

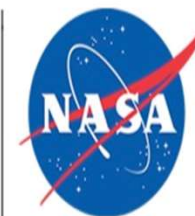
2019 Tennessee Valley Interstellar Workshop

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In-Space Manufacturing: The Gateway to the High Frontier and an Enabling Technology for Human Space Exploration



MARSHALL
SPACE FLIGHT CENTER



Introductions



Introduce yourself:

- Name
- Affiliation/Organization
- Role
- Why are you interested in in-space manufacturing?
- Where do you see the field of in-space manufacturing in fifty years?



Outline



1. Overview of manufacturing processes and taxonomy
2. Discussion of the history of in-space manufacturing
3. NASA's in-space manufacturing project overview
4. Discussion of commercial targets and applications for in-space manufacturing
5. Discussion of suitability of manufacturing processes for in-space manufacturing
6. Roadmapping/brainstorming activity



A Note on Scope



Currently NASA Marshall Space Flight Center categorizes manufacturing processes based on operational use scenario and the application of the parts being manufactured.

“For space” manufacturing refers to ground-based manufacturing of hardware for spaceflight applications (ex. 3D printing of rocket components).

In-space manufacturing is currently defined as manufacturing in an intravehicular (crew) environment. ISM takes place inside a pressurized habitat structure (ex. International Space Station) and is primarily focused on logistics reduction and on-demand manufacturing of spares.

On-orbit servicing, assembly, and manufacturing (OSAM) refers to manufacturing, joining, and other processes in the external space environment. Processes are used to fabricate larger than launch payload faring structures, assemble these structures, and to perform repair/servicing.

In situ resource utilization (ISRU) refers to extraction and use of raw materials found in situ on planetary surfaces for manufacturing or sustained habitation.

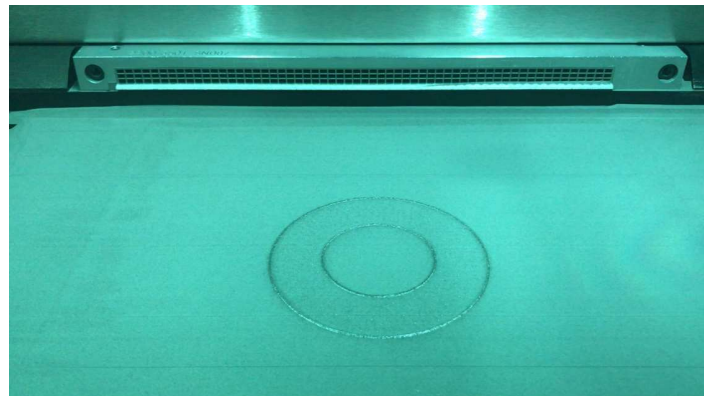
This presentation contains information on some OSAM activities (note these are not part of the ISM portfolio at this time).



Manufacturing Processes



- Additive manufacturing** builds a 3D object in layers.
- Subtractive manufacturing** constructs 3D objects by successively removing material from a solid material form.
- Hybrid techniques** use multiple manufacturing processes (usually additive manufacturing and subtractive manufacturing) within the same unit.
- Welding** joins pieces of material together by melting or plasticizing material along a joint line.



Images from NASA



Additive Manufacturing Processes



Additive manufacturing (AM) spans a broad swath of processes and materials. Processes are distinguished by the class of materials used (ex. metals or polymers), method of heating/energy (ex. laser), and form of the manufacturing feedstock (powder, wire, resin, etc.). Every AM process typically begins with a CAD file which is sliced into layers by a slicing software.

- Stereolithography (SLA)
- Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF)
- Selective Laser Melting (SLM) or Powder Bed Fusion (PBF)
- Blown Powder Directed Energy Deposition (DED)
- MELD (previously known as additive friction stir)
- Electron Beam Melting (EBM)
- Ultrasonic Additive Manufacturing (UAM)
- Kinetic Metallization
- Chemical Vapor Deposition (CVD)
- Wire+Arc
- Bound Metal Deposition

This is not a comprehensive list of AM processes. These processes have been chosen for highlight based on relevance to the subject at hand.

AM of Polymers: Stereolithography



- One of the oldest forms of 3D printing is stereolithography (SLA). In SLA, a laser beam traces along a vat of liquid photopolymer in a prescribed 2-D geometry, rapidly solidifying the material. The object being fabricated lowers on a platform/moveable table and a subsequent layer is solidified via laser heating:
<https://www.youtube.com/watch?v=yW4EbCWaJHE>
- Fabrication of overhangs is accomplished using support structures, which are subsequently removed
- Advantages: Accuracy and surface finish, water resistant, transparent (ex. flow channels)
- Disadvantages: Material management (resin), post-curing may be required

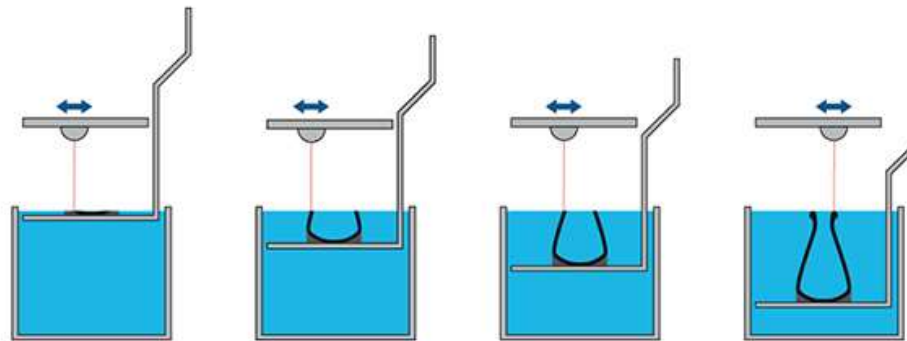
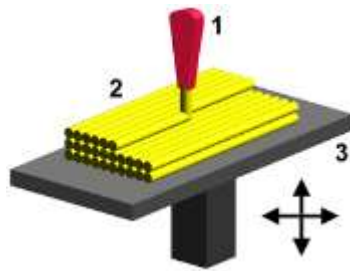


Image from i.materialise

AM of Polymers: Fused Filament Fabrication



- Also known as fused deposition modeling (FDM)
- Most common desktop 3D printing process
- Plastic wire filament is fed from a spool in a cartridge through a heated nozzle. The nozzle may move relative to the part in a manner determined by G code (machine code) to create geometry layer by layer. A more common machine configuration is for the table to raster in the x-y plane relative to a stationary nozzle
- Common materials include thermoplastics: Acrylonitrile Butadiene Styrene (ABS), Polyethylene, Polylactic Acid (PLA), polyethylene terephthalate glycol (PET-G), and Polycarbonate (PC). Higher temperature materials include ULTEM 9085 (polyetherimide/polycarbonate).
- Advantages: small systems, can be operated in office environment; good resolution
- Disadvantages: material strengths are limited (research on higher strength feedstocks for FFF is ongoing)



Fused deposition modeling:
1) nozzle ejecting molten plastic,
2) deposited material (modeled part),
3) controlled movable table



AM of Metals: Selective Laser Melting



- In SLM, metal powder housed in a hopper is spread over the surface of a build plate. A piston mechanism ensures a particular quantity of powder is dispensed for each layer. Layers are typically 30 or 50 microns in thickness.
- The laser beam passes over the powder to selectively melt it in a manner consistent with a sliced CAD file:
<https://www.youtube.com/watch?v=yiUUZxp7bLQ>
- The build plate moves downward and the sintering process is repeated until the part is complete.
- Excess powder is removed by a spreader between subsequent passes of the laser.
- Materials: Inconel, Titanium, Copper alloy (GRCop-84)
- Advantages: excellent resolution, material properties of aerospace grade metals comparable to wrought; ability to build parts with highly complex geometries
- Disadvantages: typically large systems with high power requirements; build chamber may be small relative to size of system; postprocessing required (hot isostatic press and heat treatment); powder safety; mechanical separation from build plate required

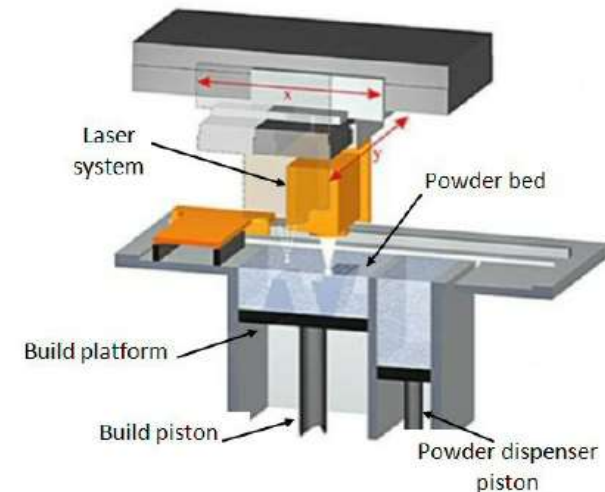


Image from custompart.net

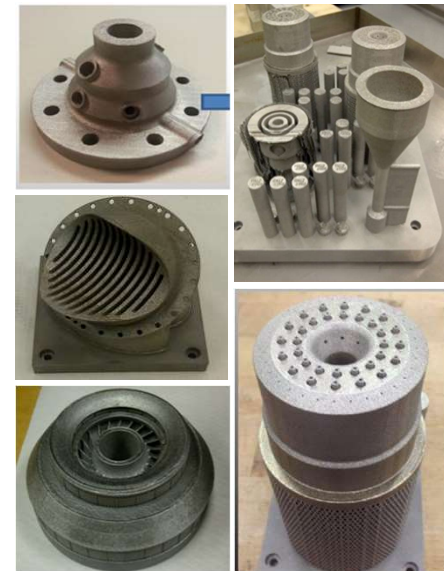


Image from NASA



SLM at NASA



J-2X Gas Generator Duct



Pogo Z-Baffle



Turbopump Inducer



RS-25 Flex Joint

Part	Cost Savings	Time Savings
J-2X Gas Generator Duct	70%	50%
Pogo Z-Baffle	64%	75%
Turbopump Inducer	50%	80%

RS-25 Flex Joint	Heritage Design	SLM Design
Part Count	45	17
# Welds	70+	26
Machining Operations	~147	~57

At NASA, SLM has been used to impart cost savings, reduce touch labor, number of welds, and part lead time for high value propulsion components.

Directed Energy Deposition (DED): Blown Powder



- Similar to SLM, but uses blown metal powder:
<https://www.youtube.com/watch?v=mkUVURLkxS4>
- Coaxial laser energy source is focused on a small spot via lenses
- Gantry or robotic system; table moves in x-y direction and head moves vertically (laser beam travels through the head)
- Inert gas shielding typically required to prevent oxidation and improve adhesion of layers
- Materials: Titanium, Stainless Steel, Aluminum, Nickel
- Advantages: metal parts of almost full density, good part resolution; large builds possible; multimaterial capability
- Disadvantages: typically large systems with high power requirements; powder safety; mechanical separation from build plate required; finish machining may be required depending on geometry (resolution not as good as SLM)

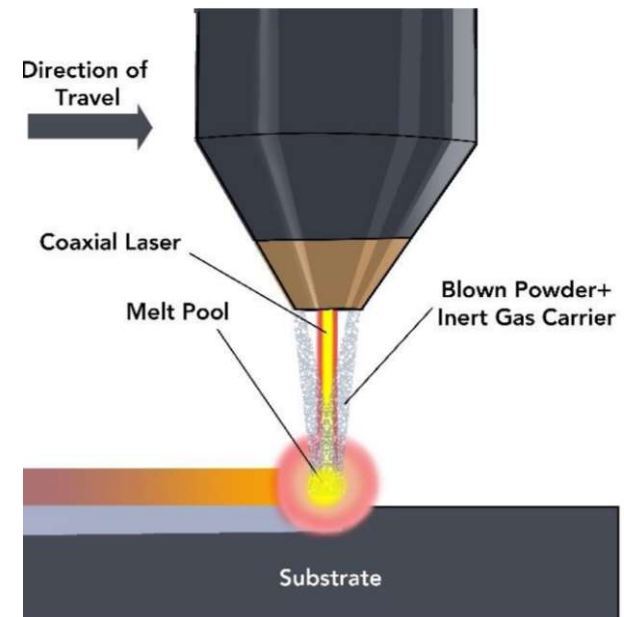


Image credit: Omar Mireles and Paul Gradi (NASA), Process pictures courtesy RPM Innovations and DM3D.

