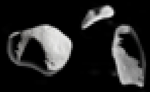


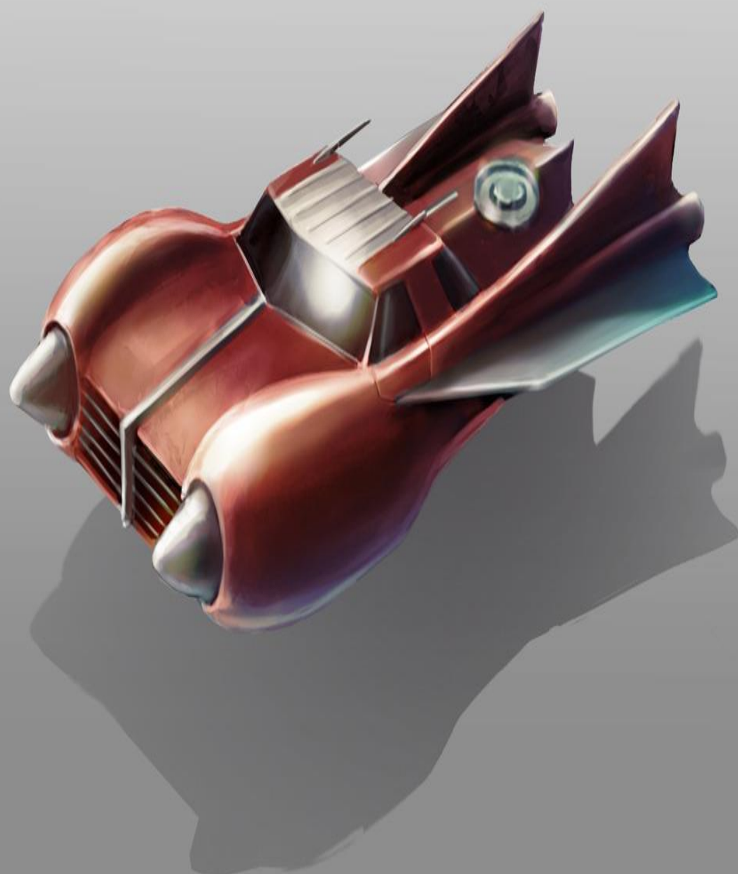



NASA's In-space Manufacturing (ISM) Overview

Intrepid Sea, Air and Space Museum
July 2016

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

What I thought I would get….

