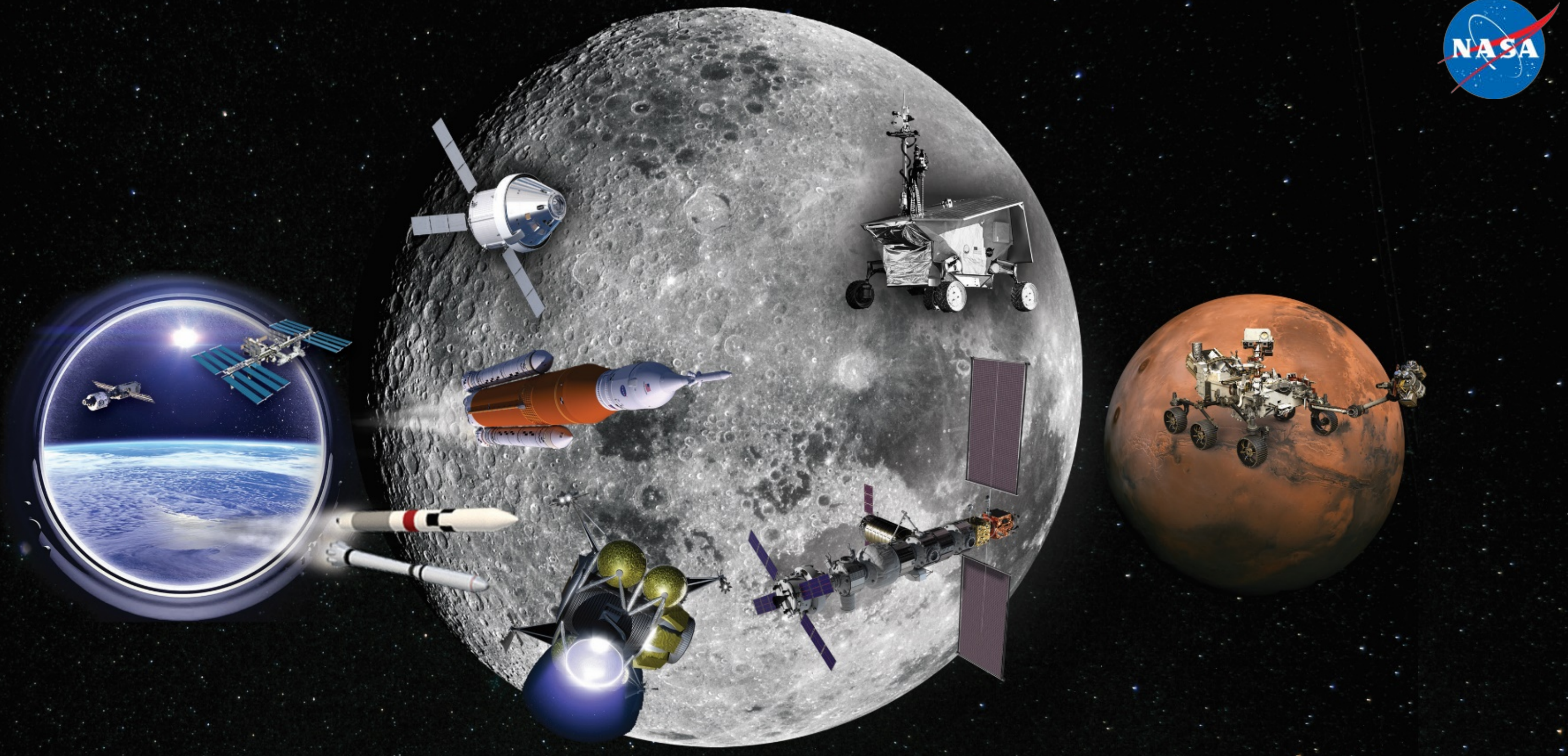

AM in Space: ISM and IRMA NASA Initiatives

R.G. Clinton Jr., PhD
Associate Director
Science and Technology Office
NASA Marshall Space Flight Center

Made For Space
May 2 - 3, 2019
Manufacturing Technology Centre
Coventry UK

Acknowledgements

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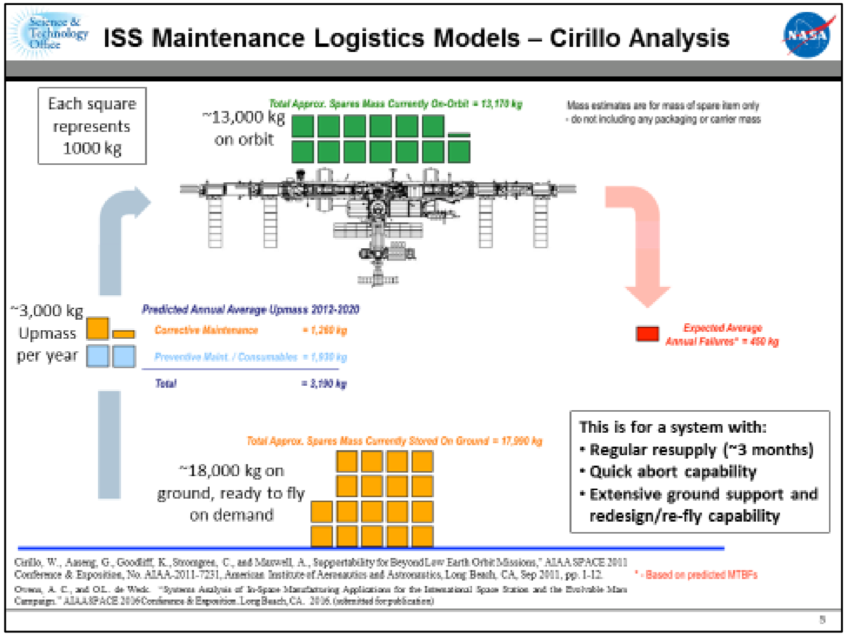
- Trey Clinton: Made In Space, AMF
- Paul Shestople: Made In Space, Archinaut
- John Lymer: Space Systems Loral, Dragonfly

Agenda

1. **Why In Space Manufacturing (ISM)**
2. **NASA’s In Space Manufacturing Initiative**
   A. ISM Path to Exploration – Key Thrust Areas
3. **NASA’s In Space Robotic Manufacturing and Assembly (IRMA) Technology Demonstration Missions**
   A. Archinaut
   B. Dragonfly
4. **3D Printed Habitat Challenge**
5. **Summary**

The Case for ISM: Why we need this capability



ISS Maintenance Logistics Models – Cirillo Analysis

Each square represents 1000 kg

~13,000 kg on orbit

Total Approx. Spares Mass Currently On-Orbit = 13,170 kg

Mass estimates are for mass of spare item only - do not including any packaging or carrier mass

~3,000 kg Upmass per year

Predicted Annual Average Upmass 2012-2020

Corrective Maintenance	= 1,260 kg
Preventive Maint. / Consumables	= 1,930 kg
Total	= 3,190 kg

Expected Average Annual Failures* = 450 kg

Total Approx. Spares Mass Currently Stored On Ground = 17,990 kg

~18,000 kg on ground, ready to fly on demand

This is for a system with:
- Regular resupply (~3 months)
- Quick abort capability
- Extensive ground support and redesign/re-fly capability

Cirillo, W., Aaseng, G., Goodliff, K., Stromgren, C., and Maxwell, A., Supportability for Beyond Low Earth Orbit Missions," AIAA SPACE 2011 Conference & Exposition, No. AIAA-2011-7231, American Institute of Aeronautics and Astronautics, Long Beach, CA, Sep 2011, pp. 1-12.