DED: Electron Beam Deposition



- Variation of Directed Energy Deposition (DED)
- Off-axis wire fed deposition
- Uses electron beam as energy source
- Requires operation in a vacuum
- Example of process: <https://www.youtube.com/watch?v=WrWHwHuWrzk>
- Advantages: high build rate; many types of metal materials can be processed with this technique; can be used for repair
- Disadvantages: high power requirements; feature resolution is limited; process may be limited to single builds (one part per build); longer setup time relative to some other AM processes



Images from NASA (Omar Mireles and Paul Gradl)

- Pulsed-wire metal inert gas (MIG) welding process
- Material in form of wire feedstock; virtually any material available in the form of welding wire can be used
- Creates near net shapes: <https://www.youtube.com/watch?v=twEoXKxaLVo>
- Advantages: scales well; wide variety of materials can be processed
- Disadvantages: power requirements; safety concerns; post-process machining required



Images from NASA (Omar Mireles and Paul Gradl)

Hybrid AM Processes



- Combine additive processes with subtractive processes within the same unit
- Typically laser powder bed fusion (L-PBF) or DED with machining following part fabrication
- Video: <https://www.youtube.com/watch?v=WyUObN8ocul>

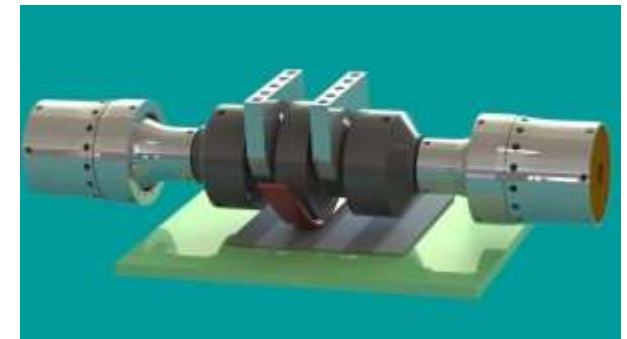




Ultrasonic Additive Manufacturing



- Uses solid-state joining technique (ultrasonic welding derived) to join layers of adjacent metal foil:
<https://www.youtube.com/watch?v=5s0J-7W4i6s>
- Foil is deposited via a feed system on a base plate
- Sonotrode applied to adjacent foils imparts high frequency acoustic energy, dispersing oxide layer and forming a metallurgic bond
- Mostly used with Aluminum alloys, but represents a capability for multimaterial that can also accommodate embedded sensors
- Advantages: safe, room temperature process (no lasers or high temperatures); can process multimaterials, functionally graded materials, and dissimilar materials; process is scaleable with variation in sonotrode frequency
- Disadvantages: post process machining required



Images from Fabrisonic



MELD



- MELD is a process derived from friction stir welding (solid-state welding process): <https://www.youtube.com/watch?v=amRccXbJFEs>
- MELD process was previously known as additive friction stir (AFS)
- Advantages: Rapid deposition, large part volume; good metallurgical properties (solid state)
- Disadvantages: poorer resolution than PBF processes (requires post-process machining for some parts)

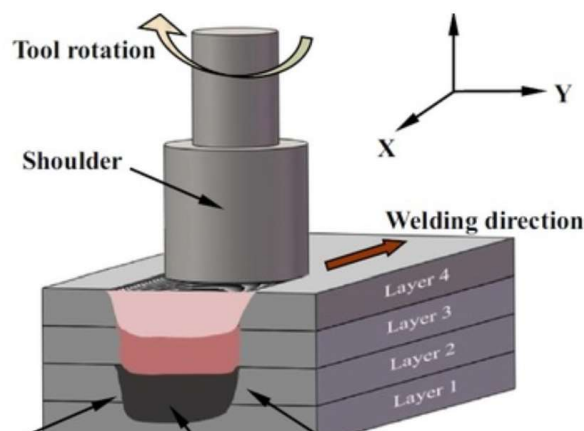


Image credit: 3DPrint.com

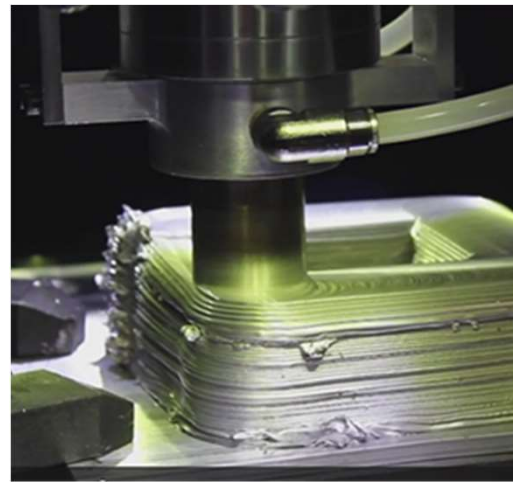


Image credit: MELD Manufacturing

Kinetic Metallization



- Metal deposition process in which powder particles are impinged on metallic substrates at high velocity: <https://www.youtube.com/watch?v=QKd-yw4o9wM>
- Bond is achieved by plastic deformation (solid state process)
- Inert gas is required to prevent formation of an oxide layer on the metal surface
- Nozzle charges and accelerates metal particles suspended in inert gas
- Advantages: can be used for fabrication or repair; typically good microstructure since material is not melted in manufacturing process; freestanding shapes can be produced
- Disadvantages: used primarily for coatings

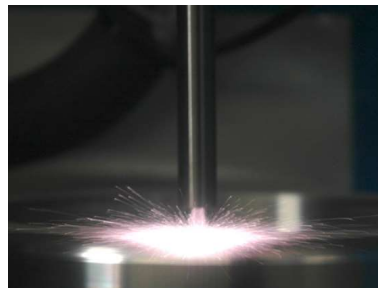


Image credit: Innovati

Chemical Vapor Deposition



- Can be used to deposit thin films on materials; typically used as a coating process
- Source gases react in a chamber to form materials, which are deposited on a heated substrate: <https://www.youtube.com/watch?v=j80jsWFm8Lc>
- Reaction byproducts which are not deposited are removed from reaction chamber

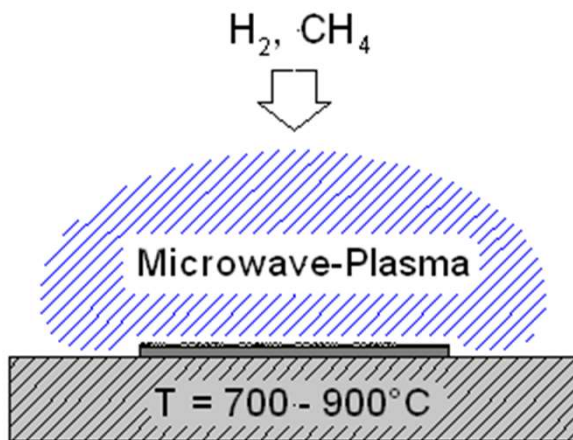


Image credit: CVD Diamond



*Coated tools can be used to reduce wear.
Image credit: NASA.*



Bound Metal Deposition



- Metal particles in a wax and polymer binder are extruded in the form of wire feedstock using a fused filament fabrication technique
- Polymer and wax are de-bound in an oven following part deposition
- Remaining metal particles are sintered to form a finished part
- Video:
https://www.youtube.com/watch?time_continue=10&v=qS5fEwF0k5s
- Advantages: printing process is relatively low power (compared with SLM); supports can be designed to disintegrate during the sintering process
- Disadvantages: part shrinkage must be predicted and accounted for in design (raft structure can be used to control shrinkage); sintering may require higher power, depending on the material and size of the part

Other AM processes



- Bioprinting
 - In bioprinting, a formulation of cells, matrix, and nutrients are dispensed from a printer cartridge, usually into a biocompatible scaffold
- 3D printing of food
 - Ingredients are heated and dispensed layer by layer
- Electronics printing
 - Dispense inks, traces, and wires
 - Pick and place capability for electronic components
 - Processes may be direct write or aerosol jet



BioFabrication Facility for the International Space Station from Techshot, Inc.



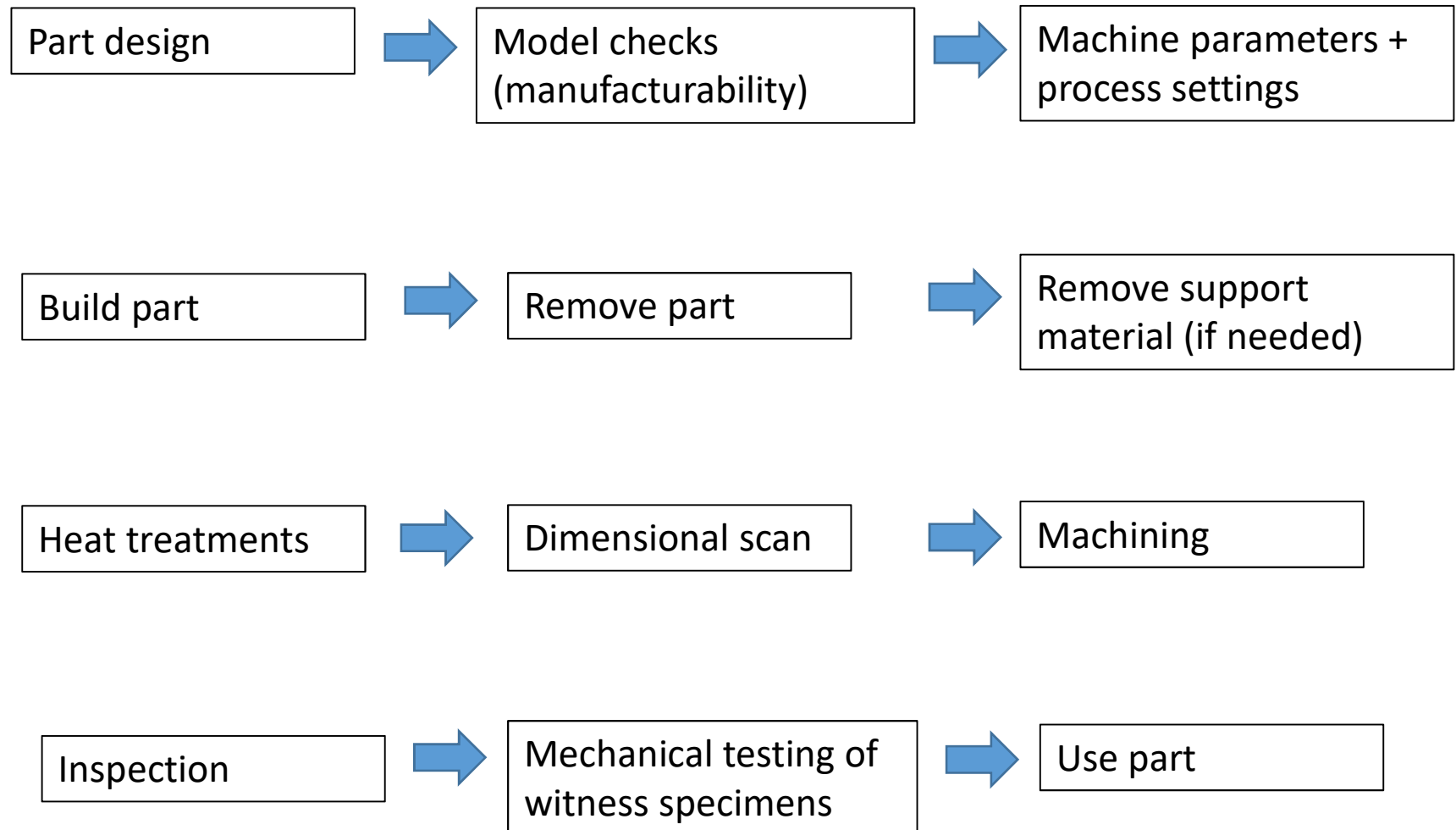
Image: 3dnatives.com.



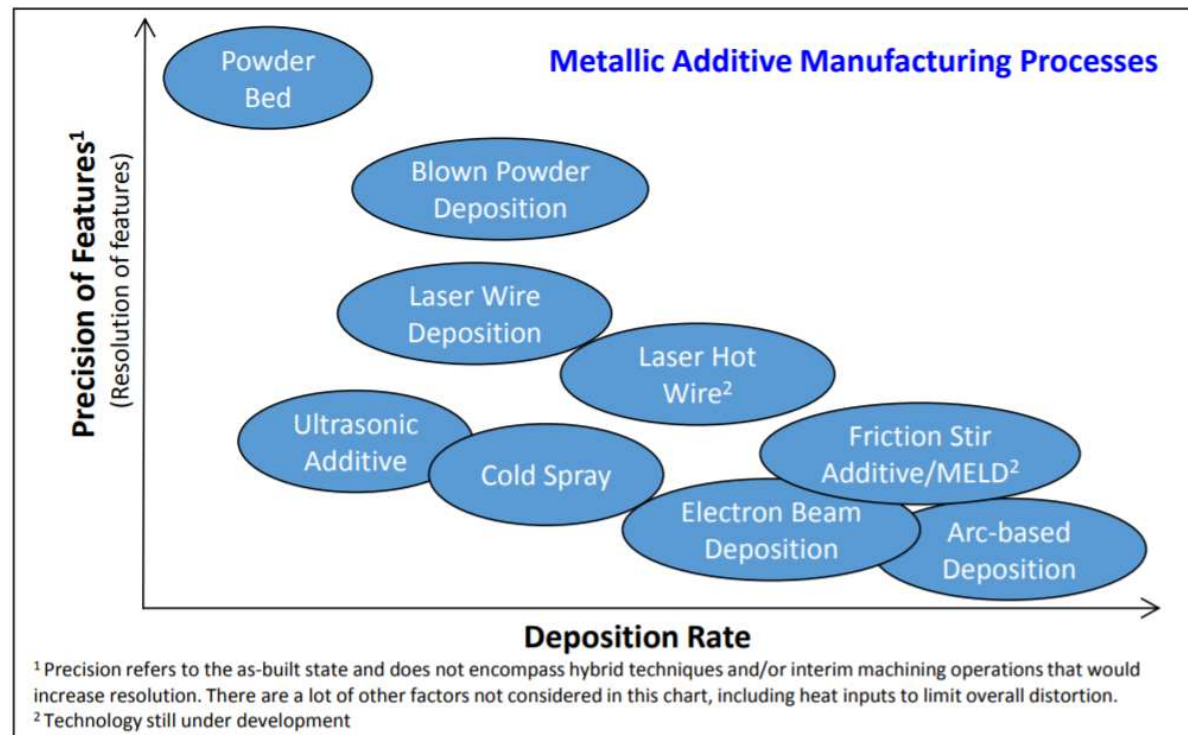
Image: NASA



Typical AM part process flow



Comparison of AM Techniques



Complexity of Features

Scale of Hardware

Material Physics

Speed of Process

Cost/Schedule

Material Properties

Internal Geometry

Availability

Slide credit: NASA. Omar Mireles and Paul Gradl.

