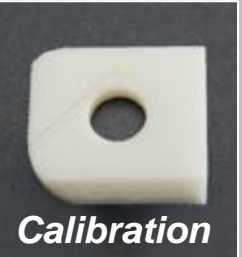
## Mechanical Property Test Articles



## Functional Tools



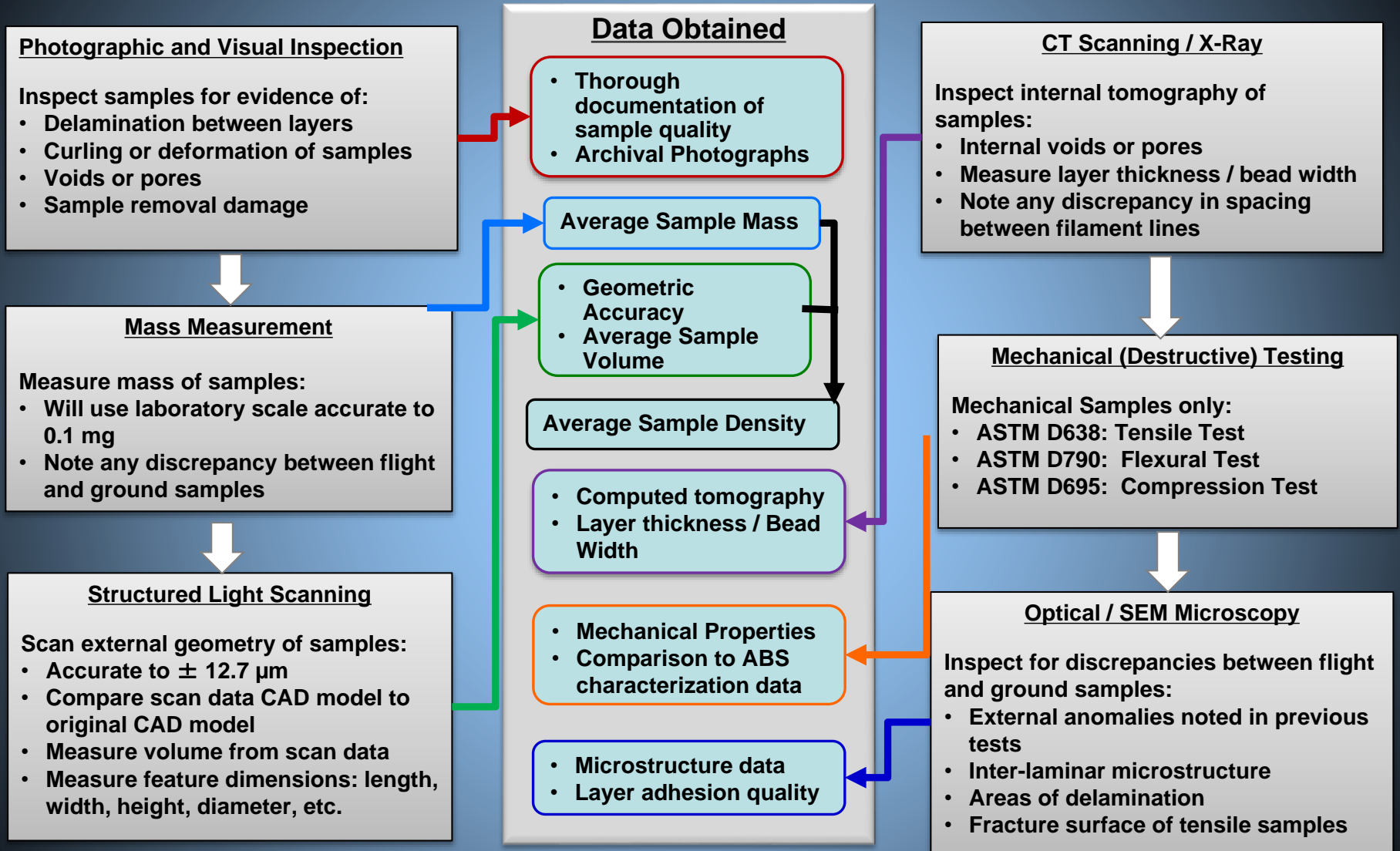
## Printer Performance Capability







# 3D Printing ISS Tech Demo Sample Testing Overview

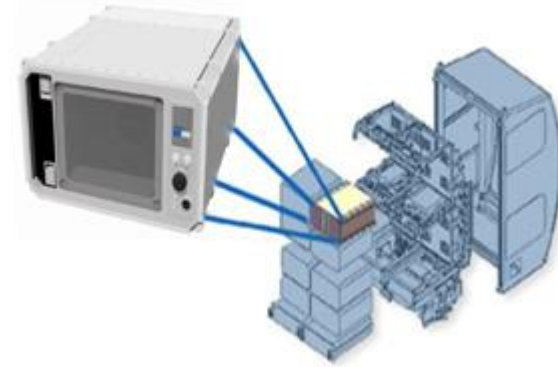






# In Space Manufacturing Elements

- ◆ **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



*Additive Manufacturing Facility (AMF)*

- ◆ **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.



*Tethers Unlimited SBIR to Develop ISS Recycler Tech Demo*

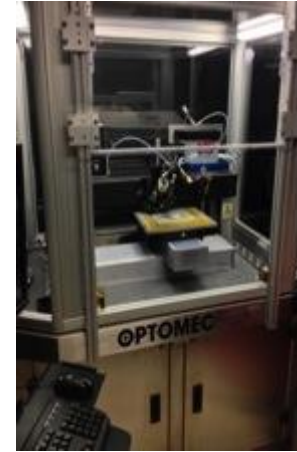
