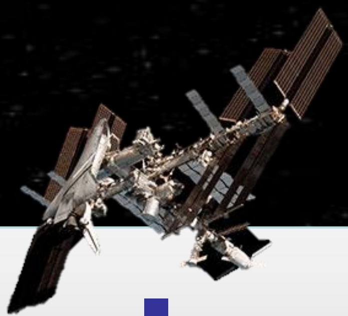

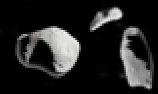


In-space Manufacturing: Pioneering a Sustainable Path to Mars

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Niki Werkheiser
NASA In-space Manufacturing Project Manager
Niki.Werkheiser@nasa.gov
256-544-8406

What is In-space Manufacturing (ISM)?

- ISM is responsible for developing the on-demand manufacturing capabilities that will be required for affordable, sustainable operations during Exploration Missions (in-transit and on-surface) to destinations such as Mars. This includes advancing the needed technologies, as well as establishing the skills & processes (such as certification and characterization) that will enable the technologies to go from novel to institutionalized.
- These technologies are evolving rapidly due to terrestrial markets. ISM is leveraging this commercial development to develop these capabilities within a realistic timeframe and budget.
- ISM utilizes the International Space Station (ISS) as a test-bed to adapt these technologies for microgravity operations and evolve the current operations mindset from earth-reliant to earth-independent.

TECHNOLOGIES

SKILLS & PROCESSES

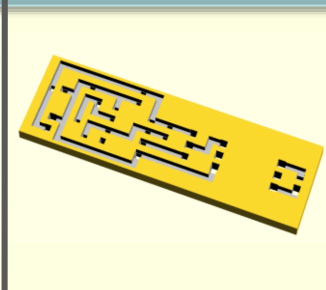
On-demand Manufacturing Capability for Exploration Missions

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

RECYCLER

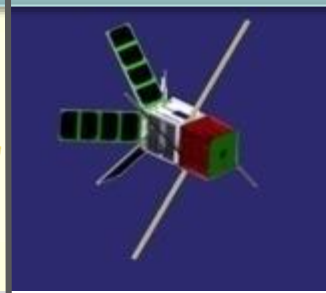
Recycling/Reclaiming 3D Printed Parts and/or packing materials into feedstock materials. This capability is crucial to sustainability in-space.

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

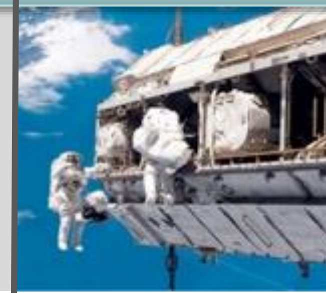


The combination of 3D Print coupled with Printable Electronics enables on-orbit capability to produce “on demand” satellites.