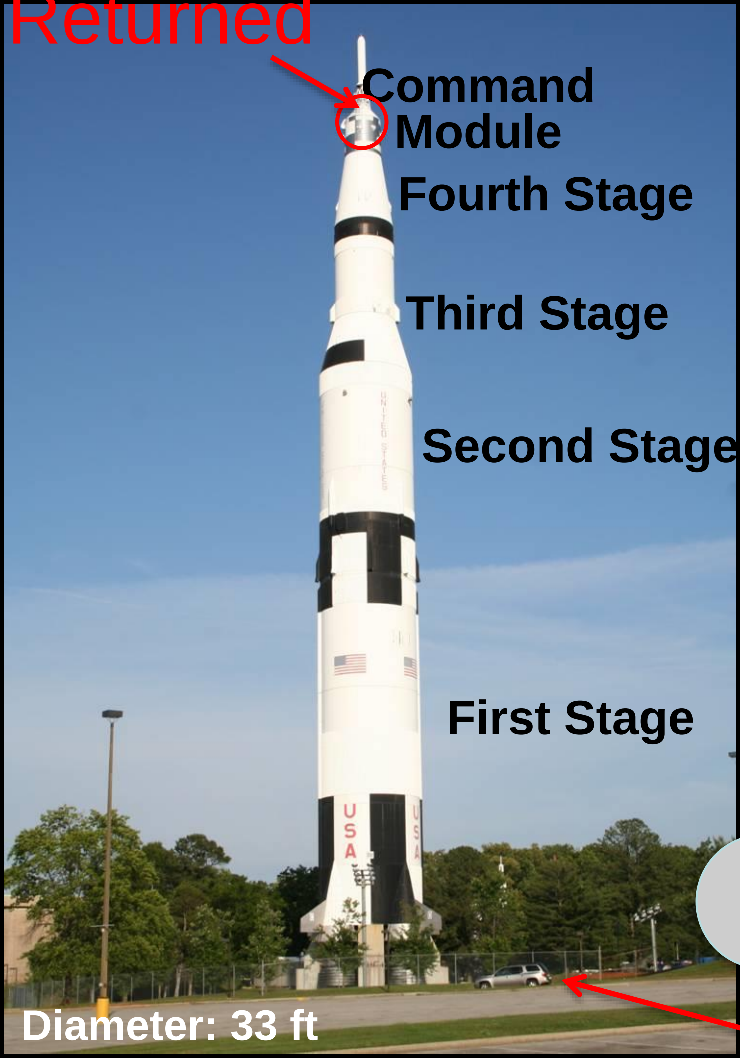


What I actually got

Images courtesy of Creative Commons

Images courtesy of Creative Commons

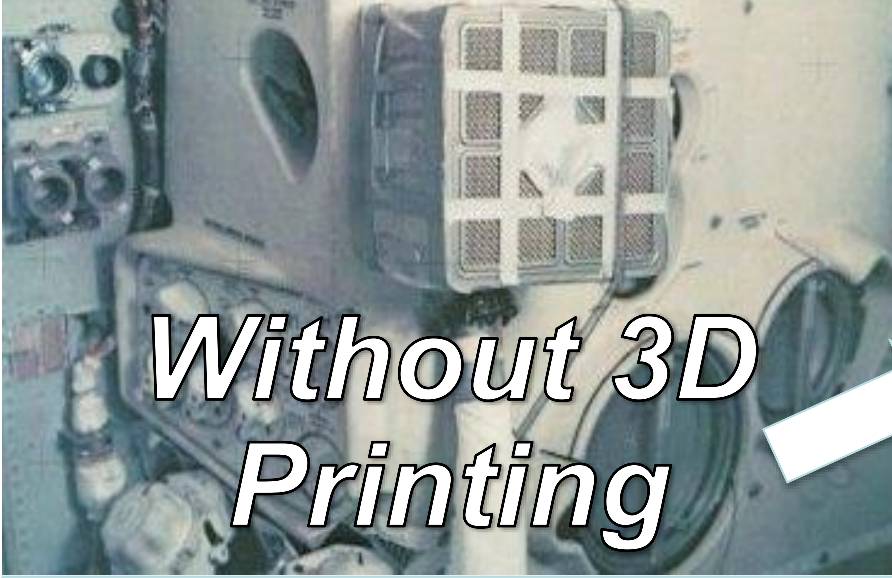
Saturn V – MASSive Perspective…

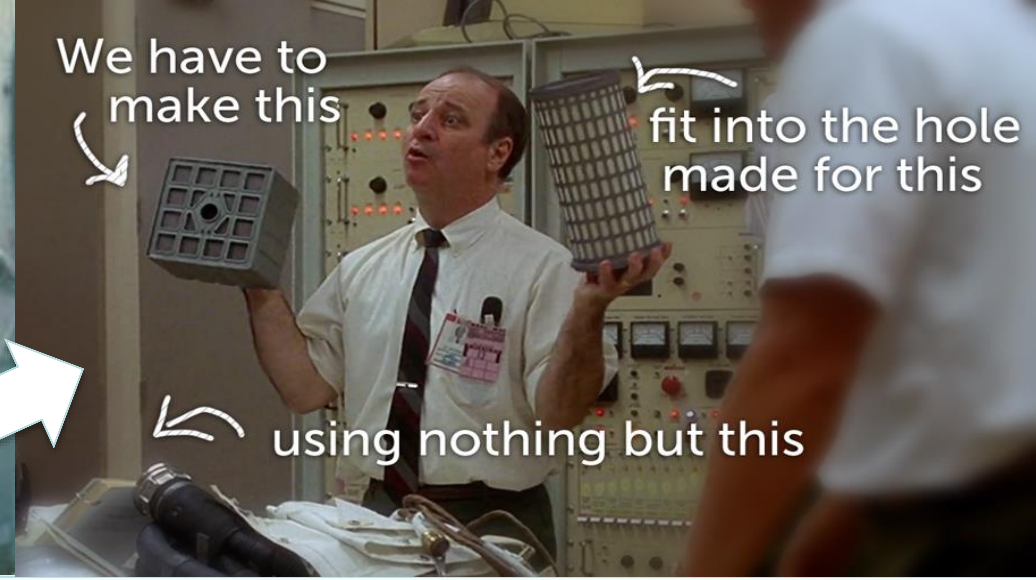


SATURN V

- 6.6M lbs sat on the launch pad.
- But only 12.8K lbs came back.
- This is equivalent to taking a road trip in a car and coming back with just the left front wheel's lug nuts!

