Committee on Space Based Additive Manufacturing

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Statement of Task

- The National Research Council has appointed an *ad hoc* committee **to explore the implications of space-based additive manufacturing** technologies for space operations and the manufacture of space hardware. In conducting the study and preparing its report the committee will:
  - **Assess** the current state of additive manufacturing
  - **Characterize the future states** envisioned
  - Discuss the **feasibility of the concept** of space-based additive manufacturing of space hardware (including, but not limited to, a fully functional small spacecraft)
  - Identify the science and technology **gaps** between current additive manufacturing capabilities and the capabilities required
  - Assess the **implications** that a space-based additive manufacturing capability would have **on launch requirements**

Statement of Task (2)

The committee may also consider the following:

- The potential **mission payloads and capabilities** that could be expected from a space-based, **additively manufactured s**pacecraft
- The role in potential missions for a single spacecraft system manufactured in space by additive manufacturing or for multiple spacecraft systems, including **disaggregated constellations and fractionated satellites**
- **Concepts of operations for space-based manufacture** of space hardware (including small spacecraft) using additive manufacturing
- Whether it is possible to develop a **high-level heuristic tool** for first-order **assessments of space-based, additively manufactured small spacecraft concepts** in their integrated planning and process efforts.

Focus on 20 to 40 years down the road

Direction from sponsor summed up as:

"If what you're doing is not seen by some people as science fiction, it's probably not transformative enough."

Sergey Brin, Google Co-Founder, Google Driverless Car Project

Potential Applications/Impacts

- Tools and spare parts on ISS
- Repair on-orbit instead of launching new satellites
- Reducing logistics footprint on human space missions (for instance, packaging materials)
- Construction of large structures in space (antennas, support structures)
- Construction of habitats on planetary surfaces
- Manufacturing spacecraft parts (solar panels) or even entire spacecraft in space
- IMPACT – Changes to the basic architecture of space

Note: there are several companies (e.g., Lockheed Martin, Orbital Sciences) that are already working on additive manufacturing of entire spacecraft on the ground.

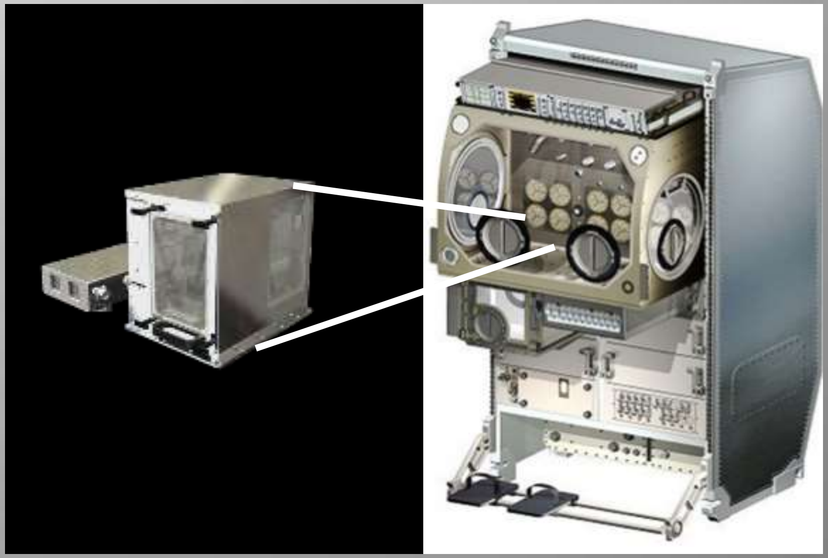
Meeting 1

- **August 20-22, Washington**
  - **Heard from sponsors: Space Command, AFRL, NASA OCT.**
  - **Made In Space Inc.**
  - **Experts in additive manufacturing field.**

Initial ISS Mission

3D Print – Proof of Concept Experiment

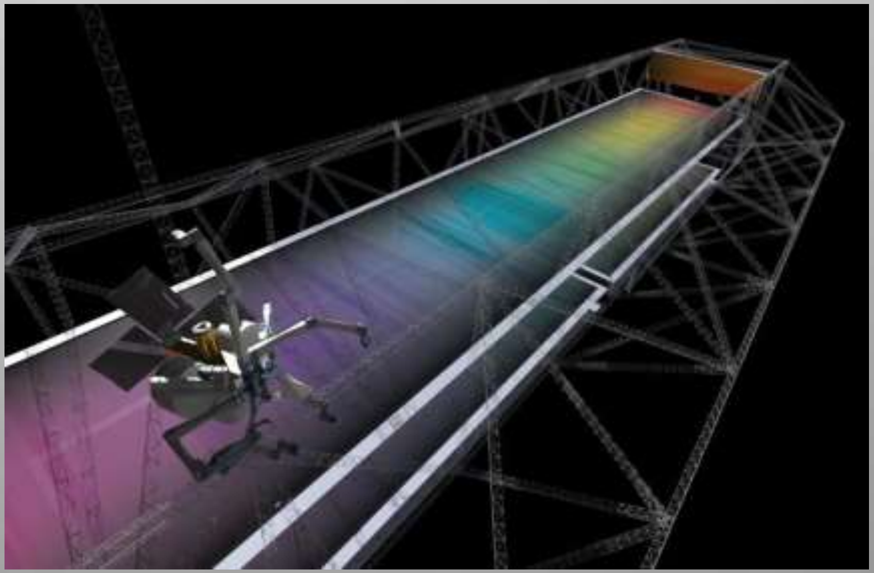
- Partnered with NASA to perform the “3D Printing in Zero-G Experiment”.
- Proving ground for later technologies.
- Launch manifested: SpaceX-5, 2014.