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*

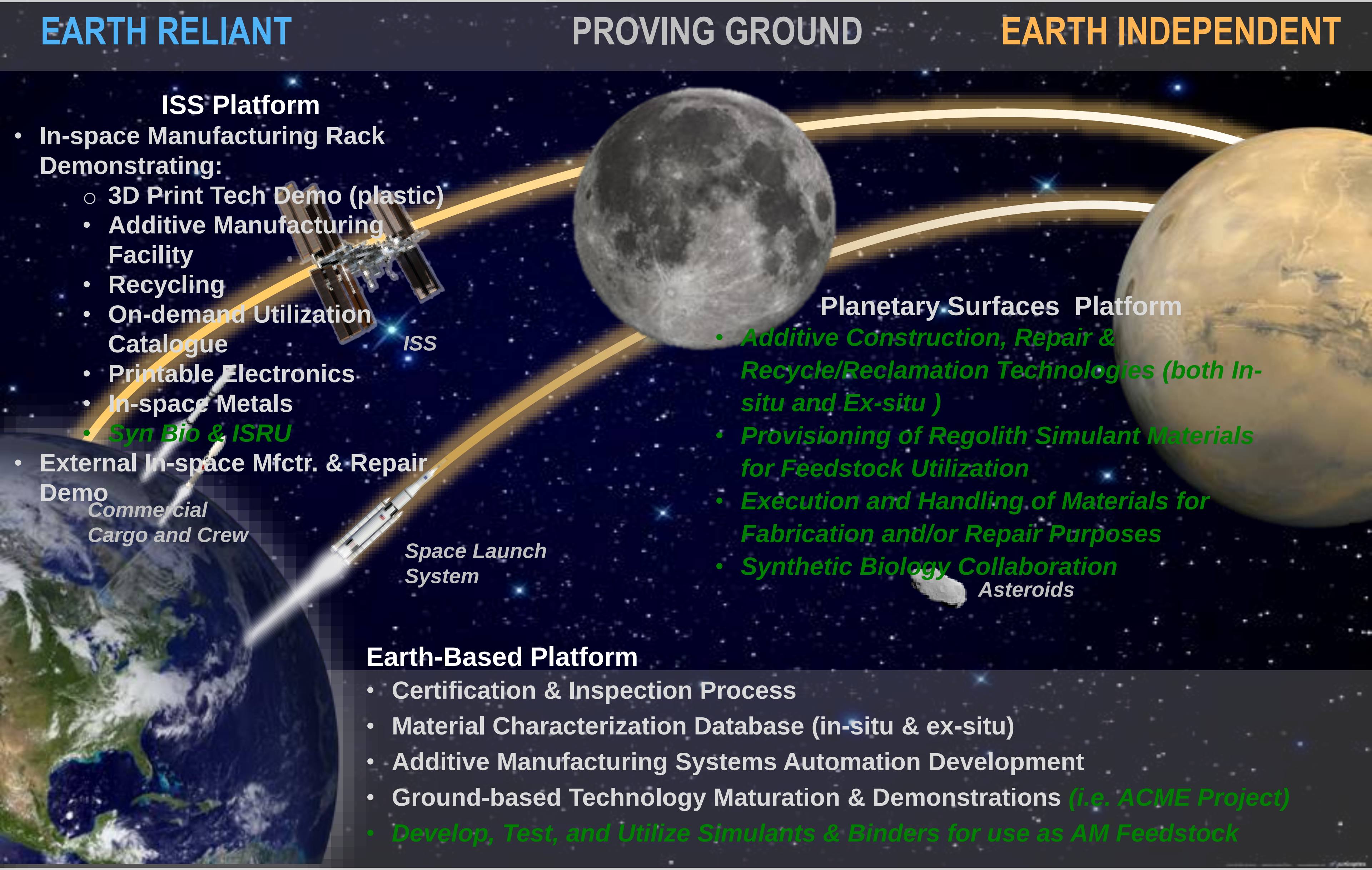
ADDITIVE CONSTRUCTION

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

ISM Technologies Under Development for Sustainable Exploration Missions

In-space Manufacturing (ISM) Path to Exploration



EARTH RELIANT | **PROVING GROUND** | **EARTH INDEPENDENT**

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

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*

Earth-Based Platform

- 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*

** Green text indicates ISM/ISRU collaboration*

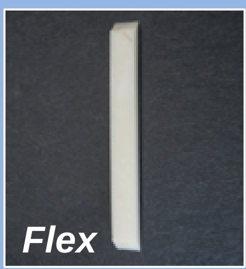
ISM Step #1: First 3D Printer in Space!

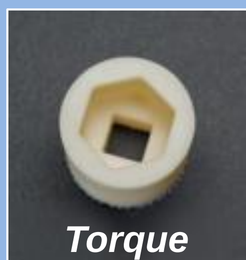
- The 3D Print Tech Demo launched on SpaceX-4 (9/21/14) and was installed in the Microgravity Science Glovebox on ISS. The printer was designed and built by Made in Space, Inc. under NASA Small Business Innovation Research contract.
- To date, 21 parts have been printed in space (13 unique designs); 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. Test & Analyses is underway with results to be openly published December 2015

Images courtesy of NASA

3D Printer International Space Station (ISS) Technology Demonstration Initial Samples

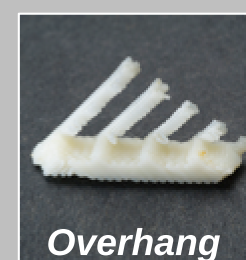
Mechanical Property Test Articles





Functional Tools

Printer Performance Capability



In-Space Manufacturing Tasks (cont.)