Subtractive Techniques



- Milling uses computer data to subtractively remove material from a part
- Design files are used to generate a tool path (Gcode) which governs the movement of the cutting tool in relation to the part
- Undercuts and cavities are challenging. Ability to fabricate complex parts from a block of material increases with the number of axes of the mill.
- Milling can be used as a standalone manufacturing technique or in combination with AM processes to generate a finished part
 - Milling provides closer tolerances than many AM processes
 - hybrid AM means milling takes place in the same unit as the AM process



Image: NASA

Subtractive Techniques



- CNC lathe is used to remove material from bar stock (“turning” a part).
- Electrical discharge machining (EDM) is used to remove material (and to separate metal parts from a build plate)
 - Current discharge is created between two electrodes when a voltage is applied
 - The electrodes are separated by a dielectric liquid.
 - may be die-sink (RC circuit is used to charge the electrodes) or wire-sink (wire is the EDM tool electrode)



Image: NASA

Welding



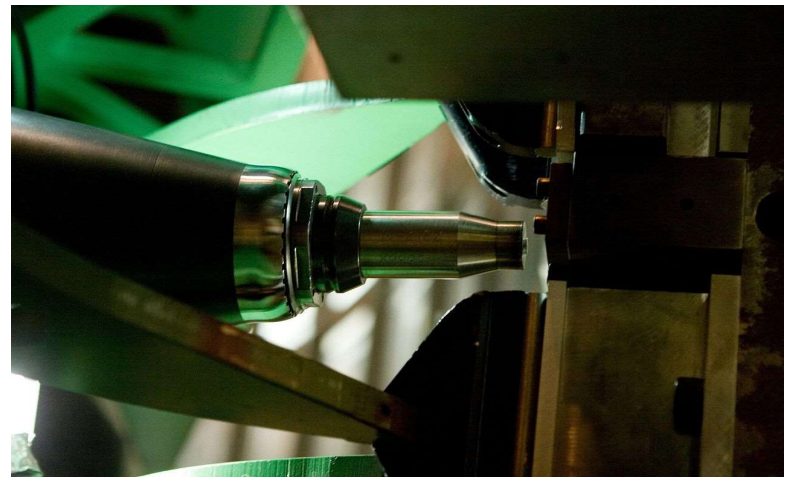
Several AM processes previously discussed are derived from welding.

Arc welding creates an electric arc between a workpiece material (base material to be joined) and an electrode. This results in melting of the material along the joint line.

- can use AC (alternating current) or DC (direct current)
- filler material may also be used
- flux may be used to protect against oxidation



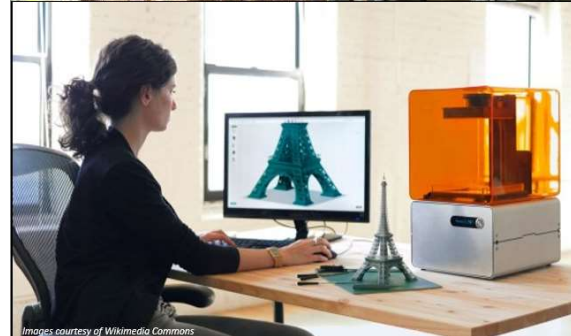
Solid state welding processes do not melt the material. An example is friction stir welding, in which a rotating tool creates sufficient friction heating to plasticize the material along the joint line. Other examples include ultrasonic welding and cold pressure welding.



AM and the Maker Movement



“When I talk about the maker movement, I make an effort to stay away from the word ‘inventor’—most people just don’t identify themselves that way. ‘Maker,’ on the other hand, describes each one of us, no matter how we live our lives or what our goals might be.” –Dale Dougherty, MIT Press Journal



Large Facilities
Mass Production
Time
Big Workforce

= Independence



Transition Questions



*What processes we've discussed thus far are adaptable to the space environment?
What processes can be operated internally in a crewed environment? What
processes are better suited for external applications or robotic operation as a
freeflyer (ex. fabrication of large space structures) or in a precursor mission
scenario (ex. planetary surface manufacturing of infrastructure)?*

*What figures of merit should we use to evaluate processes for adaptation to
space?*

*What historical experiments related to in-space manufacturing are you familiar
with?*

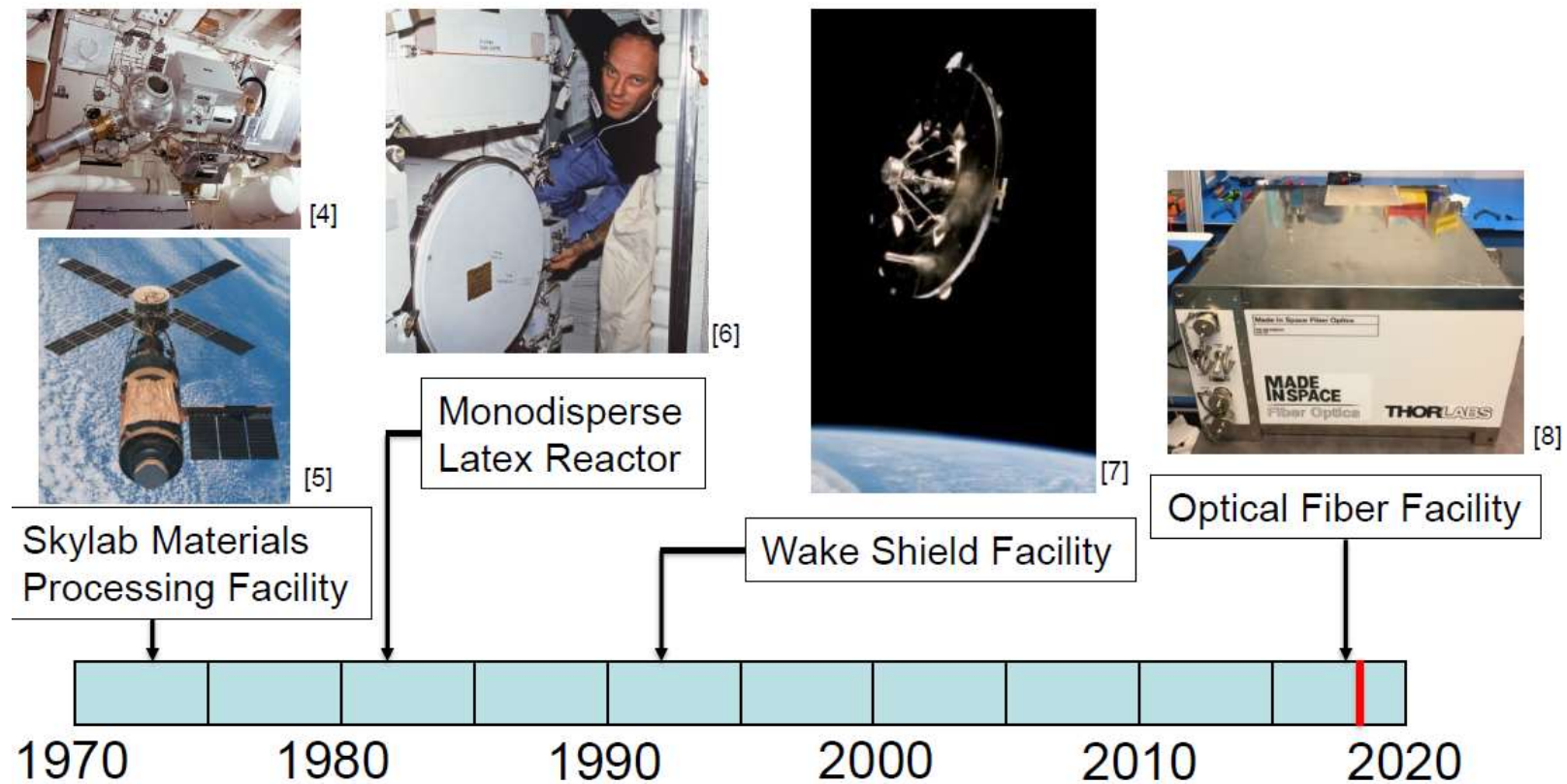


Considerations in Evaluating Processes for In-Space Manufacturing



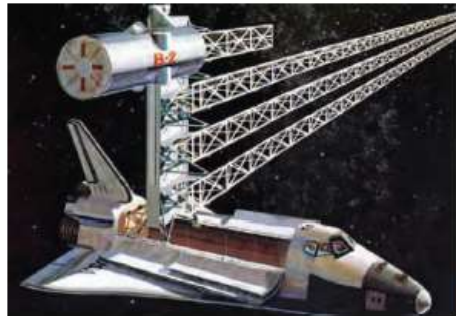
- Power
- Volume
- Mass
- Safety
- Material quality
- Post processing requirements
- System can be operated autonomously or teleoperated
- Debris generated and management of material waste
- Build rate
- Ability to recycle materials
- Range of metals which can be processed
- Ability to operate in a reduced gravity environment
- System scalability
- Feedstock form, life, and storage

History of In-Space Manufacturing



Slide credit: Matthew Moraguez, MIT

History of In-Space Manufacturing



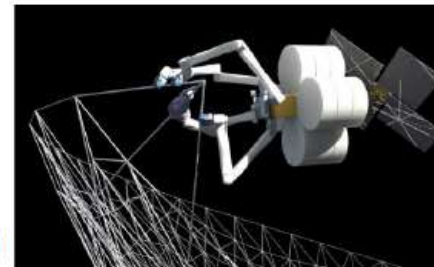
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SCAFEDS

Beam
Builder



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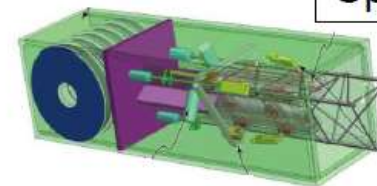
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SpiderFab



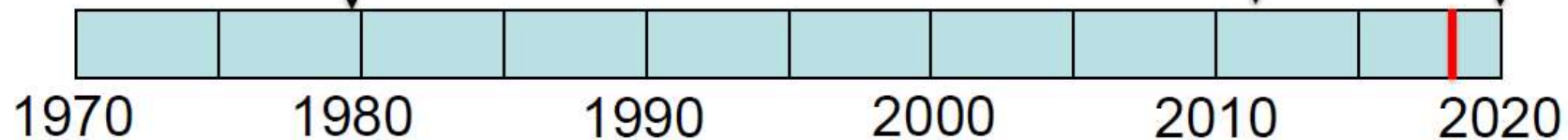
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Archinaut



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Trusselator


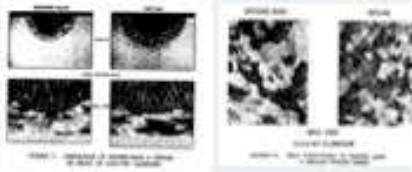






Slide credit: Matthew Moraguez, MIT



In-Space Welding



Year	Activity	Country	Process	Vehicle	Images	Outcome
1969	Vulcan, Self-contained experiment	Russia	EB, Arc	Soyuz 6		First demonstration of on-orbit welding.
1973	M551 Materials Melting, Self-contained experiment	US/MSFC	EB	Skylab I		Demonstrated metallurgy of 2219-T87 welds in microgravity.
1984	First Manual Electron On-orbit Manual Weld	Russia/Ukraine	EB	Salyut 7		Demonstrated concept and challenges of maintaining control during welding in a space suit.
1989	On-orbit Electron Beam Welding Experiment Definition	US (MSFC/Martin Marietta)	EB	Ground Demo only		Demonstrated on-orbit repair concept, weld schedule, and 2219-T87 metallurgy utilizing beam deflection.
1990s	International Space Welding Experiment	US (MSFC)/Ukraine (Paton Weld Institute)	EB	Space Shuttle (Not Flown)		Demonstrated safety challenges associated with manual EVA welding.
1995	Versatile Space Welding System Phase II SBIR	US (MSFC/Electric Propulsion Lab)	Arc	Ground Demo Only		Developed Hollow Cathode Arc Weld System

NASA's In-Space Manufacturing Project

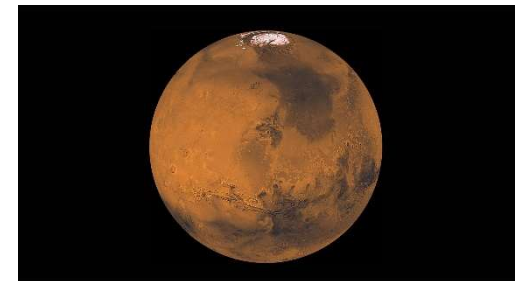


Tea.
Earl Grey.
Hot.