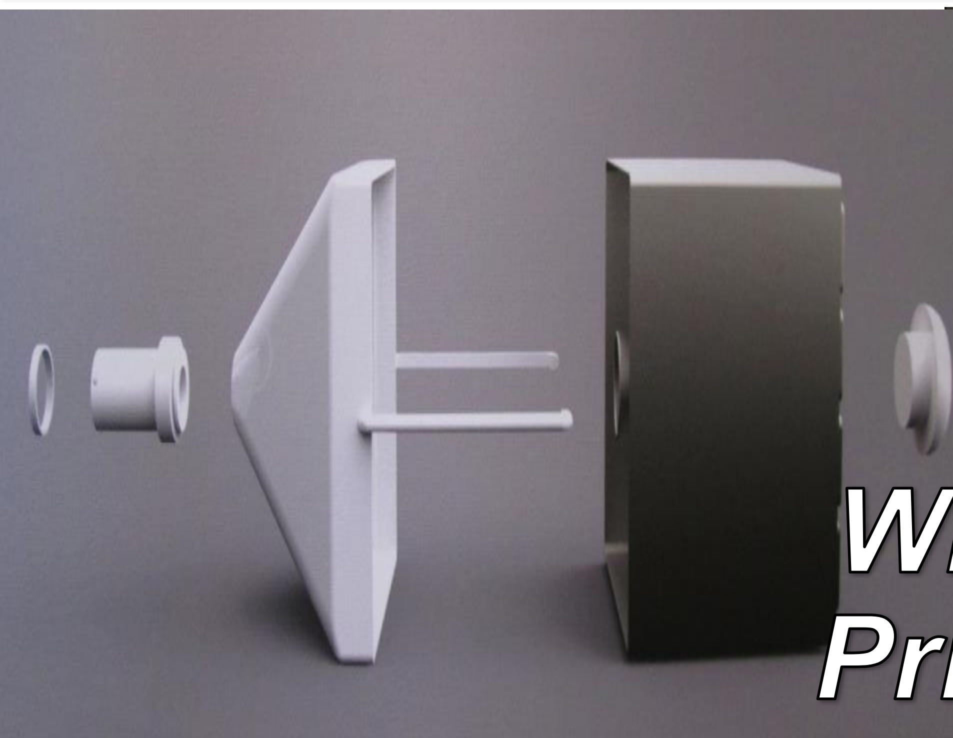
Image courtesy of NASA

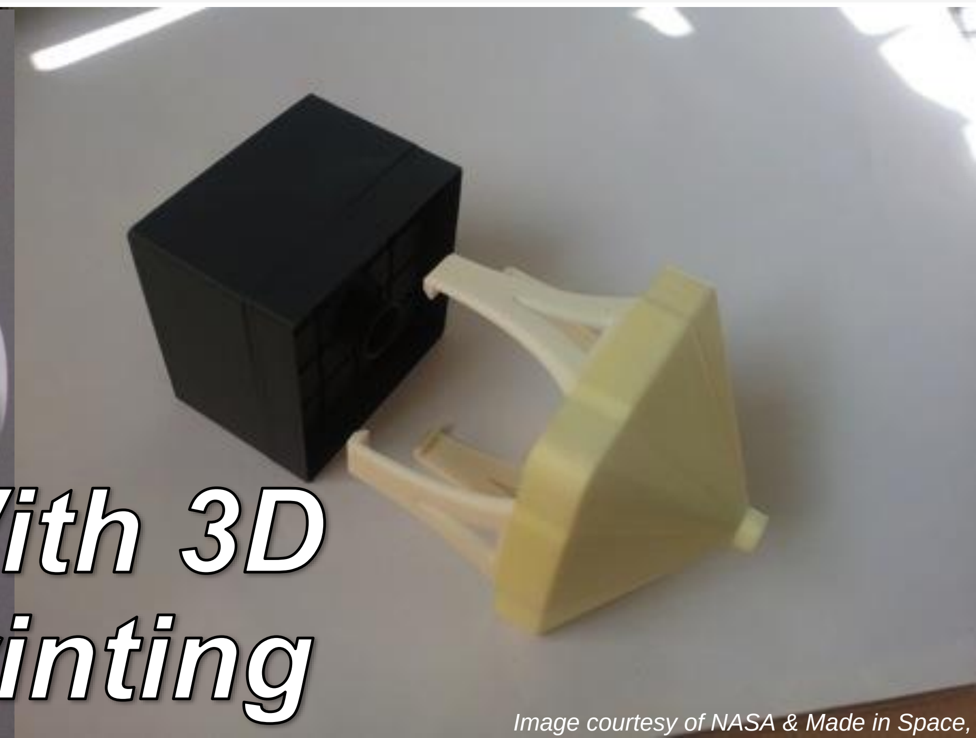




Without 3D Printing

Square peg in Round Hole? No problem!





With 3D Printing

Image courtesy of NASA & Made in Space,

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

Design
Optimize

Characterize

Certify

\=

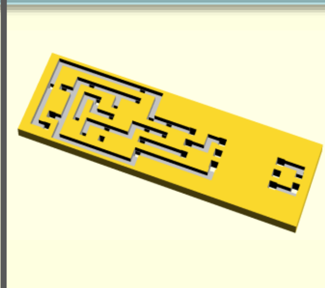
On-demand Manufacturing Capability for Exploration Missions

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

RECYCLER

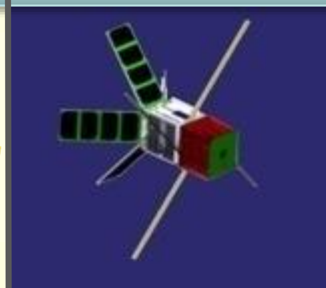
Recycling/Reclaiming 3D Printed Parts and/or packing materials into feedstock materials. This capability is crucial to sustainability in-space.

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

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

ISS

Commercial Cargo and Crew

Space Launch System

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*

Asteroids

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*

** Green text indicates ISM/ISRU collaboration*

In-space Manufacturing Phased Technology Development Roadmap

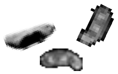
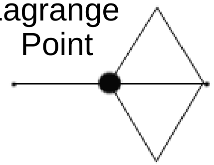
Earth-based	Demos: Ground & ISS	Exploration




Plastic Printing Demo
Mat. Char.
3D Print Tech Demo

Recycler
Utilization Testing
AMF

Metal Printing
Fab Lab
Self-repair/ replicate
Digital Mfctr.
External In-space Mfctr

Asteroids

Lagrange Point

Lunar

Mars


Pre-2012

