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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** spacecraft

• 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.
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*

<table>
<thead>
<tr>
<th>F42 Standard Process Name</th>
<th>Companies (Country)</th>
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<tbody>
<tr>
<td>Binder jetting</td>
<td>3D Systems/Z Corp (USA)</td>
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<td>ExOne (USA)</td>
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<td>Directed energy deposition</td>
<td>Optomec (USA)</td>
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<td>POM (USA)</td>
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<td>Sciaxy (USA)</td>
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<td>Stratasys (USA)</td>
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<td>Material extrusion</td>
<td>Makerbot (USA)</td>
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<td>Bits from Bytes (UK)</td>
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<td>Material jetting</td>
<td>Solidscape (USA)</td>
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<td>Objet (Israel)</td>
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<td>Powder bed fusion</td>
<td>3D Systems (USA)</td>
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<td>EOS (Germany)</td>
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<td>ReaLizer (Germany)</td>
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<td>Arcam (Sweden)</td>
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<td>Sheet lamination</td>
<td>Fabrisonic (USA)</td>
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<td>Mcor (Ireland)</td>
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<td>Vat photopolymerization</td>
<td>3D Systems (USA)</td>
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<td>Envisiontec (Germany)</td>
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* 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.
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
<table>
<thead>
<tr>
<th>ASTM Technologies</th>
<th>Material</th>
<th>CURRENT Strengths</th>
<th>CURRENT Weaknesses</th>
<th>Surface</th>
<th>Space</th>
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<tbody>
<tr>
<td>Vat Photopolymerization</td>
<td>Photopolymer</td>
<td>Accurate compared to other technologies; creates relatively fine features; ideal for prototyping</td>
<td>sensitive to radiation, may result in degradation in space; difficult to handle in space; limited long-term stability</td>
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<tr>
<td>Material Jetting</td>
<td>Photopolymer, wax</td>
<td>Build material contained in “cartridges” so storage is less difficult than for vat-based processes;</td>
<td>Liquid droplets can be problematic</td>
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<tr>
<td>Binder Jetting</td>
<td>Metal, polymer, ceramic,</td>
<td>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</td>
<td>Presence of both powders and liquid droplets; without post-processing material properties are weaker</td>
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<td>Material Extrusion</td>
<td>Polymer</td>
<td>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</td>
<td>Weaker parts due to poor interlayer bonding; material is expensive</td>
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<tr>
<td>Powder Bed Fusion</td>
<td>Metal, polymer, ceramic</td>
<td>Good material properties; relatively fine feature till 0.1 mm; Lasers can melt or sinter almost anything</td>
<td>Powders are problematic in zero gravity</td>
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<td>Sheet Lamination</td>
<td>Hybrids, metallic, ceramic</td>
<td>Raw material is easily transportable and simple to handle in a zero or low gravity environment</td>
<td>Material inefficiencies and lack of recycling make it a poor choice for space – Lots of waste material</td>
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<td>Directed Energy Deposition</td>
<td>Metal (powder, wire)</td>
<td>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</td>
<td>have a high material deposition rate, but relatively low resolution</td>
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*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**