"Every revolutionary idea seems to evoke three stages of reaction:

- 1. It's completely impossible.*
- 2. It's possible, but it's not worth doing.*
- 3. I said it was a good idea all along."*

-Arthur C. Clarke



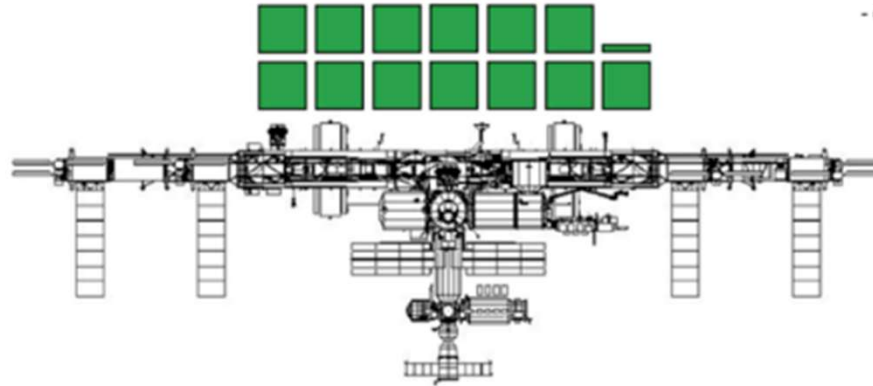
Why manufacture in space: The logistics quandary of long endurance spaceflight



Each square
represents 1000
kg

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

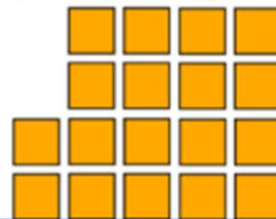


Predicted Annual Average Upmass 2012-2020

		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



- Based on historical data, 95% of spares will never be used
- Impossible to know which spares will be needed
- Unanticipated system issues always appear, even after years of testing and operations

* - Based on predicted MTBFs

Image credit: Bill Cirillo
(LaRC) and Andrew Owens
(MIT)



In-Space Manufacturing Removes Constraints

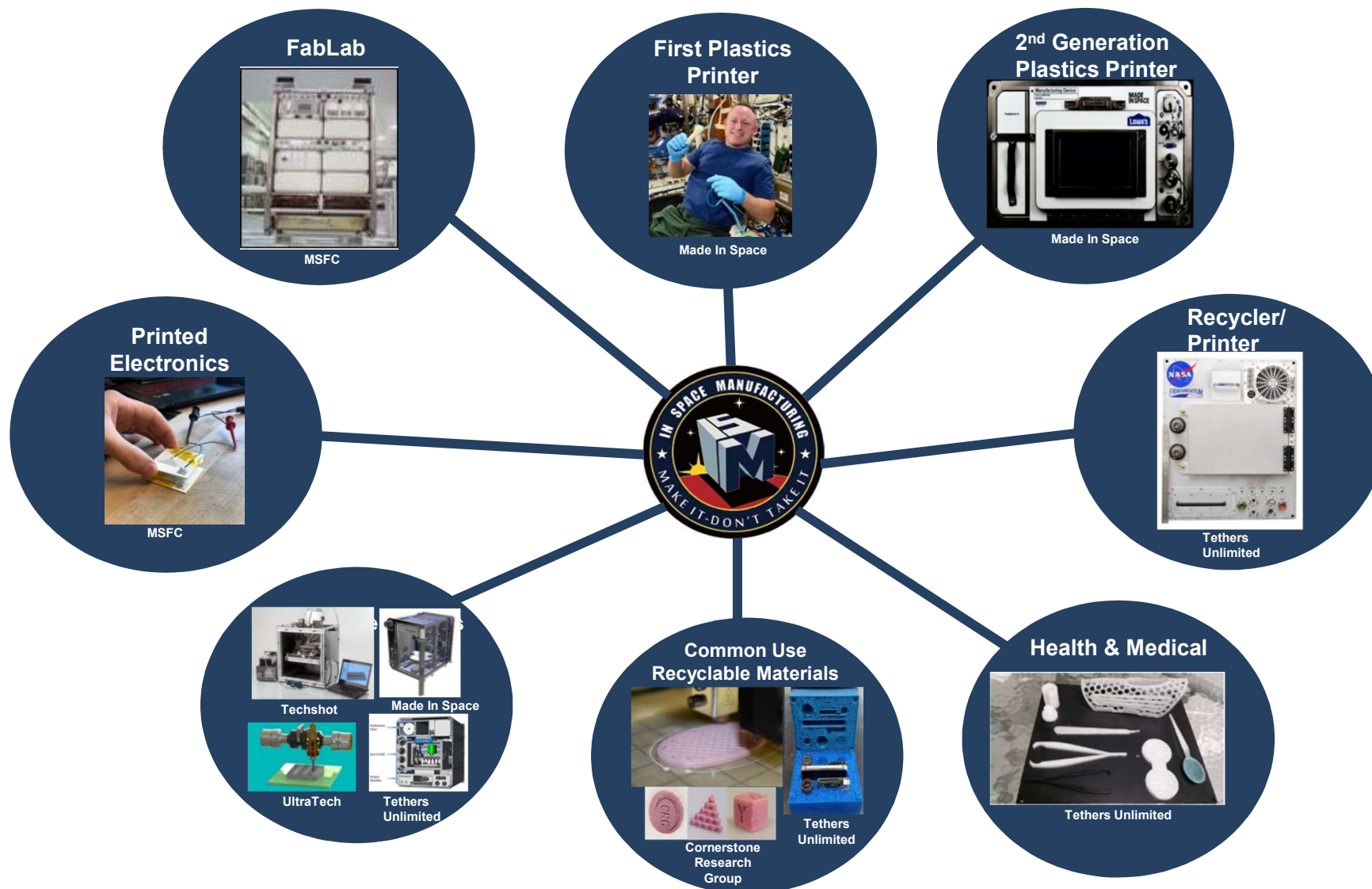


Constraint ¹	Constraint removed by ISM?
Structures must be designed for launch loads.	ISM enables structures which are optimized for operation in space, not for launch loads.
Structures must fit within launch vehicle payload fairings.	ISM enables structures whose size is limited only by the fabrication volume of the ISM capability.
Materials must be disposed of at the end of their lifecycle.	Materials can be recycled and used for further manufacturing.
All the spare parts and equipment needed for on-orbit servicing or repair and replacement activities must be prepositioned.	Spare parts can be made on-demand. ISM capabilities can enable on-orbit servicing and repair of equipment.
Component reliability and redundancy (R&R) largely driven by mission life/duration.	Redundancy is augmented by ISM capability to make components on demand. R&R requirements may be reduced in some instances when an ISM capability is present.

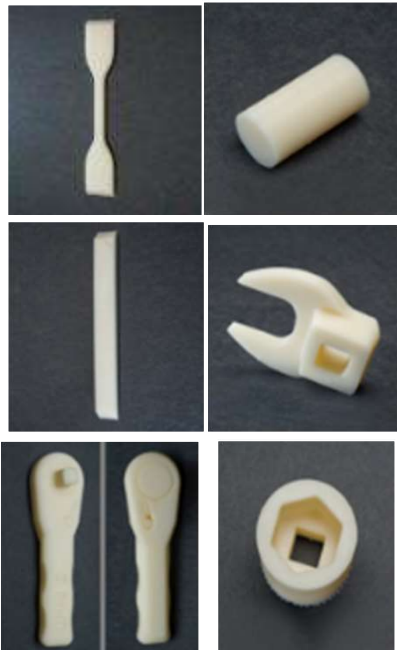
Paradigm shift

1. Table adapted from Moraguez, Matthew. "Technology Development Targets for In-Space Manufacturing." Master's thesis. MIT, 2018

In-Space Manufacturing (ISM) Project Portfolio



3D Printing in Zero G Technology Demonstration Mission



Phase I prints (Nov-Dec 2014) consisted of mostly mechanical test coupons as well as some functional tools

Phase II specimens (June-July 2016) provided additional mechanical test coupons to improve statistical sampling

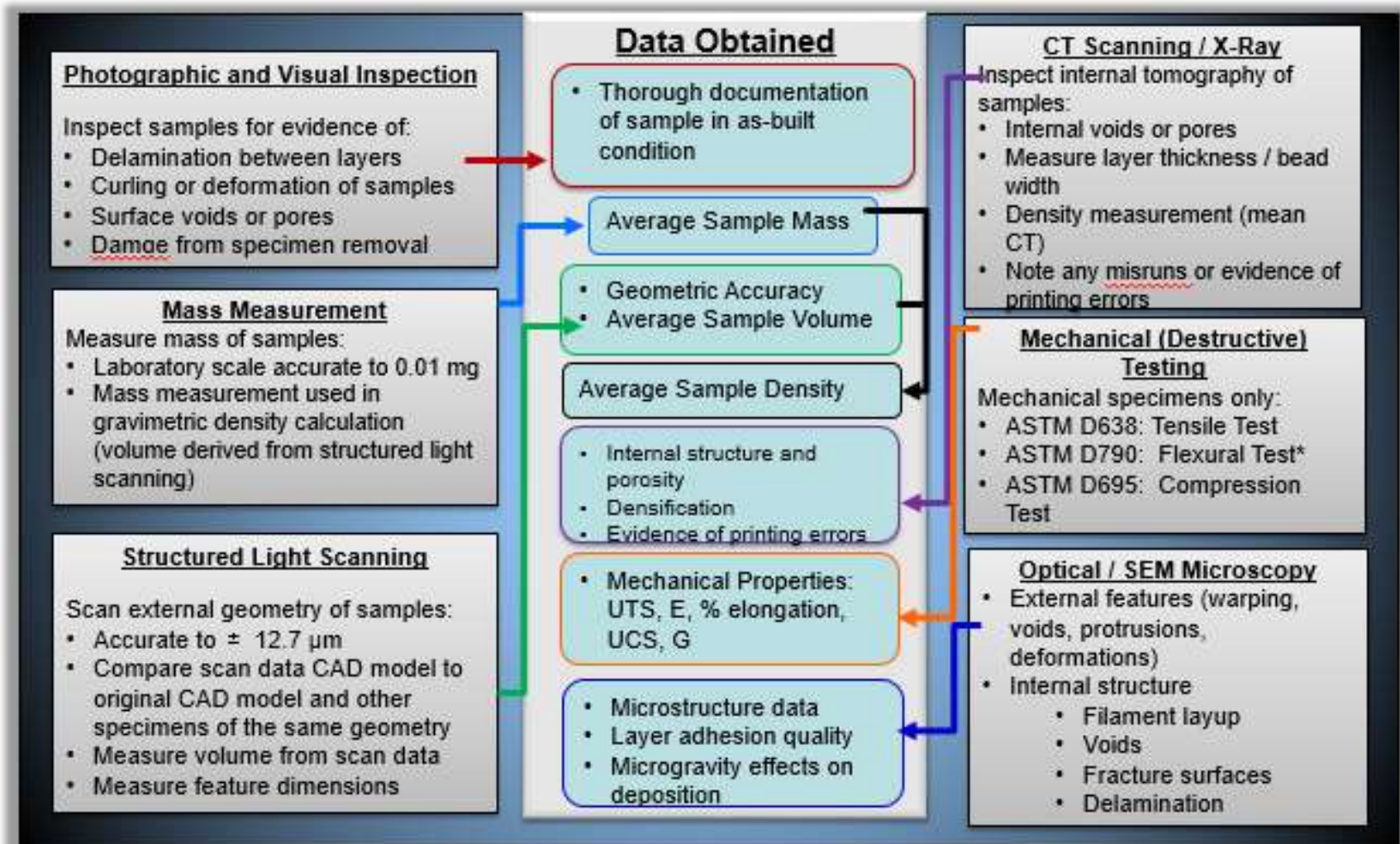
- ISM has been investigating use of fused filament fabrication (FFF) in microgravity since 2014.
- 3D Printing in Zero G Technology Demonstration Mission (first printer on ISS) manufactured 55 parts of ABS on-orbit.
- ISM is a user of the Additive Manufacturing Facility, a commercial facility from Made in Space, Inc. capable of printing with multiple thermoplastics: ABS, ULTEM 9085 (PEI/PC), and High Density Polyethylene (HDPE).
 - ISM is currently using AMF to conduct materials characterization studies of ABS using a composite testing methodology



3D Print Specifications

Dimensions	33 cm x 30 cm x 36 cm
Print Volume	6 cm x 12 cm x 6 cm
Mass	20 kg (w/out packing material or spares)
Power	176 W
Feedstock	ABS Plastic

Testing of specimens from the 3D Printing in Zero G Technology Demonstration Mission



*flexure specimens not part of phase II

Summary of results from 3D printing in Zero G Technology Demonstration Mission

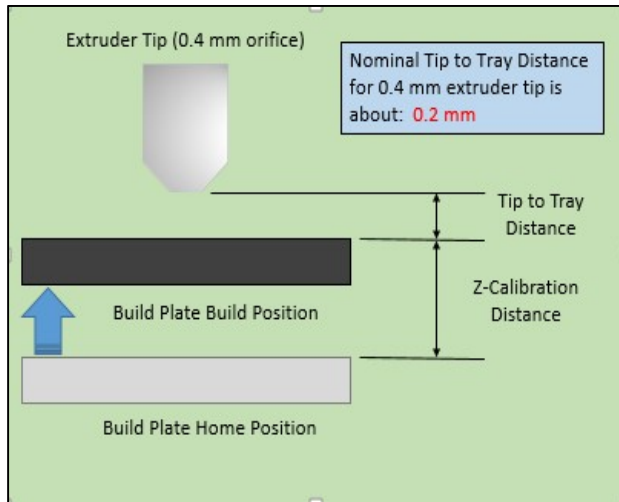
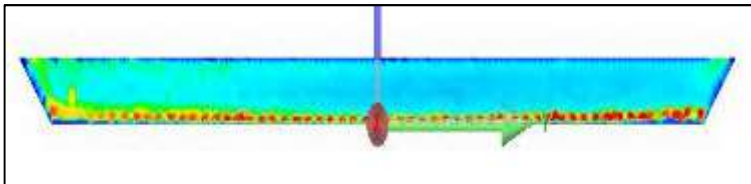


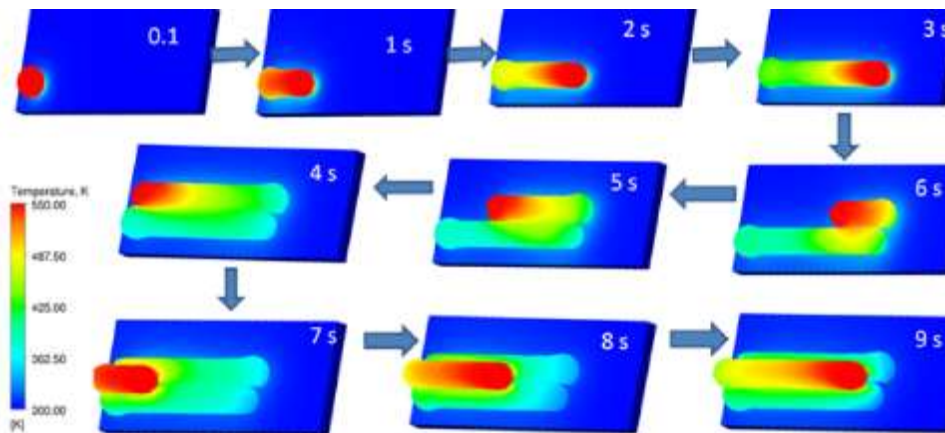
Illustration of variations in extruder standoff distance which contributed to variability in flight and ground prints.