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

2014

- **In-space:3D Print: First Plastic Printer on ISS Tech Demo**
- **NIAC Contour Crafting**
- **NIAC Printable Spacecraft**
- **Small Sat in a Day**
- **AF/NASA Space-based Additive NRC Study**
- **ISRU Phase II SBIRs**
- **Ionic Liquids**
- **Printable Electronics**

2015 - 2017

- ***3D Print Demo***
- ***Future Engineer Challenge***
- ***Utilization Catalogue***
- ***ISM Cert Process***
- ***Add. Mfctr. Facility (AMF)***
- ***In-space Recycler SBIR***
- ***In-space Material Database***
- ***External In-space 3D Printing***
- ***Autonomous Processes***
- ***ACME Simulant Dev. & Test for Feedstock; Ground Demo***

2018 - 2024

ISS: "Fab Lab" *Utilization/Facility Focus*
- In-space Recycler Demo
- Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics
- Printable Electronics Tech Demo
- Synthetic Biology Demo
- Metal Demo Options
- ***ACME Ground Demos***

2025-35

Lunar, Lagrange FabLabs
- Initial Robotic/Remote Missions
- ***Provision feedstock***
- ***Evolve to utilizing in situ materials (natural resources, synthetic biology)***
- ***Product: Ability to produce, repair, and recycle parts & structures on demand; i.e.. "living off the land"***
- Autonomous final milling to

Planetary Surfaces Points Fab
- Transport vehicle and sites would need Fab capability
- ***Additive Construction & Repair of large structures***

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.