- ◆ **Launch Packaging Recycling Phase I SBIR (2015)**
  - Objective: Recycle launch packaging materials into feedstock to help close logistics loop



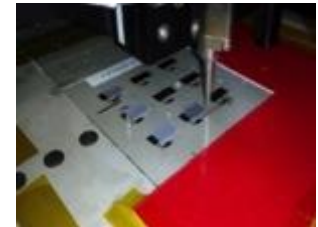
# In-Space Manufacturing Elements

## ◆ 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

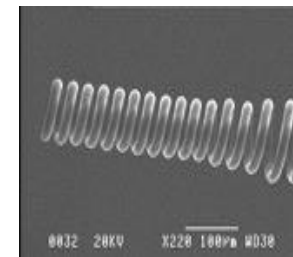


*Printable  
Electronic  
Technologies*



## ◆ 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



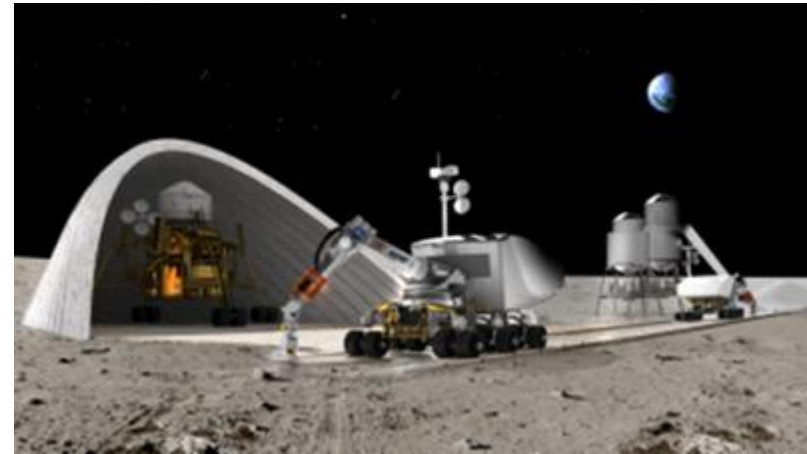
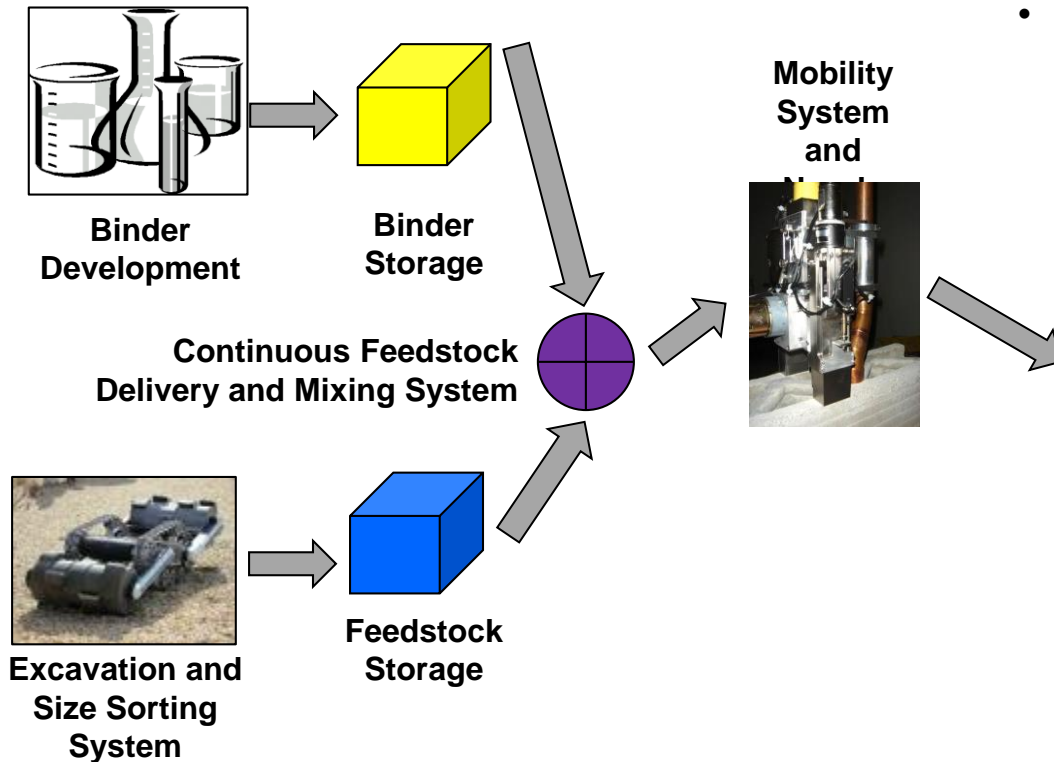
*Spring Created  
by Adaptive  
Manufacturing*