Owens, A. C., and O.L. de Weck. "Systems Analysis of In-Space Manufacturing Applications for the International Space Station and the Evolvable Mars Campaign." AIAA SPACE 2016 Conference & Exposition. Long Beach, CA. 2016. (submitted for publication)

* - Based on predicted MTBFs

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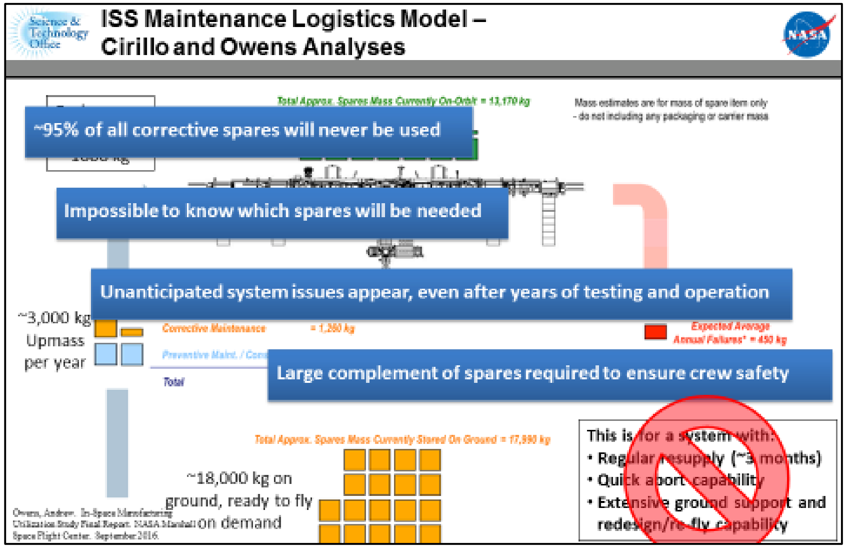

ISS Maintenance Logistics Model – Cirillo and Owens Analyses

~95% of all corrective spares will never be used

Impossible to know which spares will be needed

Unanticipated system issues appear, even after years of testing and operation

Large complement of spares required to ensure crew safety

Total Approx. Spares Mass Currently On-Orbit = 13,170 kg

Mass estimates are for mass of spare item only - do not including any packaging or carrier mass

~3,000 kg Upmass per year

Corrective Maintenance = 1,260 kg

Preventive Maint. / Cons

Total

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This is for a system with:
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Owens, Andrew. In-Space Manufacturing Utilization Study Final Report. NASA Marshall Space Flight Center. September 2016.

Current maintenance logistics strategy ***will not be effective*** for deep space exploration missions

Benefits from Incorporation of ISM

ISM offers the potential to:

- Significantly reduce maintenance logistics mass requirements
- Enable the use of recycled materials and in-situ resources for more dramatic reductions in mass requirements
- Enable flexibility, giving systems a broad capability to adapt to unanticipated circumstances
- Mitigate risks that are not covered by current approaches to maintainability

ISM Path to Exploration - Key Thrust Areas

FabLab


MSFC

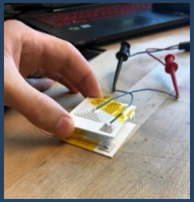
First Plastics Printer


Made In Space

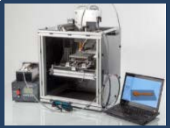
2nd Generation Plastics Printer


Made In Space

Printed Electronics

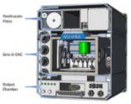

MSFC

Recycler/ Printer


Techshot


Made In Space


UltraTech


Tethers Unlimited

Common Use Recyclable Materials


Cornerstone Research Group


Tethers Unlimited

Health & Medical


Tethers Unlimited

The First Step: The 3D Printing in Zero G Technology Demonstration Mission (Phase 1)

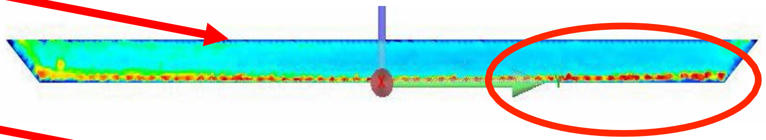
The 3DP in Zero G Tech Demo delivered the first 3D printer to ISS and investigated the effects of consistent microgravity on fused deposition modeling

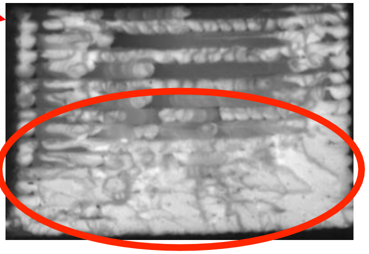
Phase I Prints (Nov-Dec 2014): mechanical property test articles; range coupons; and functional tools

Printer inside Microgravity Science Glovebox (MSG)

Key Observations:

- Tensile and Flexure: Flight specimens stronger and stiffer than ground specimens
- Compression: Flight specimens are weaker than ground specimens
- Density: Flight specimens slightly more dense than ground specimens; compression specimens show opposite trend
- Structured Light Scanning: Protrusions along bottom edges (more pronounced for flight prints)
- Microscopy: Greater Densification of Bottom Layers (flight tensile and flexure)



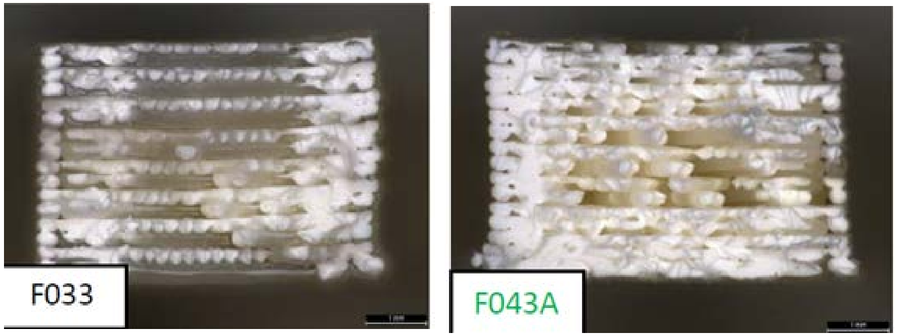


Conclusions

- Z-Calibration distance variation suspected to be primary factor driving differences between flight and ground samples
- Potential influence of feedstock aging are being evaluated further

Key Results: The 3D Printing in Zero G Technology Demonstration Mission (Phase II)

- Phase II Prints:
  - 25 specimens (tensile + compression) built at an optimal extruder standoff distance.
  - 9 specimens printed with *intentionally decreased extruder standoff distance* to mimic Phase I flight process conditions
- Key findings:
  - No substantive chemical changes in feedstock
  - No evidence of microgravity effects noted in SEM, SLS, CT analysis. Some internal structure variation between builds and with changes in process settings (primarily compression)
  - All prints to date with 3DP appear to be broadly part of the same family of data
  - Phase I data variations appear traceable to:
    - ***Differences in manufacturing process settings (extruder standoff distance)***
    - Data scatter - characteristic of many additively manufactured materials and processes.
    - Printer variability

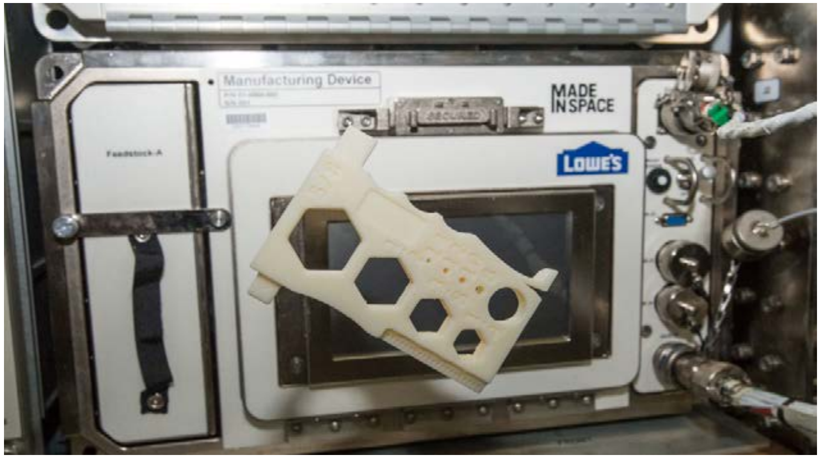


Cross-section of PII tensile specimen manufactured at optimal extruder setting (left) compared with specimen manufactured at a reduced extruder standoff distance (right). Right image has a cross-section characteristic with PI flight prints.