Meeting 2

- November 12-14, Irvine
  - Will hear from NASA STMD.
  - Other experts in additive manufacturing field.
  - Tethers Unlimited.

Tethers Unlimited received NIAC Phase II award for its Spiderfab work



Next Steps for COSBAM

- November meeting, 1-2 more meetings in early 2014.
- Preparation of report, delivery to NASA and USAF late spring/early summer.

BACKUP SLIDES

What is Additive Manufacturing?

“Process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies”

- $3 billion global industry in 2012*
- $6.5 billion projected by 2019*

F42 Standard Process Name	Companies (Country)
Binder jetting	3D Systems/Z Corp (USA) ExOne (USA)
Directed energy deposition	Optomec (USA) POM (USA) Sciaky (USA) Stratasys (USA)
Material extrusion	Makerbot (USA) Bits from Bytes (UK)
Material jetting	Solidscape (USA) Objet (Israel)
Powder bed fusion	3D Systems (USA) EOS (Germany) ReaLizer (Germany) Arcam (Sweden)
Sheet lamination	Fabrisonic (USA) Mcor (Ireland)
Vat photopolymerization	3D Systems (USA) Envisiontec (Germany)

* Wohlers Report, 2012

Evolution of the Field

- Started in mid-1980’s as rapid prototyping
  - Method to quickly create product prototypes
  - Several processes developed in industry and academia, mostly plastics
  - Key support came from ONR, DARPA, and NSF
- Progressed through 90’s and 00’s
  - New materials—metals (steel, Ti, others), ceramics
  - New processes improve material, surface properties, speed, energy efficiency
  - Field of competing processes now include fused deposition, laser sintering, e-beam melting, others
- 2012-13 Industry Consolidation

Benefits and Drawbacks

- Benefits:
  - Complexity for free—effort independent of design
  - Speeds up product development
  - Scale up from one
    - Mass customization
    - Competition on design/innovation, not labor/capital costs
  - Higher material yields/less waste
  - Reduces need for inventory
- Drawbacks:
  - Expensive—materials and speed
  - Material and surface properties
  - Size limitations

Future

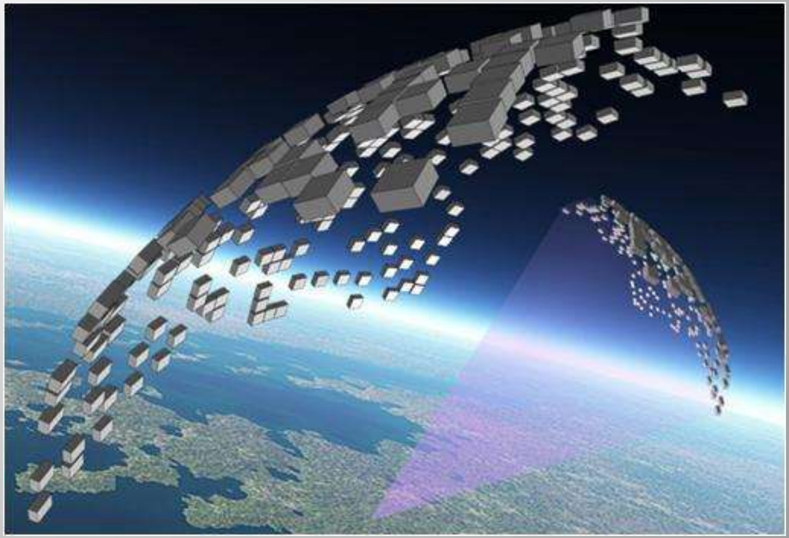
- Processes will continue to improve
  - Use of new and multi-materials (5-10 yr)
  - Hybridization of techniques (5-20 yr)
    - Between AM processes
    - AM and subtractive processes
  - Parallelization of techniques (5-20 yr)
  - Closed-loop sensing and controls for QA/QC (5-10 yr)
  - More competition as patents expire (5-10 yr)
  - Volume-based build (>20 yr)