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

**** Green text indicates ISM/ISRU collaboration***

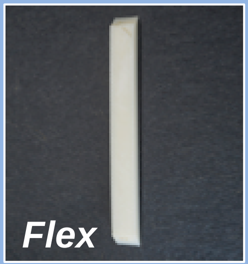
ISM Step #1: First 3D Printer in Space!

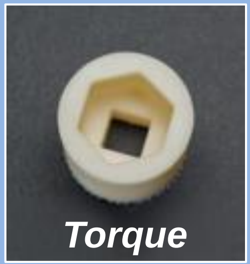
- The 3D Print Tech Demo launched on SpaceX-4 (9/21/14) and was installed in the Microgravity Science Glovebox on ISS. The printer was designed and built by Made in Space, Inc. under NASA Small Business Innovation Research contract.
- To date, 21 parts have been printed in space (13 unique designs); 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 and underwent test & analyses to compare to ground control samples. Results to be published in Spring 2016.

Images courtesy of NASA

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

Mechanical Property Test Articles





Functional Tools

Printer Performance Capability

The Capability to Manufacture Items in Space is a Critical Enabler for the Path to Mars

NASA Article Published on 9/15/15 Ranks "Understanding how to manufacture items in space" as the #1 was that ISS is helping us on our journey to Mars!!!

1. Understanding how to manufacture items in space (3-D Printing)

"As crews head to Mars, there may be items that are unanticipated or that break during the mission. Having the ability to manufacture new objects on demand while in space will greatly benefit missions. The 3-D Printing in Zero-G Technology Demonstration validates that a 3-D printer works normally in space. This is the first step towards establishing an on-demand machine shop in space, which is a critical enabling component for crewed missions to deep space."

NASA In-Space Manufacturing (ISM) Activities

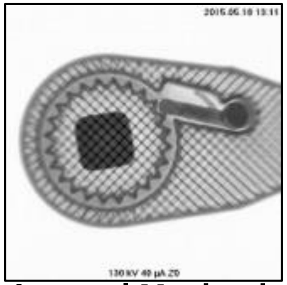
3D Printer International Space Station Technology Demonstration

- The first flight samples were received at MSFC on 3/17/15.
- All specimens have undergone photographic inspection, structured light scanning, CT, and 2D X-ray evaluation. Mechanical test coupons from the flight experiment have completed destructive testing. All testing has been completed.
- Data Analyses TIM to review and “vet” results, hypotheses, and next-steps.
- Full results for these initial parts to be published externally in February 2016.
- Next operations for 3D Print Tech Demo to resume in late 2015/early 2016 and will include additional statistical samples, ISS Oxygen Generator System (OGS) Airflow Adaptor, & STEM part(s).

AMF - Additive Manufacturing Facility - Made In Space

- ISS Commercial printer owned by Made in Space, Inc. with anticipated launch on Space X 8 (early CY 2016)
- Incorporates lessons learned from 3D Printer ISS Tech Demo
- NASA has SBIR Ph. II Enhancement for initial AMF prints and developing IDIQ for additional on-orbit ops.
- Expanded materials capabilities: ABS, ULTEM, PEEK

3D Printer Installed in MSG on ISS



Ratchet, Internal Mechanism (flight)

Compression Coupon (flight)

Additive Manufacturing Facility

NASA In-Space Manufacturing Activities (cont.)

Material Characterization Database Development

- Objective: Characterize microgravity effects on printed parts and resulting mechanical properties; Develop design-level database for microgravity applications for incorporation into the MSFC Materials and Processes Technical Information System (MAPTIS)

On-demand ISM Utilization Catalogue Development

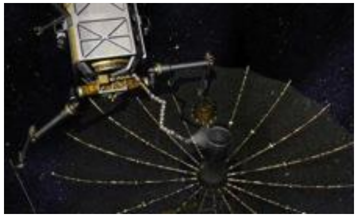
- Objective: Develop a catalogue of pre-approved parts for in-space manufacturing and utilization. This includes establishing the safety and certification processes to institutionalize this capability.
- ISM Design & AM experts have been working with ISS users, and NASA Exploration System Designers.