Structured light scan of flight flexure specimen

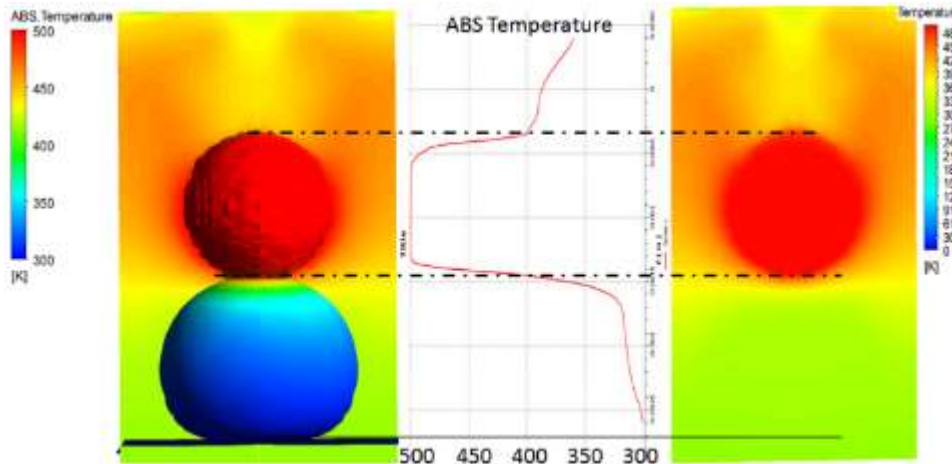


- Phase I and II flight and ground prints (ground prints were manufactured on the 3DP unit prior to its launch to ISS) showed some differences in densification, material properties and internal structure
- Differences were determined, through SEM analysis, chemical analysis of the specimens, and a subsequent ground-based study using the identical flight back-up unit to be largely an artifact of differences in manufacturing process settings between ground and flight. Variation is also hypothesized to be attributable to build to build variability
- Complete results published in *Journal of Manufacturing Technology Research*

Modeling and simulation of FFF in microgravity



- Objective is to model FDM process in space (initially for ABS) and predict structural properties of the manufactured parts
- Use physics based analysis of FDM to determine what physics phenomena may be distinct in space-based manufacturing
- Developed FE model in ANSYS CFX for coupled fluid flow and heat conduction problem associated with filament extrusion and deposition
 - Uses ABS parameters available in the literature
- Performed qualitative analysis of inter-diffusion between two molten roads based on polymer reputation theory for long-chain molecules
- Concluded that the reputation time is much smaller than the time to cool down to glass transition temperature
 - Filaments can be assumed perfectly welded
- ***No significant changes in road shape, filament temperature distribution, die swell, or evolution of temperature profile noted in modeling and simulation due to variation in gravity parameter***



Slide credit: Dr. Dogan Timucin, Ames Research Center

Use of the Additive Manufacturing Facility (AMF)



The Made in Space Additive Manufacturing Facility (AMF)

- Additive Manufacturing Facility (AMF) is the follow-on printer developed by Made in Space, Inc.
- AMF is a commercial, multi-user facility capable of printing ABS, ULTEM, and HDPE.
- To date, NASA has printed several functional parts for ISS using AMF



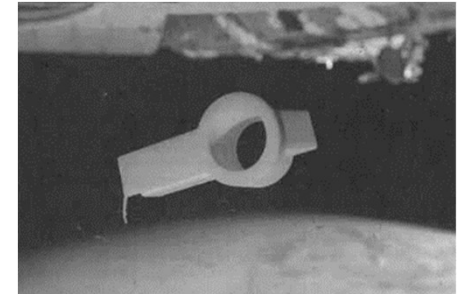
SPHERES Tow Hitch: SPHERES consists of 3 free-flying satellites on-board ISS. Tow hitch joins two of the SPHERES satellites together during flight. Printed 2/21/17.



REM Shield Enclosure: Enclosure for radiation monitors inside Bigelow Expandable Activity Module (BEAM). Printed 3/20/17 (1 of 3).



Antenna Feed Horn: collaboration between NASA Chief Scientist & Chief Technologist for Space Communications and Navigation, ISM & Sciperio, Inc. Printed 3/9/17 and returned on SpaceX-10 3/20/17.

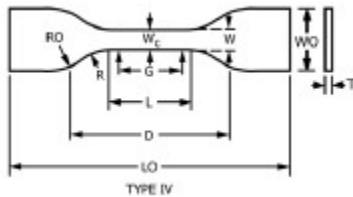


OGS Adapter: adapter attaches over the OGS air outlet and fixtures the velocicalc probe in the optimal location to obtain a consistent and accurate reading of airflow through the port. 7/19/2016.

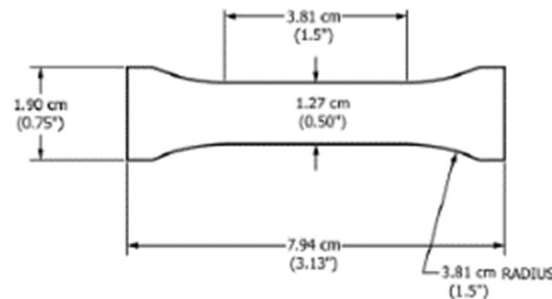
AMF materials characterization activities



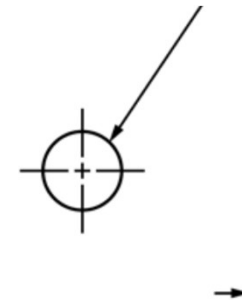
- To inform continued utilization of AMF by NASA, a materials characterization plan was developed and is now on contract with Made in Space
- Initial plan is to develop characteristic properties for ABS produced by AMF, but plan is extensible to other materials
- Testing methodology similar to composites. Test coupons are machined from printed panels (**4 mm thickness**).
- Panels printed at 0 (for tension and compression), 90, and +/-45 layup patterns.



Type IV tensile specimen from ASTM D638



Thin-type compression specimen from ASTM D695. Requires support jig.



Flatwise tension from ASTM C297. Used to measure tensile strength in the through thickness of the specimen.

Higher strength polymer feedstock development



- Development of feedstocks compatible with fused filament fabrication systems
 - Target property thresholds approach those of Aluminum alloys

Actuated Medical Inc. (AMI) SBIR (now in phase II)

- Carbon fiber reinforced PEEK (poly ether ether ketone) feedstock for 3D printing of medical devices and parts with strength requirements beyond those of traditional thermoplastic compositions
- Retrofit kit for standard desktop printers to enable printing of this feedstock in commercially available systems
- Laser-assisted heating following layer deposition significantly reduces anisotropy in the printed part

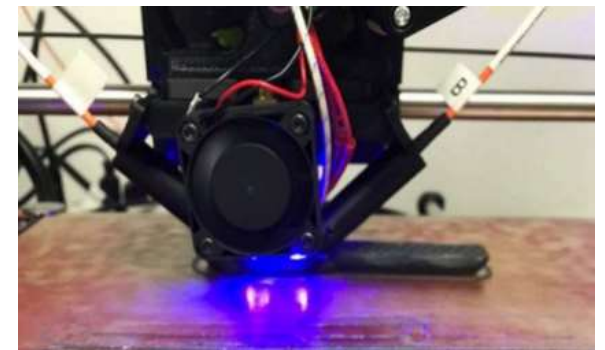


Image from Actuated Medical, Inc.

Geocomposites SBIR (now in phase II)

- Dual nozzle fused filament fabrication for printing of matrix with continuous fiber reinforcement
- Material strengths for some configurations are greater than 200 MPa in tension

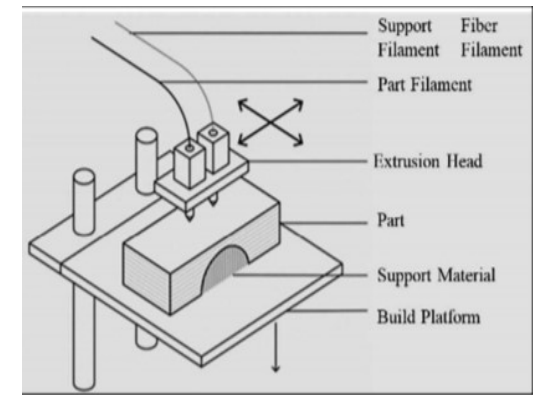


Image from Geocomposites



Recycling



- Recycling is critical to reducing logistics requirements for space missions and closing the manufacturing loop. ISM focuses on technologies to enable reuse of plastics, metals, and packaging materials.
- ISM manufacturing technology development for recycling capabilities
 - **ReFabricator payload from Tethers Unlimited, Inc. (TUI)** installed on International Space Station in early 2019.
 - capability to recycle printed polymer parts into filament feedstock for further manufacturing
 - **Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA), a ground based prototype system in development from TUI**, can process virgin or metal scrap material into ingots
 - Debris from machining of metal to fabricate a part is collected and can be used for further ingot manufacturing

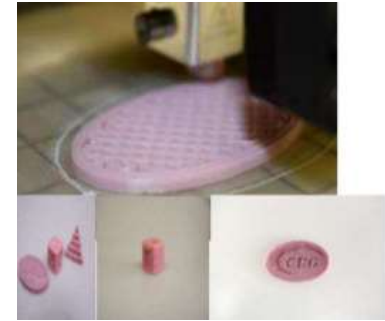


ReFabricator (image from TUI)

Enabling Technologies for the Recycling Ecosystem



- ISM also has the goal of developing recyclable packaging materials and sustainable approaches which enable a recycling ecosystem for ISS.
 - **Polyethylene based thermally reversible material** can be processed into films and foams and recycled into filament for 3D printing (Cornerstone Research Group)
 - **Customizable, Recyclable ISS Packaging (CRISSP)**
 - Polymer 3D printed foams with custom infills engineered for specific vibration attenuation properties (Tethers Unlimited, Inc.)
 - **ERASMUS is a multimaterial recycling capability** with an integrated dry heat sterilization chamber for polymer parts (Tethers Unlimited, Inc.)
 - **Automated in-process quality control of recycled filament production** and polymer 3D printing (Cornerstone Research Group)



Thermally reversible polymers for 3D printing (Cornerstone Research Group)



CRISSP from TUI



ERASMUS from TUI

Metal Additive Manufacturing for ISS (SBIRs)



- Challenges to metals fabrication in microgravity: power/volume/mass constraints, safety considerations, debris generation and control of debris (ex. machining), high temperature operating regimes for manufacturing and processing



Images from Fabrisonic

- Ultra Tech Machinery and Fabrisonic are developing the ultrasonic additive manufacturing process for use on ISS**
 - Creates metallurgical bonds via acoustic energy imparted to adjacent layers of material using a sonotrode

Metal additive manufacturing for ISS



Images from Made in Space, Inc.

- **Vulcan unit from Made in Space**
 - Derived from wire-fed welding process
 - Unit has multiple subsystems:
 - additive manufacturing unit (polymers and metals)
 - mill for finish machining
 - environmental control unit for debris capture
 - robotic capability for part manipulation

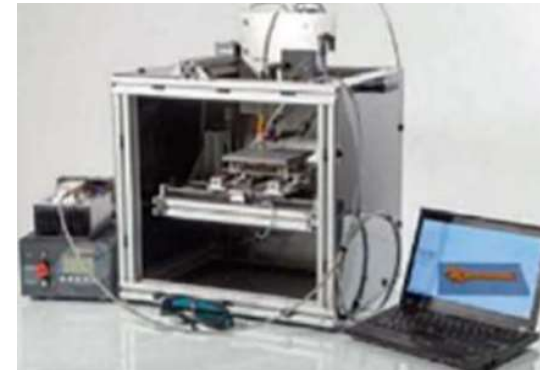


Image from Techshot, Inc.

- **Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) from Techshot, Inc.**
 - Wire-fed additive manufacturing process for metals
 - Uses inductive heating and operates in a vacuum
 - Low power laser provides additional heating



Multimaterial Fabrication Laboratory



Ultimately, an integrated “FabLab” facility with the capability to manufacture multi-material components (including metals and electronics), as well as automation of part inspection and part removal will be necessary for sustainable exploration opportunities.