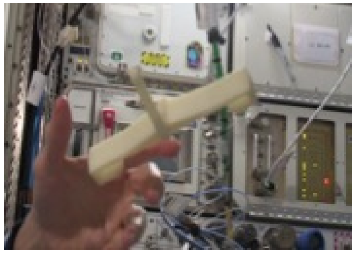
Specimen set	Average ultimate tensile strength (KSI)	Coefficient of variation
Phase II	3.68	6.71
Phase II optimal	3.63	6.61
Phase II off-suboptimal	3.93	0.07
Phase I ground	3.46	1.71
Phase I flight	4.04	5.95

Overall, we cannot attribute any of the observations to microgravity effects.

ISM Utilization and the Additive Manufacturing Facility: Material Characterization and Example Functional Parts



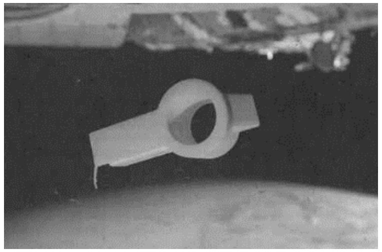
AMF on ISS with printed multi-purpose tool floating in front (photos courtesy of MIS)



SPHERES Tow Hitch

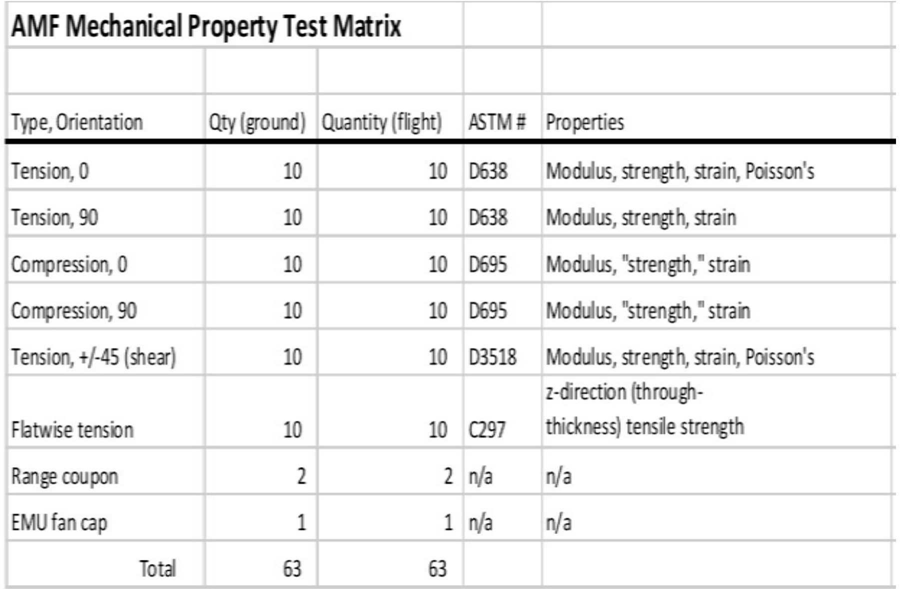
Antenna Feed Horn

REM Shield Enclosure



OGS AAA Adapter

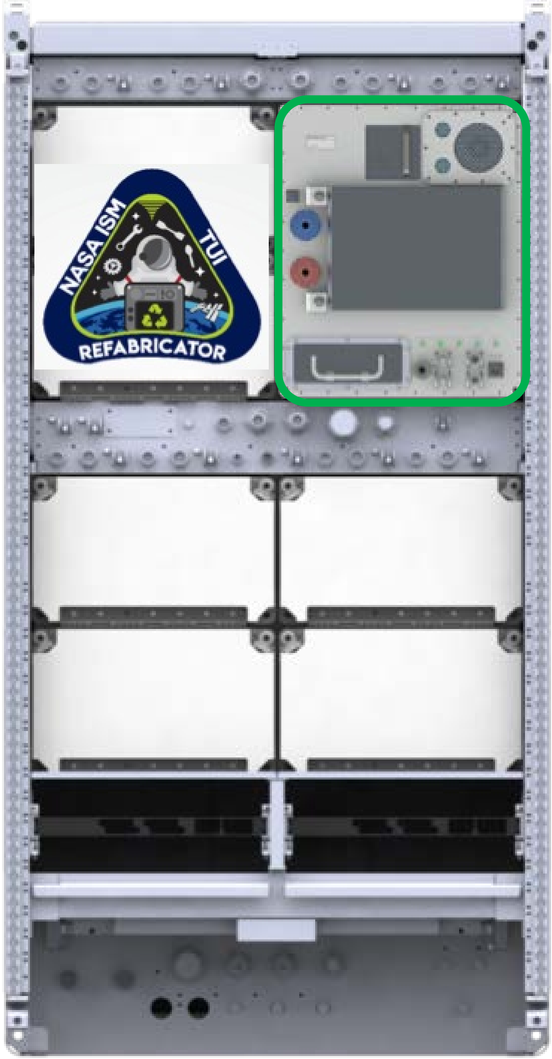
- Additive Manufacturing Facility (AMF), the second generation printer, is a commercial, multi-user facility developed by Made in Space, Inc.
- Upgrades beyond 3DP include:
  a) Print with multiple material (ABS, ULTEM 9085, and HDPE
  b) Integral cameras/sensors for automated monitoring
  c) Maintenance procedures reduce crew time
  d) Leveling and calibration with on-board systems
- Materials characterization task developing baseline mechanical properties on ABS (test matrix below)



AMF Mechanical Property Test Matrix

Type, Orientation	Qty (ground)	Quantity (flight)	ASTM #	Properties
Tension, 0	10	10	D638	Modulus, strength, strain, Poisson's
Tension, 90	10	10	D638	Modulus, strength, strain
Compression, 0	10	10	D695	Modulus, "strength," strain
Compression, 90	10	10	D695	Modulus, "strength," strain
Tension, +/-45 (shear)	10	10	D3518	Modulus, strength, strain, Poisson's
Flatwise tension	10	10	C297	z-direction (through-thickness) tensile strength
Range coupon	2	2	n/a	n/a
EMU fan cap	1	1	n/a	n/a
Total	63	63		