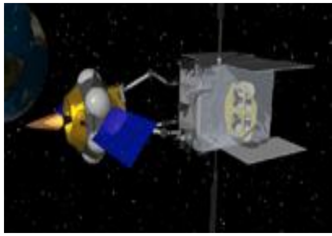
External In-space Manufacturing (EISM)

- Objective: External Additive Manufacturing shows great promise for Exploration missions. Targeted Areas of Interest include autonomous, on-demand manufacturing technologies which work in external space environments
- NASA and Defense Advanced Research Projects Agency (DARPA) are planning the release of an EISM Broad Agency Announcement (BAA) in early 2016 to explore the technologies available today that could be utilized for a future in-space demonstration.

Compression Testing of Mechanical Flight Sample 7/21/15

ISM Printed OGS AAA Flow Adaptor for Ground Testing

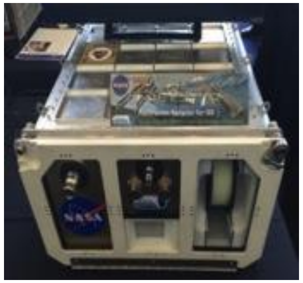




NASA In-Space Manufacturing Activities (cont.)

In-space Recycler ISS Tech Demonstration Development

- 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

Common-use Packaging & 3D Printing Materials

- Objective: Identify common-use materials for packaging i.e. foam, bubble wrap, plastic bags, etc.) and 3D printing feedstock.
- Three companies selected for Ph. 1 award in 2015 including TechShot, Cornerstone Research, & Tethers Unlimited, Inc.

Common Use Materials for 3D Printing & Packaging

Multi-material "Fab Lab" with Printable Electronic Capability

- Objective: Develop capability for on-demand, in-space manufacturing for multiple materials, electronics, inspection, automated part removal, etc.
- Currently working to "print" RFID Antennae and Tags for NASA Logistics Reduction Team.
- Utilizing patented dielectric and conductive inks developed at NASA

Printable Electronics

Additive Construction by Mobile Emplacement (ACME)

- Objective: Develop a capability to print custom-designed expeditionary structures on-demand, in the field, using locally available materials (lunar and martian regolith for NASA, concrete for terrestrial applications).
- Joint initiative between NASA STMD and the U. S. Army Corps. of Engineers.
- Technology Development and Curved Wall demonstration in FY15 and FY16 with full-scale demonstration in FY17.

Additive construction Concept on extraterrestrial surface

In-space Manufacturing STEM & Outreach: Leveraging External Platforms for Technology and Skillset Development

Future Engineers STEM Program: National K-12 challenges focused on designing 3D printed parts; made possible thru a Space Act Agreement (SAA) between NASA and American Society of Mechanical Engineers (ASME).

- Website includes tutorials on how to design parts for 3D printing, links to free design tools aimed at various ages, videos on living & working in space, and design galleries with all previous student entries. (**www.futureengineers.org**)
- Motto is, “Engineering is a state of mind, not a degree” with the goal to instill confidence in students by equipping them with the skills to make whatever they can imagine.
- Challenges have two age divisions: Junior (K-12) and Teen (13-18)
- To date, two national K-12 Challenges have been conducted.
  - 1st Challenge was to design a tool that astronauts could use on ISS. Teen winner’s part will be printed on ISS later this year.
  - 2nd Challenge was to design any sort of space container (science samples, food, etc.) was announced on 5/12/15 and closes 8/2/15.
  - The next two challenges are under development with the first expected to be announced in February 2016.

NASA’s Center for Excellence for Collaborative Innovation:

- GrabCAD Handrail Clamp Assembly Challenge: Developed challenge to design a 3D Printed version of the Handrail Clamp Assembly commonly used on ISS using materials and dimensions of on-orbit 3D Printer.
- Received nearly 500 entries in three weeks with five winners were selected; NASA maintained all IP rights. Challenge was conducted for under $3K on NASA credit card purchase order.

Future Engineers Crew Tool Winner: Multi-purpose Maintenance Tool (MPMT)

Future Engineer Winners

ISS Handrail Clamp Assembly GrabCAD (top) & traditional (bottom)

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.**