Phase A of the Fabrication Laboratory effort focuses on demonstration of a metal manufacturing capability that is compatible with International Space Station (ISS) constraints

- 2000 W maximum power draw, 576 lb weight limit for system, 16 cubic feet of volume
- System must fit in an EXPRESS rack and also include an inspection capability
- Crew time requirements for part handling and processing should be minimized

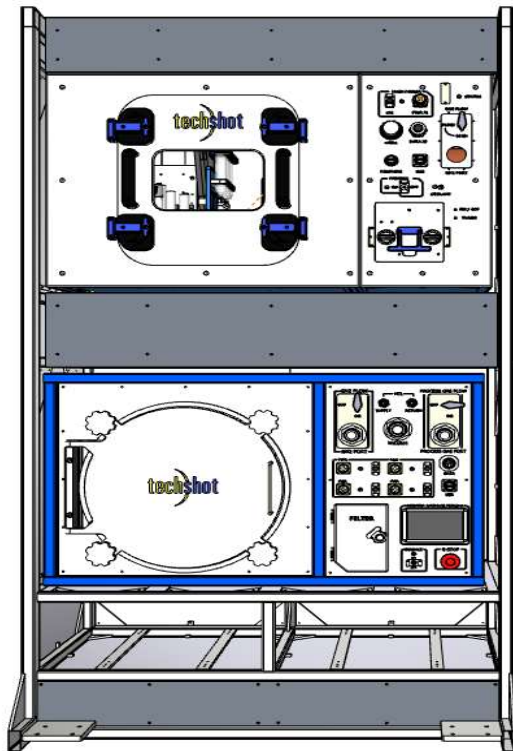
Techshot, Inc. and Tethers Unlimited, Inc. are currently funded under separate 18-month activities to develop ground-based prototype systems for demonstration under phase A.

Priority metal materials for phase A demonstration were identified by NASA as Ti-64 and AA 7075.

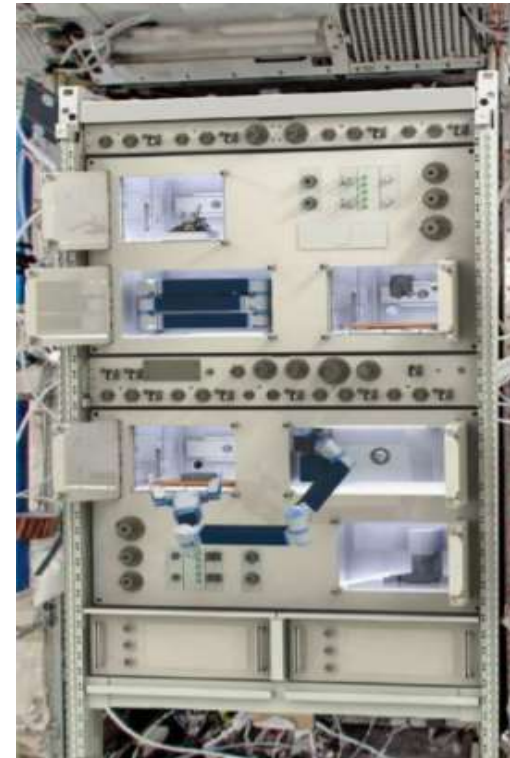


*Image of EXPRESS rack.
Image from NASA.*

Multimaterial Fabrication Laboratory



Techshot rendering of Multimaterial Fabrication Laboratory system, which includes capabilities for printing of metals, postprocessing of material, and in-process monitoring. Manufacturing technique is similar to bound metal deposition. Image from Techshot.



Empyrean Fabrication Laboratory concept rendering. Rack includes a robotic arm capability, control systems, and dimensional part inspection using structured light scanning. Image from TUI.

Printable Electronics



- A manufacturing capability for electronics will be needed to fabricate, assemble, and repair electronic parts on the long duration, long endurance missions NASA will pursue in the post-ISS era
 - Historically, many ISS system failures are electronic in nature
- **ISM is developing new on-demand printing and packaging technologies for next generation flexible, wearable sensor devices** which can be used in crew health monitoring applications (radiation exposure, carbon dioxide levels, cortisol, respiration)
- Other sensor applications include habitat monitoring and vehicle structural health monitoring
- Additional developments with on-demand printing capabilities include energy storage and power generation



Image of cortisol sensor (coin shown for scale)



First-generation CO₂ sensor

Printable Electronics



Evaluating technologies to enable multi-material, on-demand digital manufacturing of components for sustainable exploration missions

Material processing



nScript 3D
Multi-Material
Printer

nScript 3D multi material printer

- 4-head capability:
 - SmartPump for inks
 - 2 nFD heads for filament polymers
 - Pick & place head for discrete electronic components.
 - nMill for polishing, drilling, subtractive processing
- High precision 3D deposition in a 300x300x150mm volume. Developing materials and processes leading to a multi material FabLab for International Space Station.
- Recent addition of a laser sintering capability.



Voltera electronics
printer

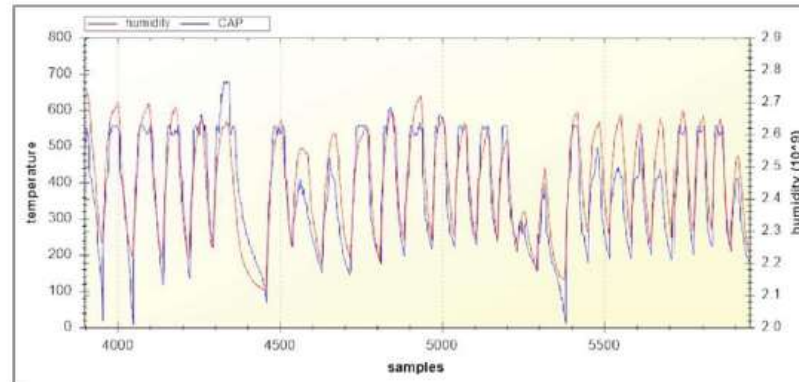
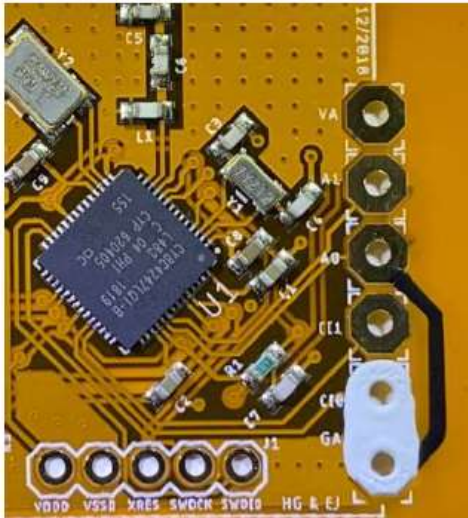


Voltera Electronics Printer

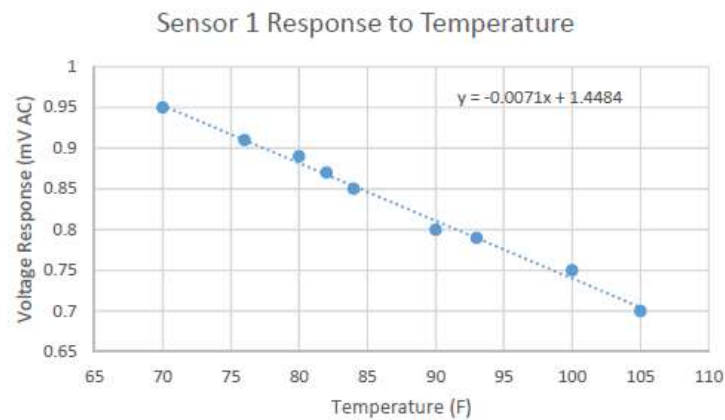
- Added in 2018 for quick-turnaround prototyping of sensors and testing of inks.
- Printing resolution is good for prototyping and general electrical circuits, but not fine pitch devices or tight line spacing.



Printable Electronics



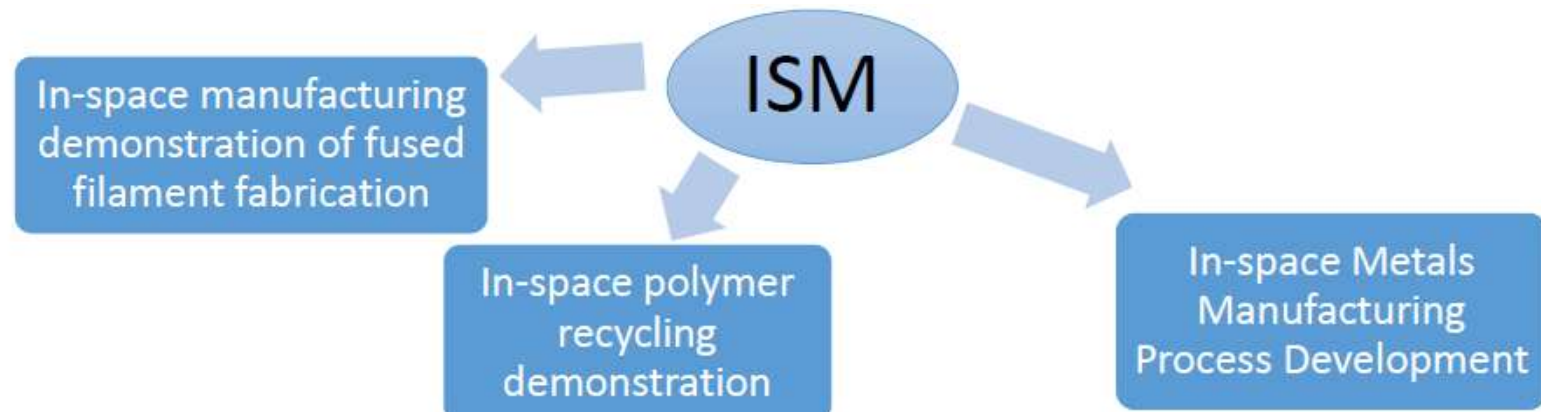
Humidity/Respiration
Sensor



Composite
Temperature &
Pressure Sensor



Physics-Based Materials Modeling



NASA Ames Research Center (ARC) physics group provides analysis and modeling support of in-space manufacturing. The ARC team has significant experience in modeling physics phenomena and materials in microgravity.

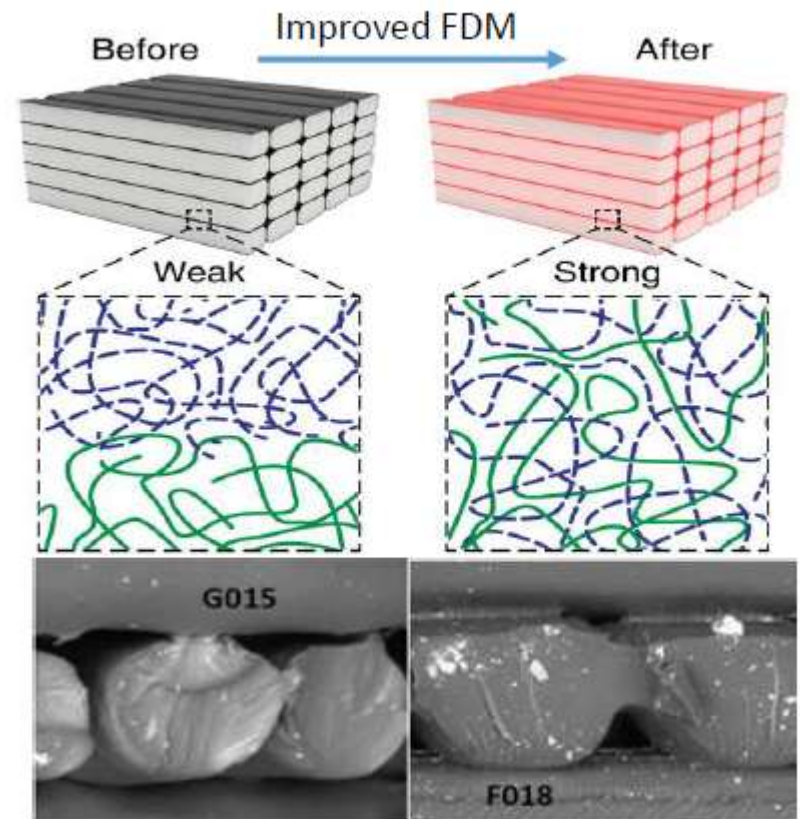
- Development and *validation* of computational models to support understanding of processes in zero-G environments
- Reveal specific features of materials manufactured in micro-gravity that are distinct from earth-processed specimens
- Enable physics based analysis of the ISM payloads before launch.
- Reveal possible gaps in experimental performance.
- Support verification and validation of parts manufactured in-space

Strength of the manufactured parts (elastic moduli, fracture strength and toughness, anisotropy, plasticity etc.) is determined by the properties of material and filament interfaces.

The interfacial properties are controlled by welding.