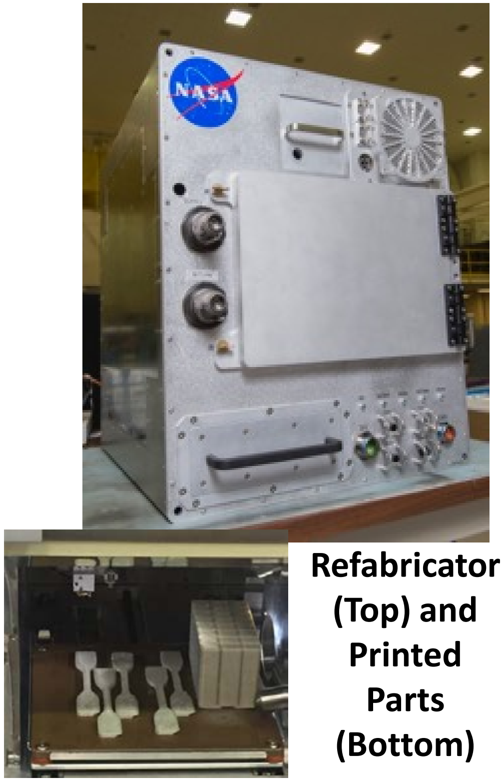
In-Space Recycling & Reuse: ISS Refabricator
Closing the Manufacturing Loop



Mission Goal of Refabricator

Demonstrate how the integrated polymer Recycler/3D Printer can increase mission sustainability by providing a repeatable, closed-loop process for recycling plastic materials/parts in the microgravity environment into useable feedstock for fabrication of new and/or different parts.

- Technology Demonstration Mission conducted under SBIR contract with Tethers Unlimited, Inc. (TUI)
- Refabricator is an integrated 3D printer (FDM) which recycles ULTEM plastic into filament feedstock through a novel TUI process which requires no grinding.
- Designed to be self-contained and highly automated.
- Installation and activation on the ISS EXPRESS Rack on 2/14/19



Refabricator (Top) and Printed Parts (Bottom)

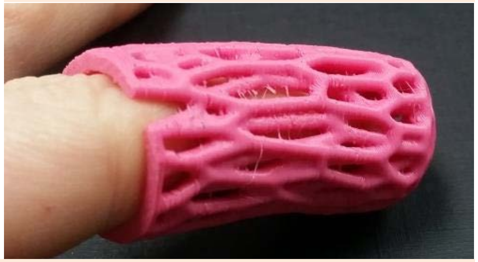
In-Space Recycling & Reuse: Food & Medical Grade Refabricator & Sterilizer

The 1st Generation Exploration Recycler will include a 3D Printer, Recycler, and dry-heat Sterilizer to fabricate and recycle polymer parts, including food and medical-grade items which make up a high percentage of trashed materials on the ISS. This effort is underway through a Phase II SBIR entitled “ERASMUS” with TUI. Refabricator design and testing is informing the ERASMUS activity.

- ISM is working with the AES Logistics Reduction (LR) team at JSC for application cases.
- TUI digitally reconstructed the NASA-provided urine funnel drawing and made adaptations in order to better support its manufacturability.
- ERASMUS also addresses food (i.e. spoon), medical device (i.e. otoscope specula, finger splint), and specimen production.
- Prototypes are provided to the JSC Logistics Reduction team for further testing and analyses.
- Next Steps:
  - Evaluate process-induced degradation and re-use capabilities.
  - Develop a medical device 3D printing and sanitization process.
  - Part production and customization.
  - Breadboard-level verification of the complete ERASMUS process.

Printed, Recycled, Sanitized Urine Funnels

Printed, Recycled, Sanitized Spoons



Voronoi Patterned Finger Splint

Common Use Materials Development - Recyclable Materials: SBIR Activities

- Logistics analyses indicate a dramatic impact of recycling capability to reduce initial launch mass requirements for long duration missions
  - Current packaging materials for ISS represent a broad spectrum of polymers: LDPE, HDPE, PET, Nylon, PVC

- Tethers CRISSP (Customizable Recyclable ISS Packaging) seeks to develop common use materials (which are designed to be recycled and repurposed) for launch packaging (Phase II-E SBIR)
  - Recyclable foam packaging made from thermoplastic materials using FDM
  - Can create custom infill profiles for the foam to yield specific vibration characteristics or mechanical properties

- Cornerstone Research Group (CRG) is working under a Phase II-E SBIR on development of reversible thermoset copolymer materials
  - Designs have strength and modulus values comparable to or exceeding base thermoplastic materials
  - Maintains depressed viscosity so that materials are compatible with FDM

CRISSP packaging (image from Tethers Unlimited)

FDM prints using reclaimed anti-static bagging film with reversible cross-linking additive (image from CRG)

In-Space Metal Additive Manufacturing Capability: SBIR Activities

- Made in Space Vulcan unit (Phase II SBIR)
  - Integrates FDM head derived from AMF
  - Wire and arc metal deposition system
  - CNC end-mill for part finishing
- Ultra Tech Ultrasonic Additive Manufacturing (UAM) system (Phase II SBIR)
  - Uses sound waves to consolidate layers of metal from foil feedstock
- TUI MAMBA (Metal Advanced Manufacturing Bot-Assisted Assembly) (Phase II SBIR)
  - Ingot-forming method to process virgin or scrap metal.
  - Builds on Refabricator recycling process
  - Bulk feedstock is CNC milled
- Techshot, Inc. SIMPLE (Sintered Inductive Metal Printer with Laser Exposure) (Phase II-E SBIR)
  - AM process with metal wire feedstock, inductive heating, and a low-powered laser

Illustration of Vulcan Exterior Unit (image courtesy of Made in Space)

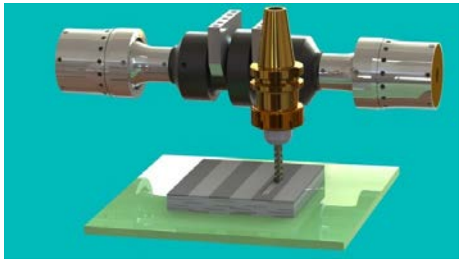
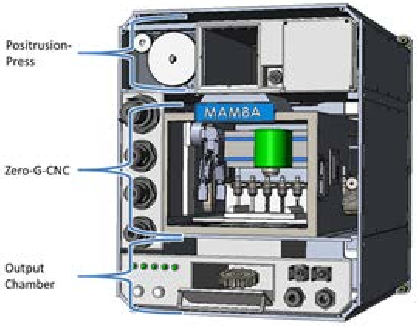
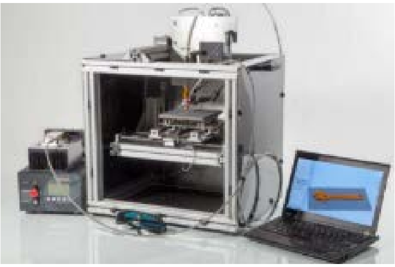


Illustration of UAM process (image courtesy of Ultra Tech)



Tethers Unlimited MAMBA concept. Image courtesy of Tethers Unlimited.

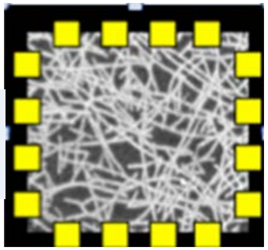


Techshot's SIMPLE, a small metal printer developed under a Phase I SBIR. Image courtesy of Techshot.