# 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)



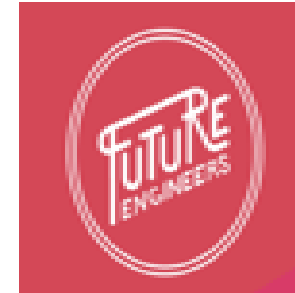




# Leveraging External Platforms for Technology and Skillset Development

**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



**Future Engineers  
Winning Part – Multi-purpose  
Maintenance Tool (MPMT)**

## **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



**ISS Handrail Clamp Assembly GrabCAD  
(left)  
& traditional (right)**





# 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**





# 3D Printing ISS Tech Demo Sample Testing Techniques

## 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.



*Visual Inspection of Flight and Ground Parts*

## 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



*Laboratory Scales utilized for Mass & Density Calculations*



# 3D Printing ISS Tech Demo Sample Testing Techniques

## 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



*ATOS Compact Scan Structured Light Scanner*

## 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



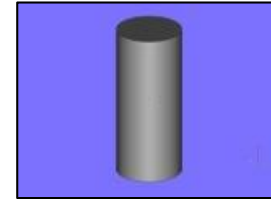
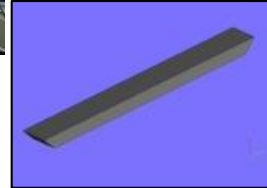
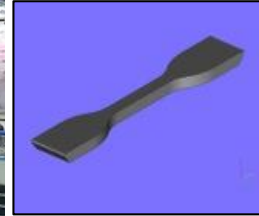
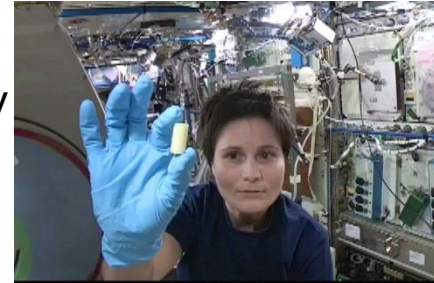
*Phoenix Nanome|x 160 CT Scan*



# 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



*Mechanical Samples for Destructive Testing*

## 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 be examined, as well as the fracture surfaces from the mechanical tests

*Leica M205-A  
Optical  
Microscope*



*Hitachi S-3700N  
Scanning  
Electron  
Microscope*