In turn, welding process is controlled by entanglement and diffusion of polymers which strongly depend on

- Molecular conformation
- Temperature - glass transition temperature
- Molecular orientation in deposition flow
- Polymer alignment
- Rheology of entangled polymers: Non-Newtonian and non-linear properties



Physics-Based Materials Modeling

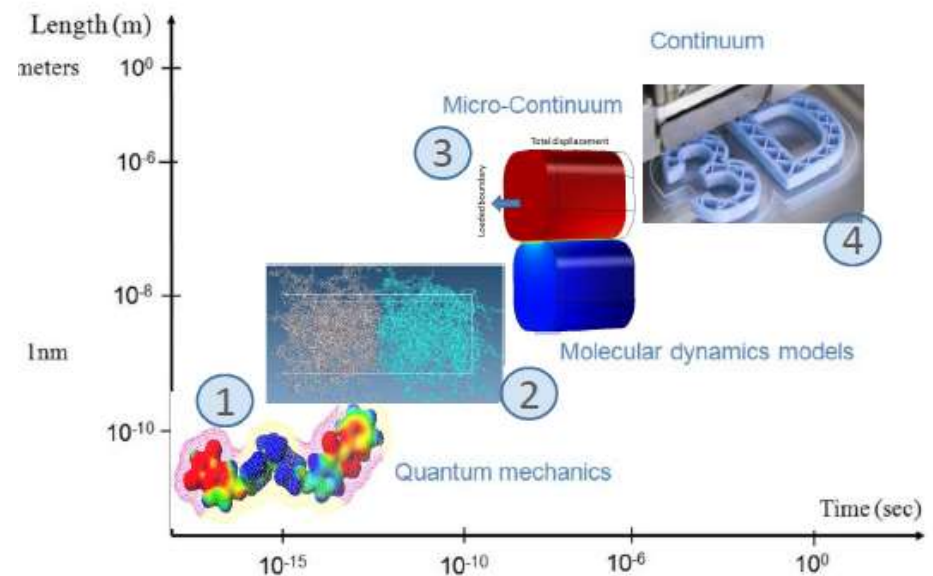


ARC developed a novel multiscale approach to support additive manufacturing of polymers in space

- The models in the multiscale approach extend from (1) quantum mechanical models of the monomers (bottom left), (2) fully atomistic model of the interface, (3) microscopic continuous model of the filament interface, and (4) model of the bulk manufactured parts.

- The proposed approach was applied to analyze polymer 3D printing

- Currently we are extending the approach to encompass analysis of a metal manufacturing process



- ISS databases cataloging part failures and problem reporting
- Heritage environmental control and life support systems (ECLSS)
- ISS medical toolkit manifest
- Intravehicular Activity (IVA) Government Furnished Equipment (GFE) Flight Crew Equipment (FCE) manifest
- In the next year, the database will also expand to include heritage spacesuit components

A NASA Space Technology Research Fellowship (NSTRF) student is using ISS and ISM databases to develop a systems modeling framework for assessing the utility of a manufacturing process in various mission scenarios

Multi-Purpose Precision Maintenance Tool



Description

Author/Origin: Robert Hillan, Future Engineers Challenge

Relevant Mission: Future Engineers Space Tool Design Competition

Date Added: June 20, 2016

Keywords: International Space Station, ISS, Tools

GitHub Repository: [Multi-Purpose Precision Maintenance Tool](#)

*Example of a part database entry
from the NASA Ames Research
Center 3D Resources website:*
<https://nasa3d.arc.nasa.gov/>



Summary



- In-space manufacturing represents a suite of manufacturing technologies available to crew on long duration missions to reduce logistics and provide a capability for on-demand repair and replacement.
- ISM requires integration with space systems designers early in the development process
- To make use of ISM, systems must be designed for accessibility and maintainability
- The ISM design database activity will be used in part to define the “what we make” of ISM and will be a key driver for requirements of ISM platforms going forward
- While ISM is currently defined as manufacturing in a crew (intravehicular – IVA) environment, processes are extensible to on-orbit manufacturing of larger than payload-faring structures and planetary surface manufacturing



Manufacturing in the External Space Environment: Archinaut*



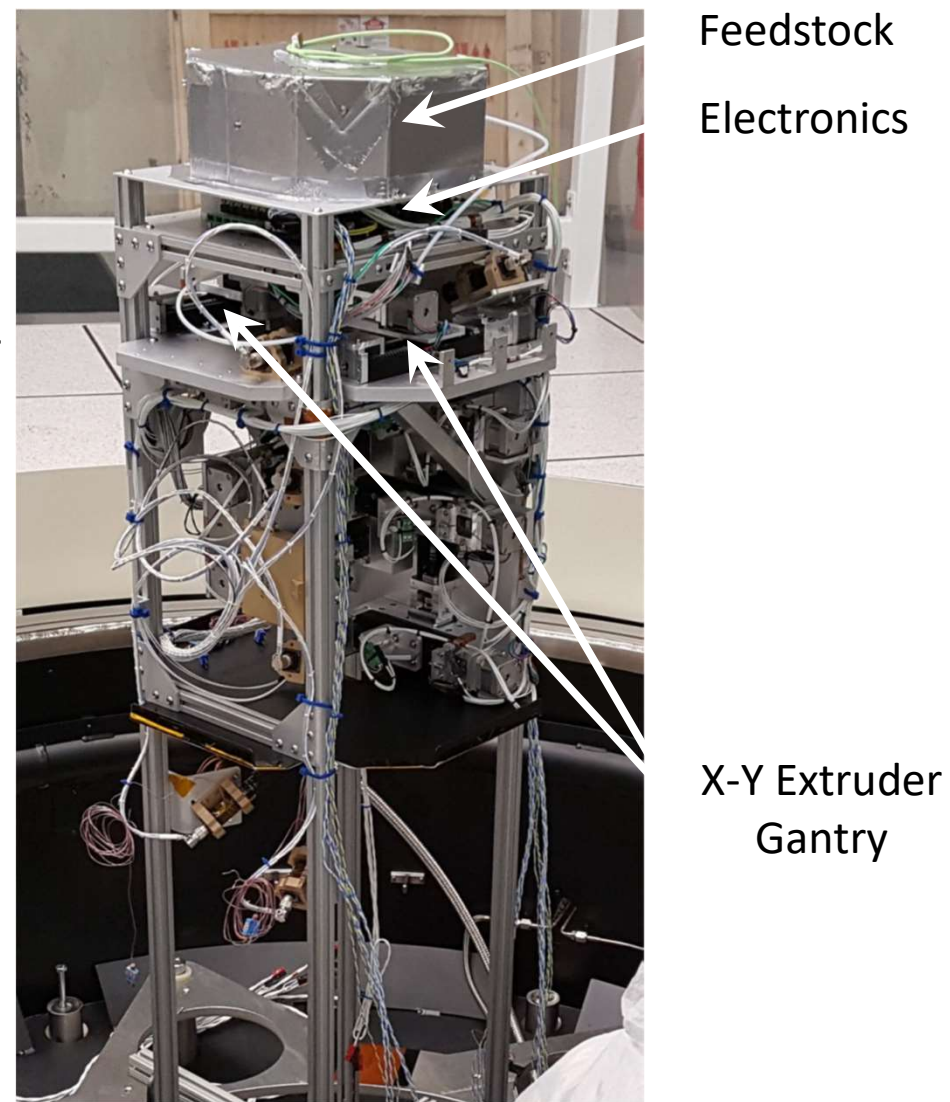
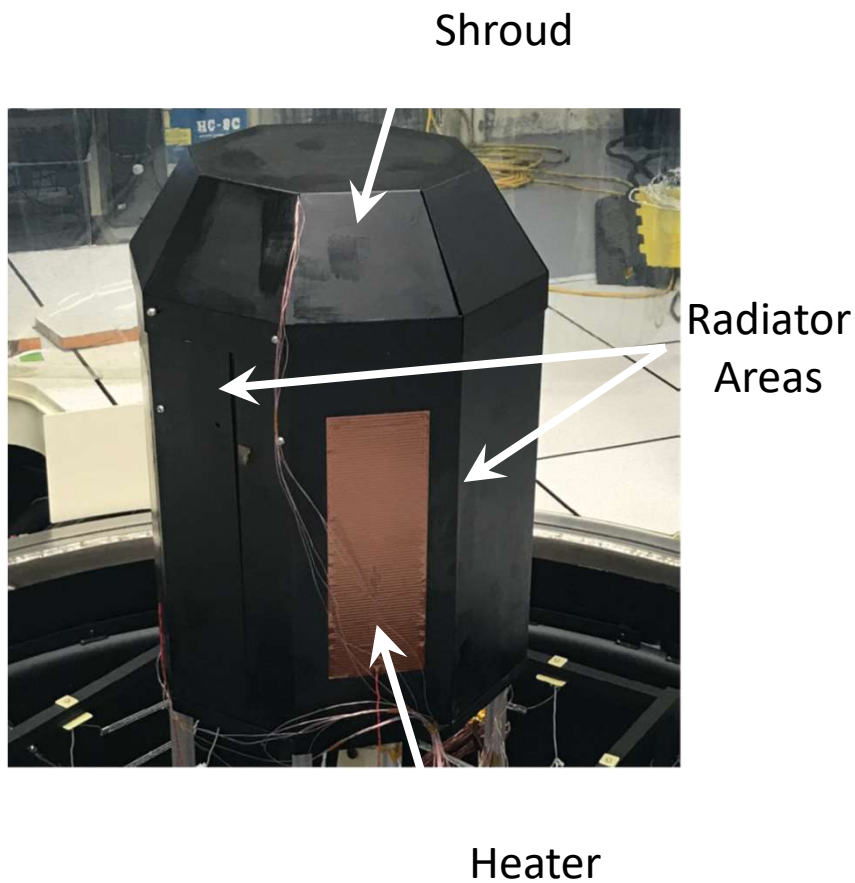
Made In Space, Inc., (MIS) is developing Archinaut, an in-space robotic precision manufacturing and assembly system for larger-than-deployable structures

- Extruder that successfully operates in space-like environment
 - Traversing system for out-of-volume printed part manipulation
 - Robotic assembly for printed and pre-fabricated simulated spacecraft parts
 - In-Situ Inspection and Validation of printed parts
-
- Polyetherimide-polycarbonate (PEI/PC) selected as primary print material
 - Demonstrate extended structure additive manufacturing of structures in a space-like environment using Extended Structure Additive Manufacturing Machine (**ESAMM**)
 - Demonstrate additive manufacturing and assembly of structures in a space-like environment using Ground-Based Manufacturing and Assembly System Hardware (**GBMASH**)

*Archinaut is not part of ISM project portfolio

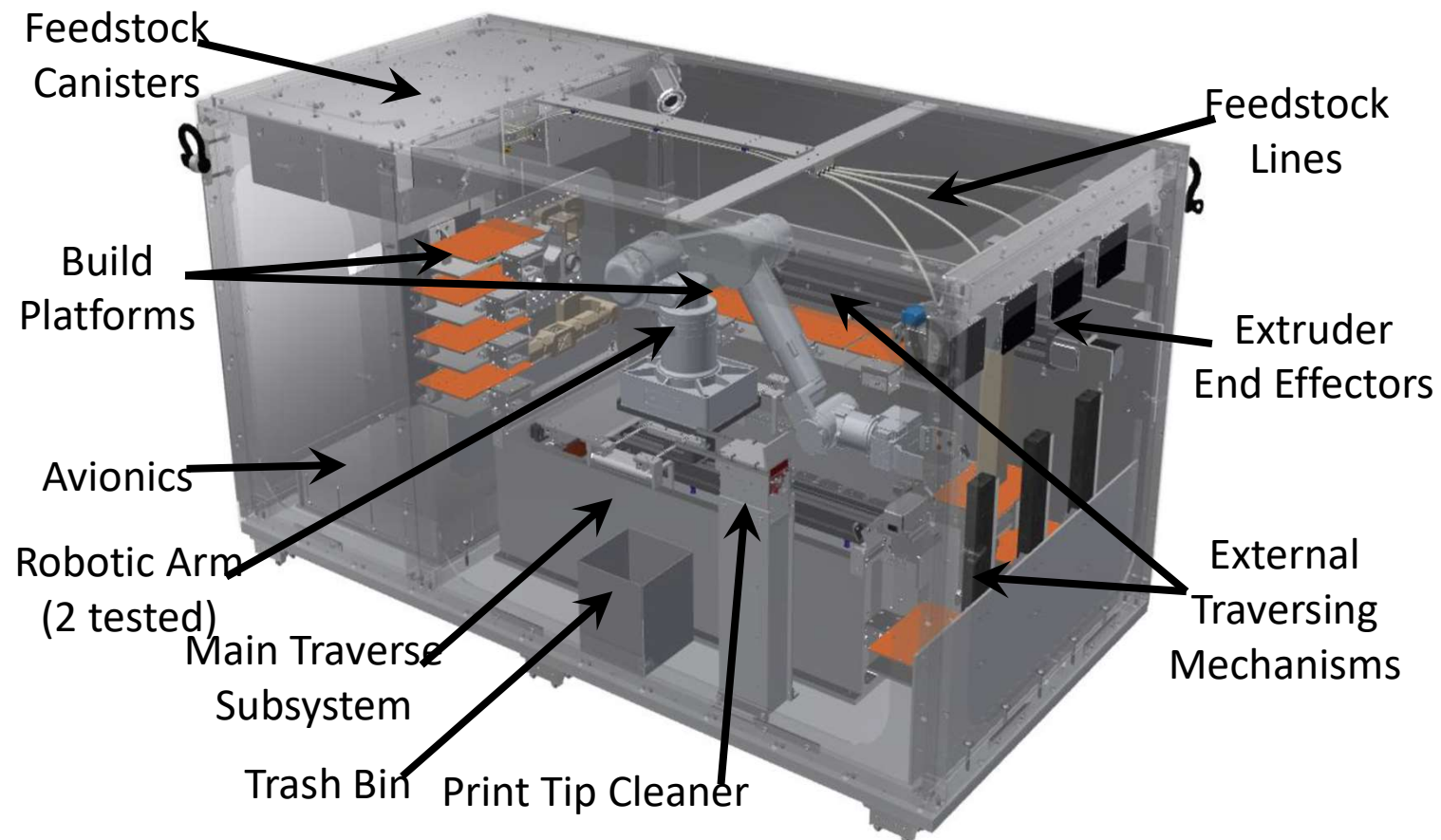
Slide credit: Lawrence Huebner, NASA LaRC