Material Characterization Database Development

- Objective: Characterize microgravity effects on printed parts and resulting mechanical properties Develop design-level database for microgravity applications.
- Phase II operations for additional on-orbit prints of engineering test articles are being planned with ISS.
- All datasets will be available through the MSFC Materials and Processes Technical Information System (MAPTIS)

On-demand ISM Utilization Catalogue Development

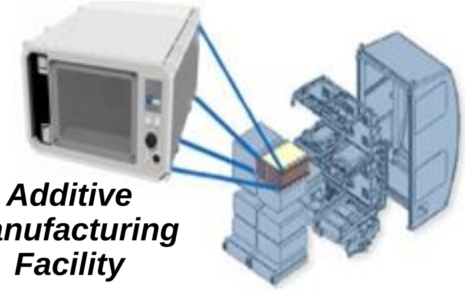
- Objective: Develop a catalogue of approved parts for in-space manufacturing and utilization.
- Joint effort between MSFC AM M&P experts, space system designers, and JSC ISS Crew Tools Office
- First parts are in design and ground test process.

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
- Anticipated launch late CY2015

Compression Testing of Mechanical Flight Sample 7/21/15

ISM Printed Part for Ground Feasibility Testing

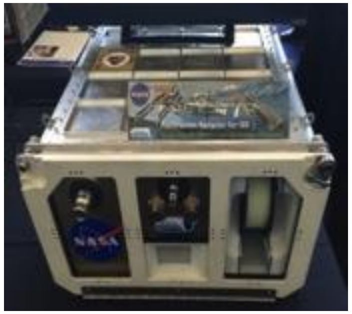


Additive Manufacturing Facility

In-Space Manufacturing Tasks (cont.)

In-space Recycler ISS Tech 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 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 (3 proposals selected for award).

In-space Printable Electronics Technology Development

- Currently building Additive RFID Antennae and RFID Tags for AES Logistics Reduction Team (AES JSC).
- Patented dielectric and conductive inks developed at NASA
- Roadmap developed targeting ISS technology demonstration.

Printable Electronics

ACME - Additive Construction by Mobile Emplacement (STMD GCD)

- 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.

Concept of ATHLETE-based autonomous additive construction system on extraterrestrial surface

In-space Manufacturing STEM & Outreach: 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
- 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 Initiative 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
- **Ultimately, ISM will utilize an ISS US Lab rack to develop an integrated “Fab Lab” with the capability to manufacture multi-material parts with embedded electronics, inspect the parts for quality, and recycle multiple materials into useable feedstock that will serve Exploration Missions.**

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

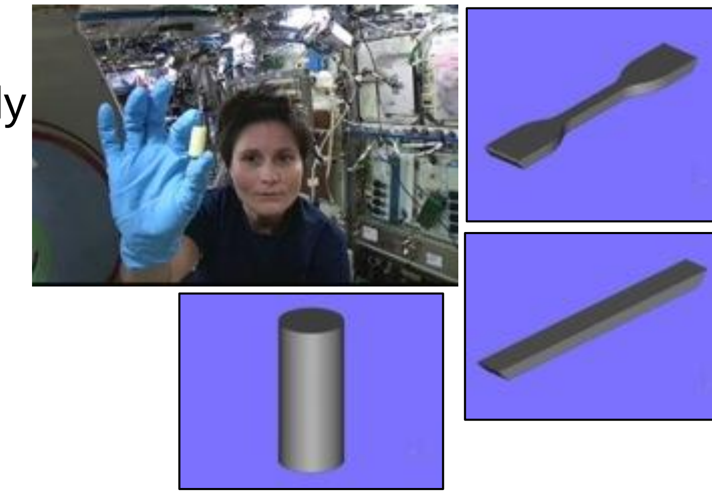
- Phoenix Nanome|x 160
- X-ray scans
- Provides 2D and 3D models of the internal structures that could affect mechanical properties
  - Internal voids
  - De-lamination of the ABS layers
- Resolution as low as 8-10 microns is possible

Phoenix Nanomelx 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 examined, as well as the fracture surfaces from the mechanical tests

Leica M205-A Optical Microscope

Hitachi S-3700N Scanning Electron Microscope