Applications

- Aerospace
  - Engine parts
  - In situ manufacturing in space
- Medical
  - Traditional materials (surgical tools, planning, implants, 5-10 year)
  - Biofabrication (regenerative med, drug testing/delivery, 10-20 year)
- Consumer
  - Print products at home via digital design repositories (5-10 year)
  - New methods of product delivery—Amazon model, Kinko’s model, iTunes model (5-10 year)
  - Democratization of design—more designers of more products (5-10 year)

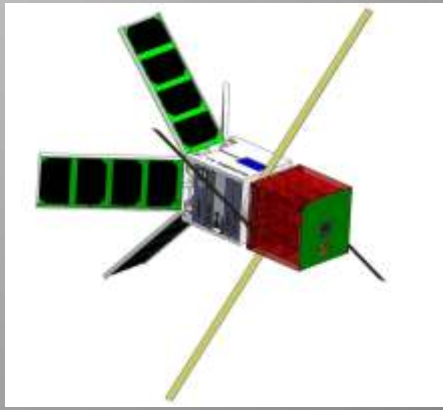
Missions of Interest

- **Swarms**
  - A standalone CubeSat mfg. platform could build swarms on demand on-orbit.
  - Dedicate more mass towards propellant & keep units in orbit longer.
  - More cost effective method of replacing single units when needed.
- **Mission Flexibility**
  - Any time you DON'T know what you need until you get there.
- **Secrecy**
  - If you DO know what you need but you don't want others to know.
- **Robotic Servicing Missions**
  - Ie. DARPA Phoenix Mission 2.0.



Example spacecraft swarm(above).

70% 3D Printed CubeSat, including propulsion, launched this year (right).



Barriers

- Lack of high-$ commercial funding
- Cost competition with established processes
- IP challenges—who owns, profits from digital designs
- Liability and regulation
  - Who is responsible for self-manufactured digital designs?
  - FDA, DoD approval for use
- Size, speed, property limitations
- Lack of design tools

ASTM Technologies	Material	CURRENT Strengths	CURRENT Weaknesses	Surface	Space
Vat Photo-polymerization	Photopolymer	Accurate compared to other technologies; creates relatively fine features; ideal for prototyping	sensitive to radiation, may result in degradation in space; difficult to handle in space; limited long-term stability	?	-
Material Jetting	Photopolymer, wax	Build material contained in “cartridges” so storage is less difficult than for vat-based processes;	Liquid droplets can be problematic	x	-
Binder Jetting	Metal, polymer, ceramic, Foundry Sand	great architecture for building structures from powders on the Moon or Mars; Allows for creation of large shapes without needing to bring all of the raw materials with you; a potentially good architecture for printed electronics in space	Presence of both powders and liquid droplets; without post-processing material properties are weaker	x	-
Material Extrusion	Polymer	Least expensive; Solid filaments and viscous melts make it highly controllable in a zero-gravity environment; Relatively cheap simple machine architecture makes it easy to customize a machine for Space; Can be used as a “concrete” manufacturing machine for creating structures on the Moon and Mars	Weaker parts due to poor interlayer bonding; material is expensive	x	x
Powder Bed Fusion	Metal, polymer, ceramic	Good material properties; relatively fine feature till 0.1 mm; Lasers can melt or sinter almost anything	Powders are problematic in zero gravity	x	-
Sheet Lamination	Hybrids, metallic, ceramic	Raw material is easily transportable and simple to handle in a zero or low gravity environment	Material inefficiencies and lack of recycling make it a poor choice for space – Lots of waste material	?	-
Directed Energy Deposition	Metal (powder, wire)	Wire plus electron beam is a great combination; Needs a vacuum; Wire is more easily handled in low gravity; – Electron beams are energy efficient; A movable gantry system enables build-up of structures that are larger than AM machine; Powder plus laser might be a good platform for Mars or Moon	have a high material deposition rate, but relatively low resolution	x	x

	1. Vat Photo-polymerization	2. Material Jetting	3. Binder Jetting	4. Material Extrusion	5. Powder Bed Fusion	6. Sheet Lamination	7. Directed Energy Deposition	Other Processes (or hybrid)
Manufacture spacecraft in orbit								
Complete*	?	?	?	?	?	?	?	?
Components**	x	x	x	√	x	x	√	?
To be assembled manually	x	x	x	√	x	x	√	?
Robotically	x	x	x	√	x	x	√	?
Manufacture components* in orbit/on space station	x	x	x	√	x	x	√	?
To be assembled manually	x	x	x	√	x	x	√	?
Robotically	x	x	x	√	x	x	√	?
Manufacture habitat or devices on a planetary body	x	x	x	√	x	x	√	?
Complete	?	?	?	?	?	?	?	?
Components	√	√	√	√	√	√	√	?
To be assembled manually	√	√	√	√	√	√	√	?
Robotically	√	√	√	√	√	√	√	?

* *Need to be somewhat specific about functionality and materials*

** *Need to be specific - to make a lens would require a different process/material than to make a valve, battery, gyroscope*