Archinaut: ESAMM



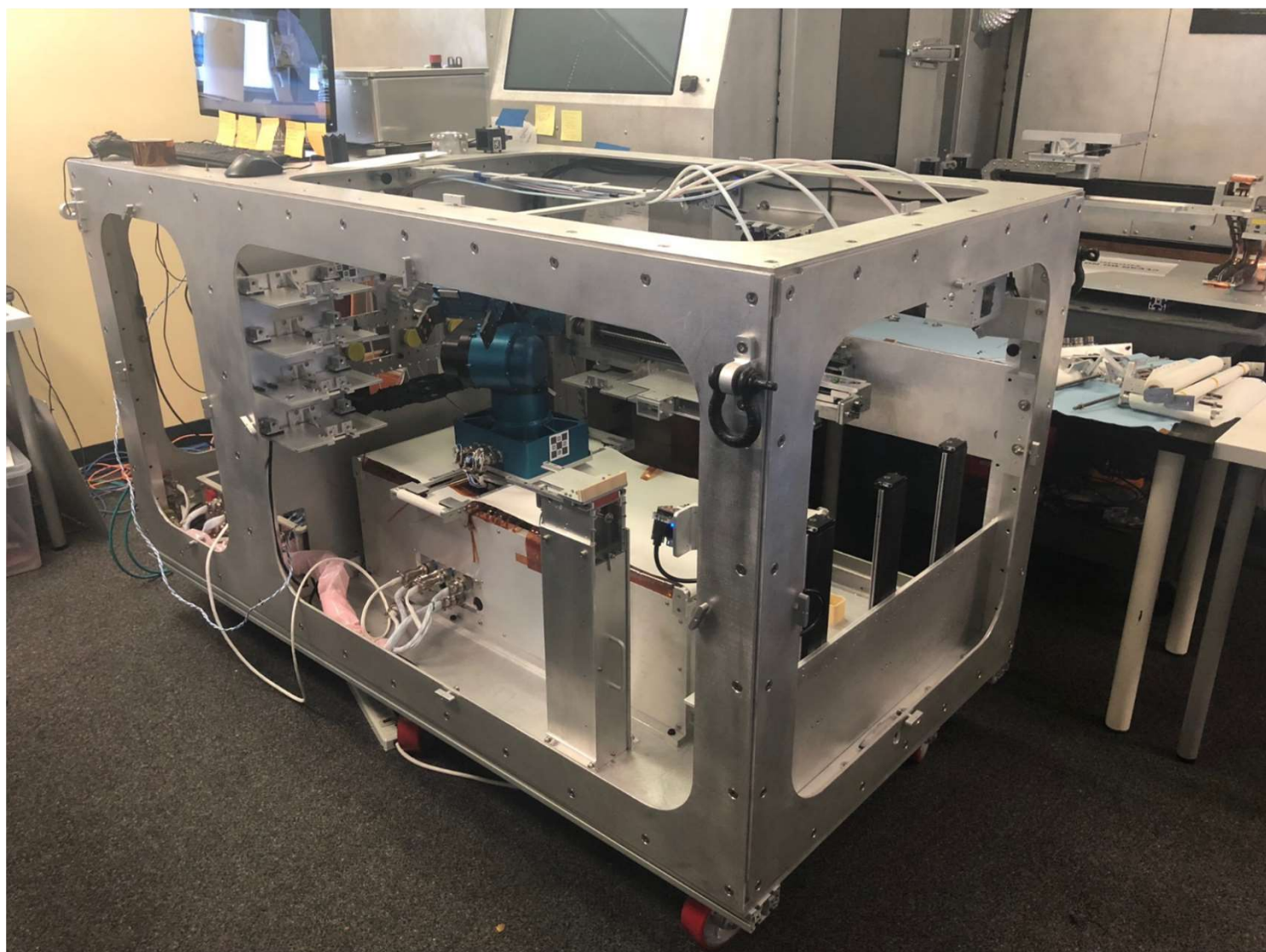
Slide credit: Lawrence Huebner, NASA LaRC

Archinaut: GBMASH



Slide credit: Lawrence Huebner, NASA LaRC

Archinaut: GBMASH



Slide credit: Lawrence Huebner, NASA LaRC

Archinaut Phase I Outcomes



- Test Flow
 - Print thin wall beam, ambient
 - Vacuum hot (50°C) survival/aliveness test
 - Vacuum cold (-20°C) survival/aliveness test
 - Print 300-mm-long thin wall beam, vacuum/cyclic temperature (0-40°C)
 - Print 850-mm-long thin wall beam, vacuum/cyclic temperature (0-40°C)
- First known 3D print demonstration in a simulated external space environment
- Post-print inspection, material characterization, and structural/mechanical properties performed on printed parts

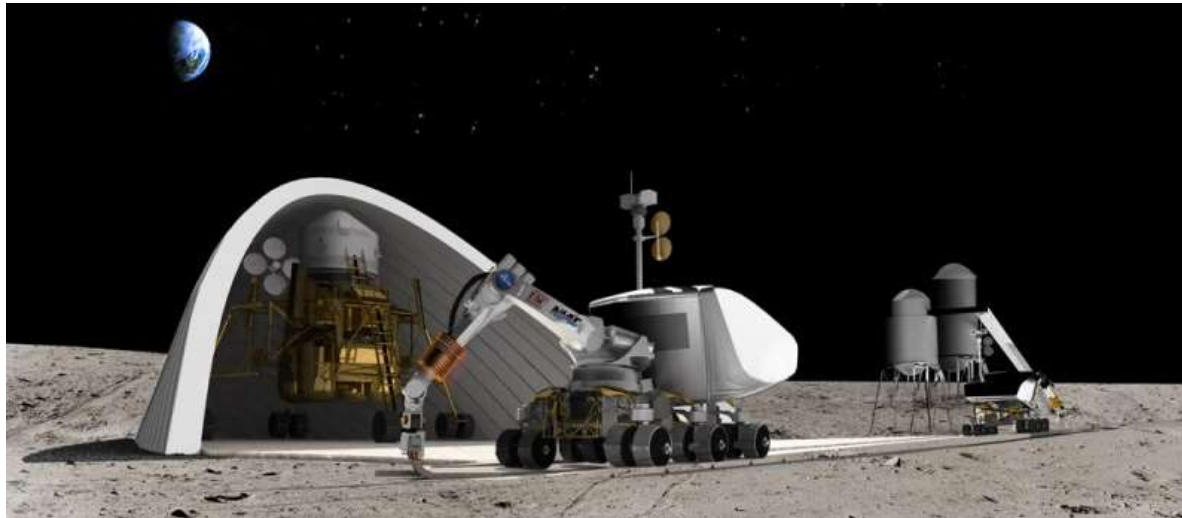


Slide credit: Lawrence Huebner, NASA LaRC

Planetary Surface Construction*



- **Advantages of 3D Automated Additive Construction (3DAAC):**
 - Removes design constraints (“manufacturing for design”)
 - Enables building and testing earlier in project lifecycle
 - Ability to work with new material formulations
 - Maximize use of in situ resources (planetary surface)



Artist's rendering of a manufacturing operation on a planetary surface.

Image credit: Contour Crafting Corp / NASA

<https://arch.usc.edu/topics/nasa-research>



Common Large Scale Printing Processes for Construction



Examples of common printing processes for construction:

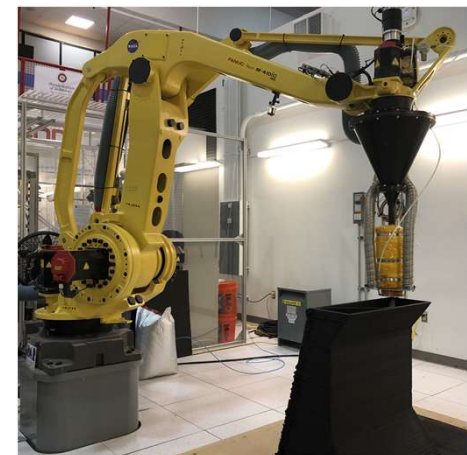
1. Cement-based materials extruded through a nozzle
 - Process used by NASA/Army Corps of Engineers/Contour Crafting in the Additive Construction for Mobile Emplacement project
2. Forced extrusion of wire, filament or pellets
 - Process used by many desktop printers

In general, printing systems take the form of:

1. Gantry style systems
 - Extruder is attached to frame that translates in three dimensions
2. 4-6 degree of freedom robotic systems
 - Extruder is the end effector of an industrial robot arm



NASA Additive Construction for Mobile Emplacement (ACME) / ACES US Army Corps of Engineers

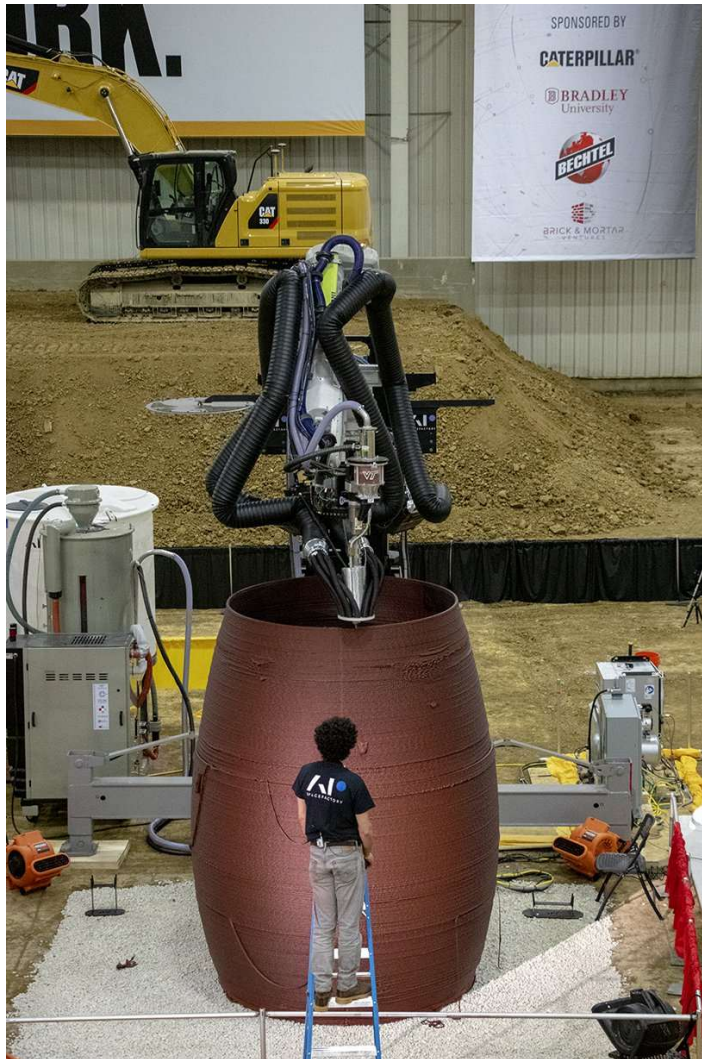


NASA KSC Swamp Works

NASA's 3D Printed Habitat Challenge



Head to head competition from April 29-May 4, 2019 at Caterpillar's Edward Demonstration Facility in Peoria, Illinois, USA



Penn State University



AI Space Factory



Head to head competition from April 29-May 4, 2019 at Caterpillar's Edward
Demonstration Facility in Peoria, Illinois, USA



Penn State University



AI Space Factory



Workshop: It's Your Turn!



Now it's your turn to make recommendations and provide inputs!

Use the sticky notes on your table to generate your ideas in response to the following questions:

1. What processes should we adapt for in-space manufacturing? What is of the “greatest good to the greatest many”?
2. What materials can we use as feedstock?
If a material or waste product can be recycled or used in another manufacturing process, identify it. Think at a system level. “One process’s trash is another process’s treasure.”
3. What ancillary processes are needed (example: extraction)?
4. What are the key applications for in-space manufacturing? What would **you** make with these capabilities on a space mission? How would you use these capabilities in a novel way that hasn't been discussed here?
5. What are the biggest barriers to in-space manufacturing implementation?



Workshop Directions



- Place sticky notes for each category on the appropriate wall.
- For each post-it, identify the mission scenario or scenarios you see as most applicable. Possibilities include:
 - International Space Station (ISS)
 - Low earth orbit (LEO): freeflyer or other persistent platform
 - Gateway (platform in lunar orbit)
 - Lunar surface (LS)
 - Mars Transit Vehicle (MTV)

Identify the time frame for implementation (10 years, 20 years, etc.)

Please take 15 minutes for this brainstorming activity.



Workshop Directions



- Go to the topic you are most interested in. Spend about 15 minutes consolidating and summarizing the ideas generated.
- Present your topic to the larger group for discussion.





Acknowledgments



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Meyya Meyyappan, NASA Ames Research Center

Curtis Hill, NASA MSFC

Tethers Unlimited, Inc.

Cornerstone Research Group

Geocomposites

Geocent

Ultra Tech Machinery

Fabrisonic

Techshot, Inc.

Made in Space, Inc.

Any mention of commercial products or vendors is for information only;
it does not imply recommendation or endorsement by NASA.