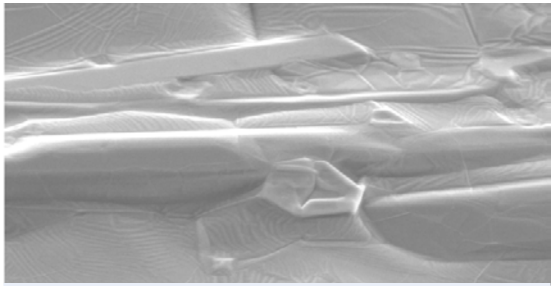
Multi-Material Fabrication With Printed Electronics

- Objective: Evaluate and develop technologies to enable multi-material, on-demand digital manufacturing of components for sustainable exploration missions.
- Working with multiple NASA centers, industry (including small businesses), academia, and Other Government Agencies (OGAs).
- Sensor Development:
  - Piezoelectric/pyroelectric-based combination pressure/temperature sensor.
  - Wearable RFID sensors.
  - Sensors to detect NH_3, CO_2 ,CO, CH_4 , H_2, and humidity.
- Ink Development
  - Inconel 718
  - Aluminum and Aluminum-tin
  - Carbon-carbon-polymer composite ink
  - Palladium-silver electrode ink
- Develop power sources to run the sensors (triboelectric) and store energy (supercapacitors) to build a self-contained system.
- Develop Flexible Electronics Sensors including the development of a flexible sensor circuit with flexible components

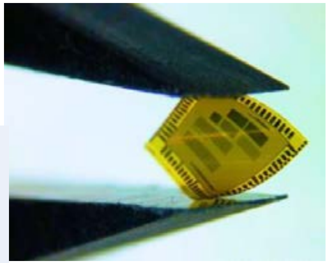
ECLSS Composite Pressure/ Temperature Sensor



Gas Sensor



Sintered Inconel 718 Ink



Flexible Electronics Sensors

NextSTEP Multi-Material Fabrication Laboratory (FabLab) Broad Agency Announcement (BAA)

WE ARE HERE!

NextSTEP
Next Space Technologies for Exploration Partnerships

DESIGN

Phase A (18 months)
Goal: Demonstrate a scalable ground-based PROTOTYPE of an ISM FabLab System able to mature into flight demonstrations on the ISS within three years.

BUILD

Phase B (12 months)
Goal: Mature the Phase A ISM FabLab System prototype into a flight integration deliverable. Phase B criteria and needed path are informed by Phase A results and will be released under a follow-on BAA.

FLY

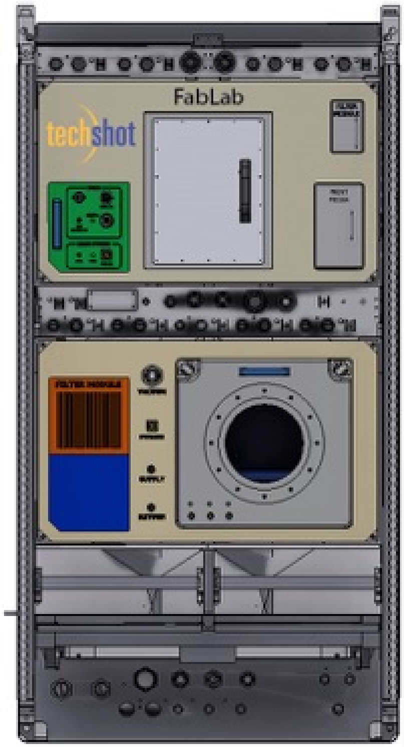
Phase C (18 months)
Goal: Demonstrate the capability of a Phase B ISM FabLab System on the ISS and evaluate risk. Phase C criteria are informed by Phase B results and will be released as a follow-on BAA or other acquisition vehicle.

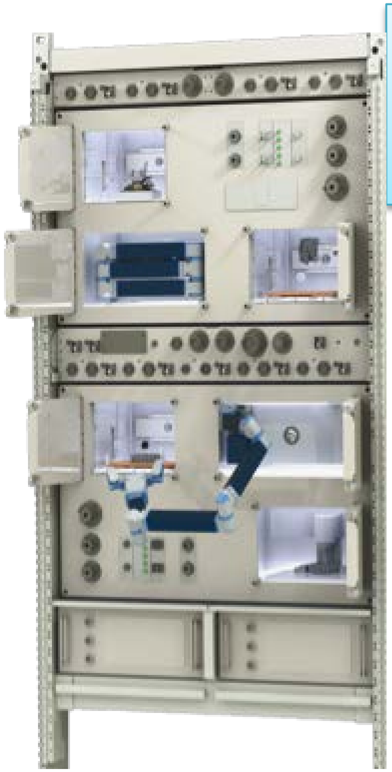
- NASA solicited proposals for the development of a Multi-Material Fabrication Laboratory (FabLab) capable of end-to-end manufacturing of precision parts for sparing, repair, and logistics support. during space missions.
  - High degree of autonomy
  - On-demand manufacturing of metallics and other materials in the microgravity environment
  - Minimum build envelope of 6”x6”x6”
  - Earth-based remote commanding
  - In-line remote/autonomous inspection and quality control
- This is the first step toward a fully-integrated, on-demand manufacturing capability that is able to produce finished, ready-to-use metallic, plastic, and/or electronic products during Exploration missions.
- The Phase B solicitation will be openly competed and is anticipated to be released late in CY 2019.

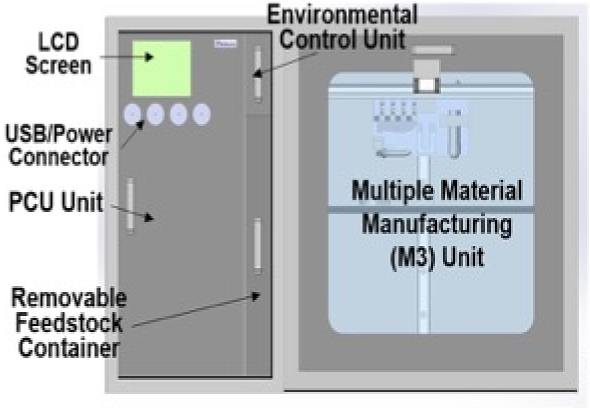
NextSTEP FabLab: Phase A Selectees

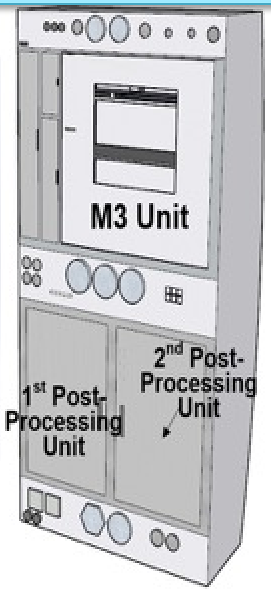
”The Techshot FabLab” - Techshot, Inc. (Greenville, IN)
Partners: nScrypt, TM Vacuum Products, University of Louisville, VITO

“Microgravity Multiple Materials Additive Manufacturing (M3AM) Technology” - Interlog (Anaheim, CA)
Partners: Argonne National Labs, Micro Aerospace Solutions, Illinois Institute of Technology







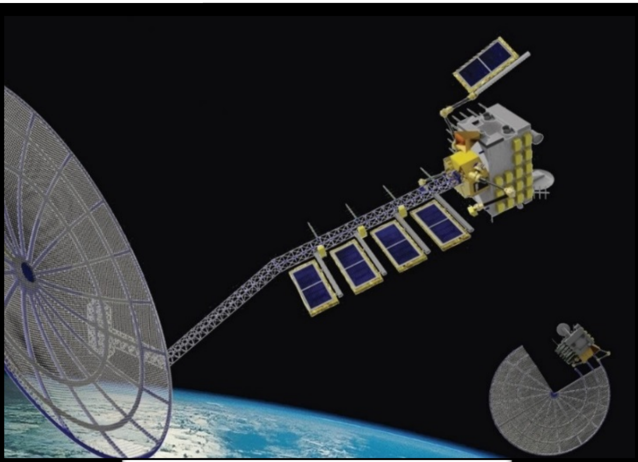


“Empyrean- Sustainable, In-Space Fabrication Laboratory for Multiple Material Manufacturing, Handling, and Verification/Validation” - Tethers Unlimited, Inc. (Bothell, WA)
Partners: IERUS, Olis Robotics

- **These companies will have 18 months to deliver the prototype, after which NASA will select partners to further mature the technologies for an ISS demonstration and 1st generation Exploration system. .**

NASA 12/7/17 Selection Announcement:

In-space Robotic Manufacturing and Assembly (IRMA): Phase 1 Concepts



Concept by Made In Space

Concept by Space Systems/Loral

Concept by Orbital ATK

	Archinaut	Dragonfly	CIRAS
	A Versatile In-Space Precision Manufacturing and Assembly System	In-Space Robotic Manufacturing, Assembly and Reconfiguration of Large Solid Radio Frequency (RF) Reflectors	A Commercial Infrastructure for Robotic Assembly and Services
Tipping Point Objective	A ground demonstration of additive manufacturing of extended structures and assembly of those structures in a relevant space environment.	A ground demonstration of robotic assembly interfaces and additive manufacture of antenna support structures meeting EHF performance requirements.	A ground demonstration of reversible and repeatable robotic joining methods for mechanical and electrical connections feasible for multiple space assembly geometries.
Team	Made In Space, Northrop Grumman Corp., Oceaneering Space Systems, Ames Research Center	Space Systems/Loral, Langley Research Center, Ames Research Center, Tethers Unlimited, MDA US & Brampton	Orbital ATK, Glenn Research Center, Langley Research Center, Naval Research Laboratory

Status: 2-year risk reduction developments completed. Phase 2 proposals selected for flight demo

Made In Space (MIS)
Archinaut – Overview and Phase I Accomplishments

Vision:

- *System that is able to robotically create spacecraft or extremely large structures in space which reduces spacecraft cost, reduces limitations rocket launch places on spacecraft design (launch loads and volumes), and removes astronauts from harm's way.*

Objectives:

- *Demonstrate extended structure additive manufacturing of structures in a relevant environment using Extended Structure Additive Manufacturing Machine (ESAMM).*
- *Demonstrate additive manufacturing and robotic assembly of structures, as well as in-situ V&V in a relevant environment using Ground-Based Manufacturing and Assembly System Hardware (GBMASH).*
- *Evaluate part quality through mechanical and structural testing.*

MIS Mechanical Engineer Deejay Riley with 850 mm Beam printed in a TVAC chamber

GUINNESS WORLD RECORDS

CERTIFICATE

The longest 3D printed
non-assembled piece is
37.7 m (123 ft 8.25 in)
and was achieved by
Made In Space, Inc. (USA)
in Moffett Field, California, USA
on 9 August 2017

OFFICIALLY AMAZING

- July 2017: Successfully demonstrated additive manufacturing in a simulated LEO environment (NASA Ames).
- August 2017: Printed "World's longest 3D printed non-assembled piece" (37.7 meters)
- August 2018: Successfully demonstrated GBMASH in Thermal Vacuum chamber (NG Space Park)

Made In Space (MIS)
Archinaut – Phase II

MIS CEO Andrew Rush with a demonstration of the ArchinautOne Solar array

Objectives:

- *Continue success of ESAMM and GBMASH to build ArchinautOne*
  - *Small satellite with best in class power capability*
  - *Operate in LEO*
  - *ESAMM unit will produce 2x 10 m beams which support 10 m^2 flexible solar panels each*
  - *Robotic arm will position vital components*
  - *In-situ V&V ensures quality product*

ArchinautOne Small Sat

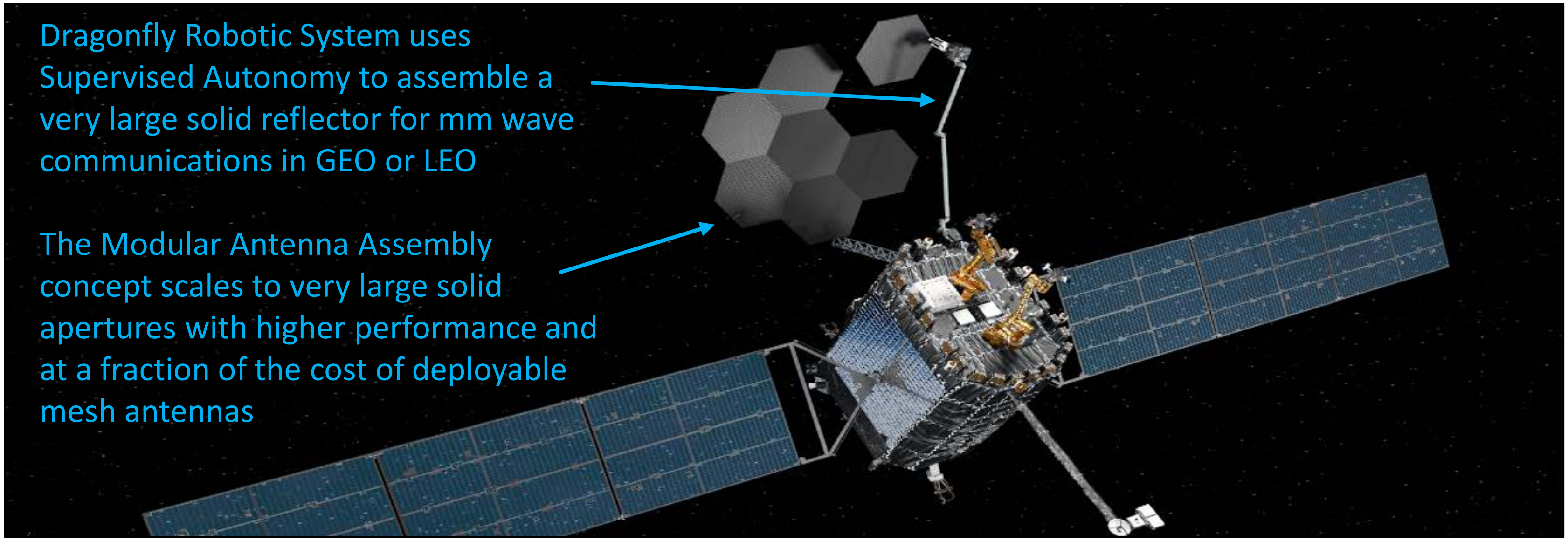
ArchinautOne Small Sat with printed solar arrays

Demonstration of small satellite with >2kW power

SSL Dragonfly: Overview

Project Overview

The Dragonfly Robotic System is an ultra-lightweight robot that integrates easily with commercial and government communications satellites to assemble large reflectors in orbit.



Dragonfly Robotic System uses Supervised Autonomy to assemble a very large solid reflector for mm wave communications in GEO or LEO

The Modular Antenna Assembly concept scales to very large solid apertures with higher performance and at a fraction of the cost of deployable mesh antennas

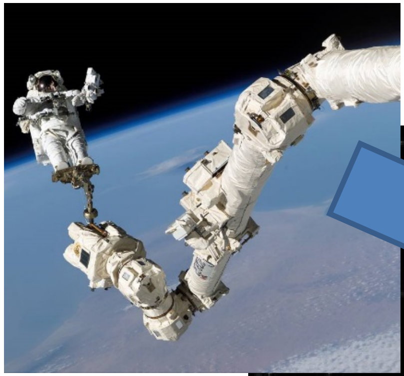
The SSL Dragonfly project is developing critical technologies to enable In-space Robotic Manufacturing, Assembly and Reconfiguration of Large Solid RF antennas.

These technologies will enable commercial and government customers to deploy:

- larger apertures for greater coverage, throughput and mission enabling optics,
- reconfigurable apertures for mission versatility, and
- re-buildable apertures for resilience and persistence in contested environments.

Dragonfly Builds on State of the Art Flight Heritage

Advanced arm control and force regulation software from ISS robotics



Dragonfly Robotic System ‘walks’ end-over-end around a large GEO CommSat to assemble a suite of antennas from a stack launched on the Earth Deck

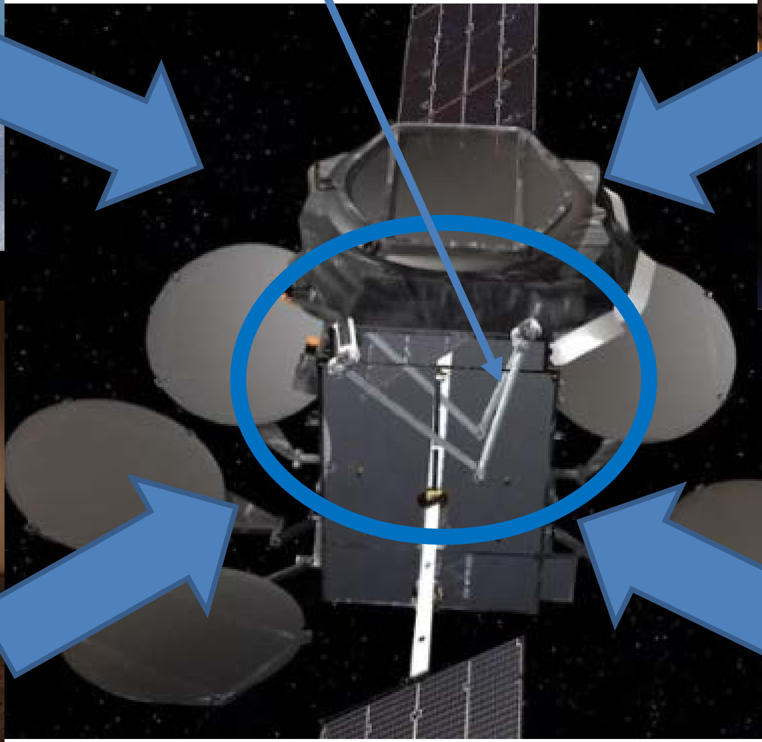
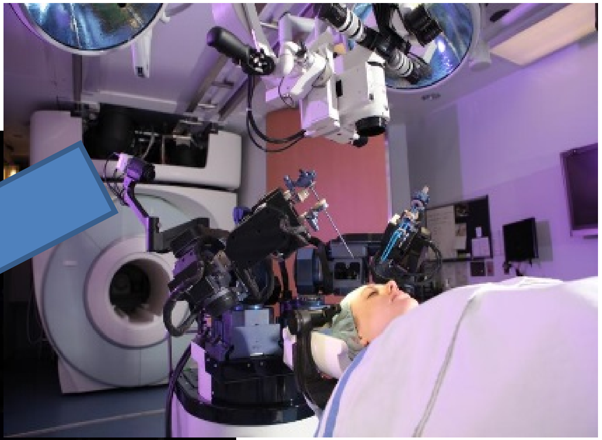
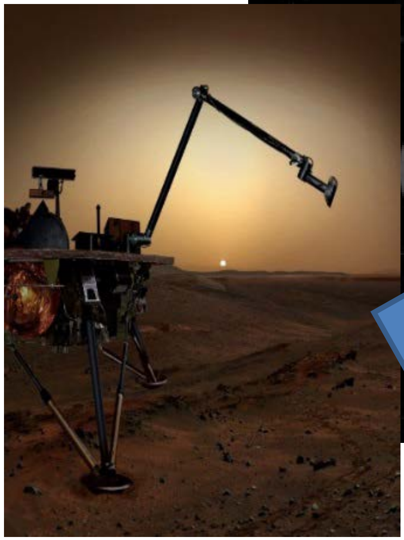


Image guidance and Supervised Autonomy from advanced neurosurgical robotics

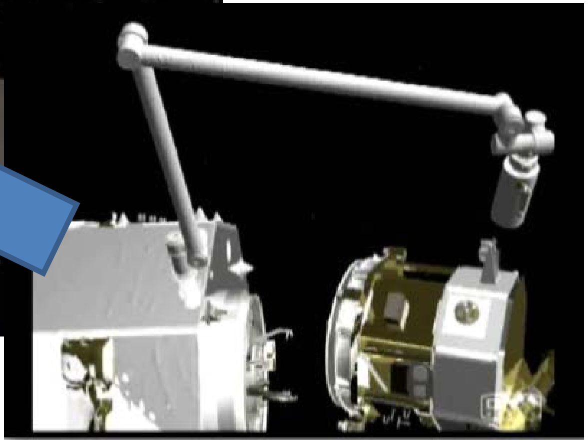




Super-light Actuators, booms and cables from Mars Phoenix and MER IDD

Dragonfly at a glance:

- 5m, 7 DoF, double ended symmetrical arm
- fully redundant, arm mounted avionics with control software and image processing
- all-in mass of 76kg

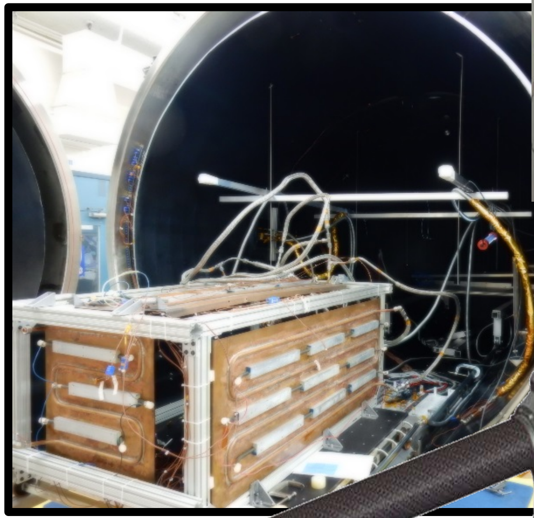


3D graphics based planning, automatic script generation and end effector from Orbital Express Mission

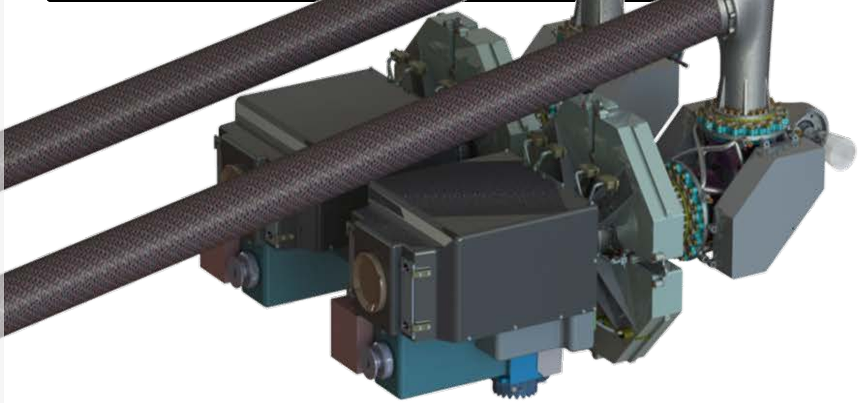
Dragonfly Accomplishments and Plans

- ***Phase 1 Accomplishments***
  - Robot system design to CDR level
  - High vacuum testing of in-space manufacturing of thermally stable, high stiffness truss elements made of carbon fiber reinforced PEEK
  - Robot system interfaces that integrate “lightly” with existing spacecraft C&DH and low rate Command/Telemetry links
  - Operating concept suited to commercial MCC protocols and staffing
- ***Phase 2 Plans***
  - Prepare robot system for demonstration flight on NASA’s Restore-L mission in LEO
  - Assemble a 3m version of the modular antenna and perform optical and RF metrology using a Ka band link
  - Fabricate a very long (~30m) boom made of carbon fiber reinforced PEEK and perform metrology for dynamics, fabrication tolerances, and thermal stability

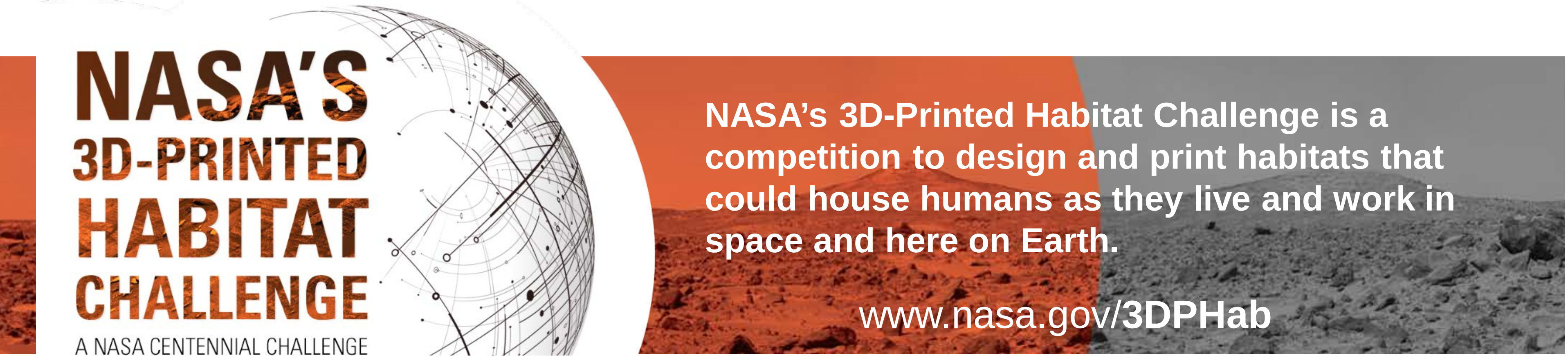
Vacuum Testing of CF-PEEK Truss manufacturing



Robot Arm Actuator Gearbox



7 DoF Robotic Arm in Launch Configuration



NASA'S 3D-PRINTED HABITAT CHALLENGE

A NASA CENTENNIAL CHALLENGE

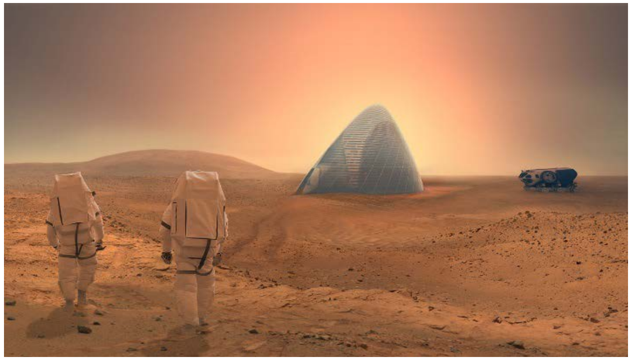
NASA's 3D-Printed Habitat Challenge is a competition to design and print habitats that could house humans as they live and work in space and here on Earth.

www.nasa.gov/**3DPHab**

Phase 1: Design Competition

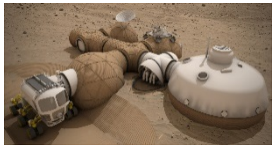
Completed Sept. 2015

$40,000 awarded



1st Place: SEArch and Clouds AO

2nd Place: Gamma



3rd Place: LavaHive

Phase 2: Structural Member Competition

Completed 9/2017

$701,024 awarded

1st Place

Foster + Partners | Branch Technology

2nd Place

Pennsylvania State University

Phase 3: Structural Member Competition

Ongoing; 5 sub-levels

$100,000 awarded to date

Level 1 BIM 1st Place: Zopherus

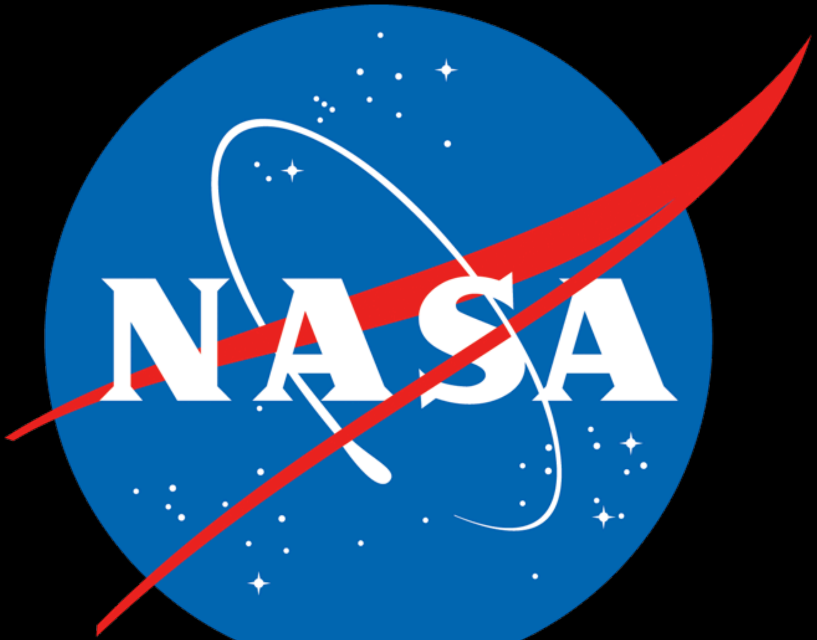
2nd Place: AI. SpaceFactory

Summary

- In Space Manufacturing has been described as an "essential technology for deep space exploration.“ (former Director, NASA ISS Program)

- Evolvable Mars Campaign Systems Analysis Group concluded from their study of ISM Utilization for deep space missions that:
  - Current maintenance logistics strategy will not be effective for deep space missions
  - ISM has the potential to significantly reduce maintenance logistics mass requirements by enabling material commonality and the possibility of material recycling and ISRU for spares
  - ISM should be considered and developed in parallel with the systems design

- MSFC is actively working with industry partners to develop ISM capabilities:
  - **Within Pressurized Volume:** Reduce logistics challenges. Keep astronauts safe and healthy in transit and on extraterrestrial surfaces (tools; spares; food-safe and medical-grade applications)
  - **External/Free Space - IRMA:** Add new commercial capabilities in spacecraft construction, assembly, and repair in LEO
  - **3D Habitat Challenge/Additive Construction:** Enable infrastructure to be robotically constructed prior to arrival of astronauts on the extraterrestrial surface, Moon or Mars.


NASA

ISM Monitoring and Inspection Capability Development

Three FabLab Phase A teams

- Developing technologies for part inspection and process monitoring
- Remote/autonomous commanding
- Feedback and control
- *Note: Capability and approach is being initiated in Phase A, and will be more fully developed in Phase B awards*

Five SBIR Phase I awards

- Maturing low TRL complementary inspection and monitoring technologies
- In-line and/or *in situ* capabilities
- Possible infusion into FabLab Phase B proposals