National Aeronautics and
Space Administration

NASA's Space Technology Mission Directorate Advanced Manufacturing Technology Portfolio

NASA Advisory Council

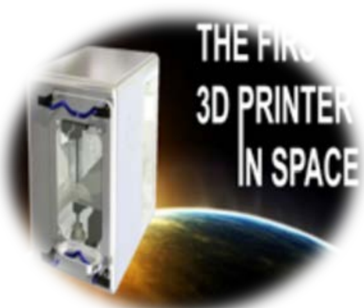
Presented by:
Dr. LaNetra Tate

April 15, 2014

NASA Advanced Manufacturing Technology Portfolio

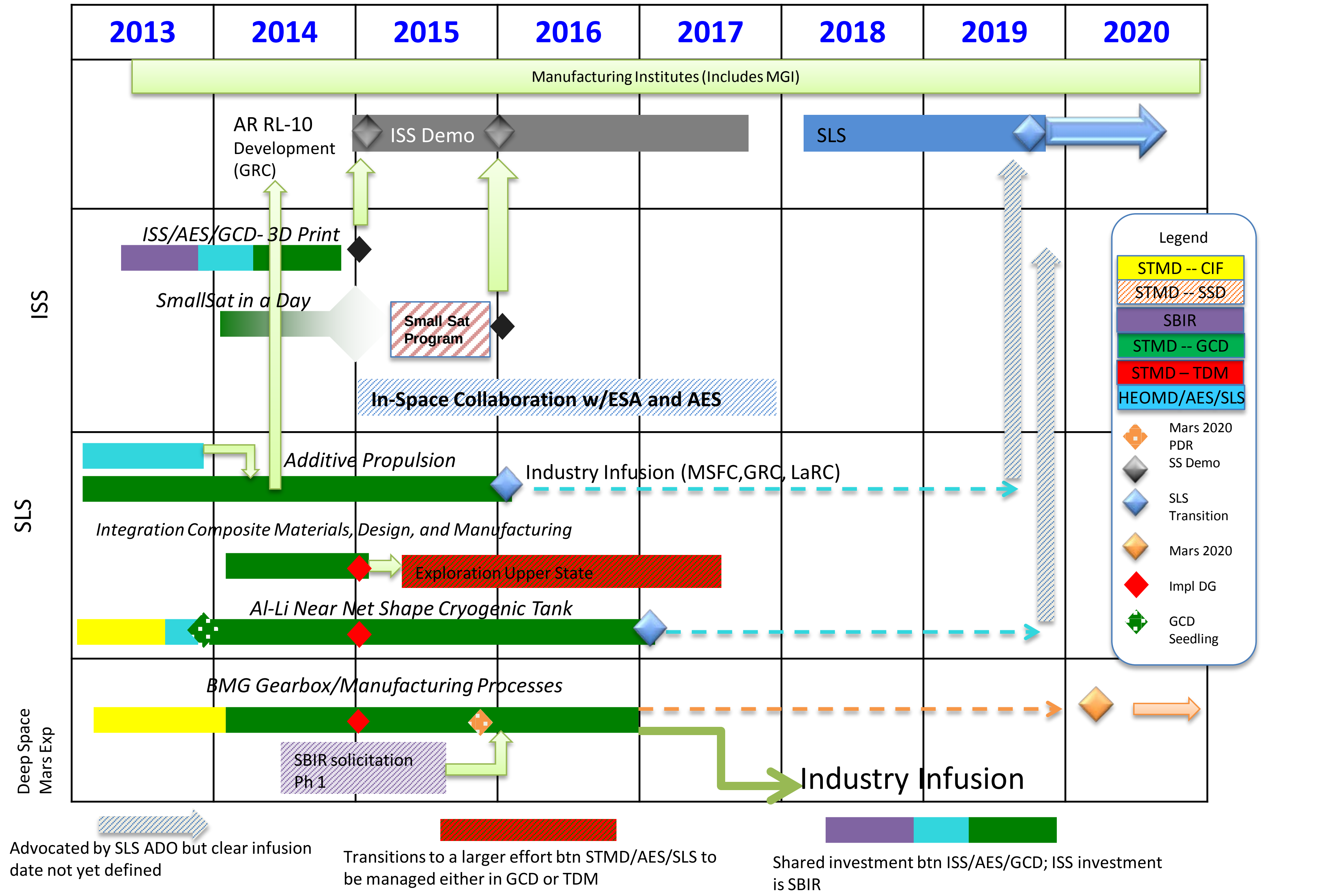
Develop advanced manufacturing technologies that enable the development of more capable and lower-cost spacecraft and launch vehicles

Collaborate with the National Manufacturing Initiative and Materials Genome Initiative, partnering with other government agencies (DOD, DOE, DOC/NIST, NSF), Industry, and Academia

ADDITIVE	***COMPOSITES***	***METALS***	***DIGITAL***	***IN-SPACE***
				

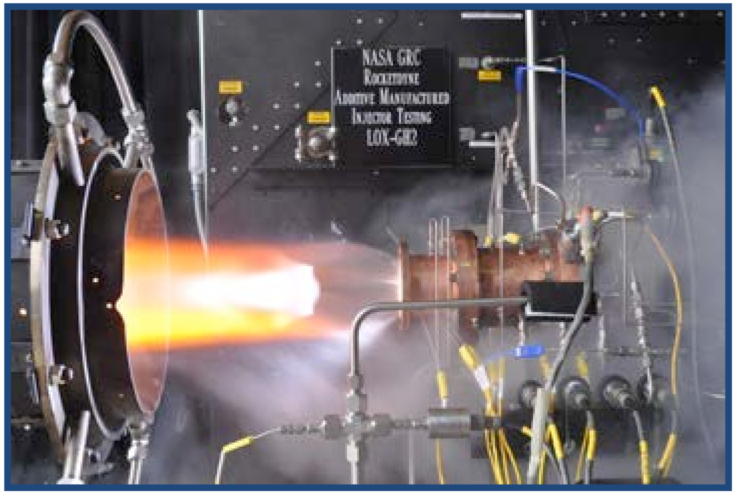
Advanced Manufacturing is Critical to all NASA Mission Areas

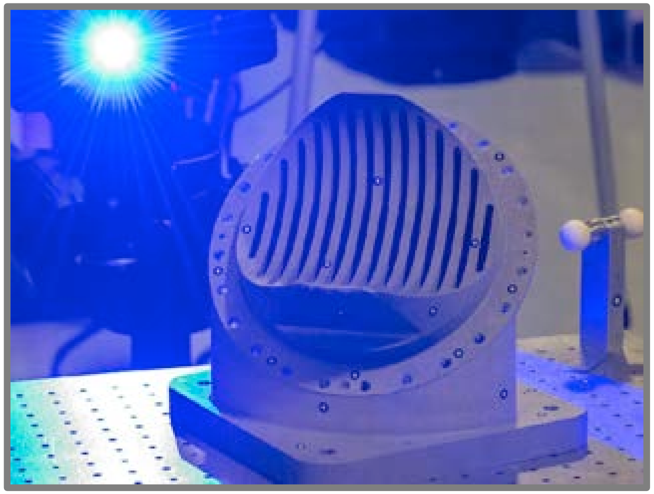
Advanced Manufacturing Strategy



NASA Additive Manufacturing For Space

- NASA is partnering with industry to develop and test rocket engine parts
- Recent efforts done at NASA on rocket engine parts, additive can save months of fabrication and machining time and thousands of dollars. An injector part that typically takes six months to fabricate at a cost of more than $10,000 was fabricated in three weeks and cost less than $5,000.





Advanced Manufacturing is Critical to all NASA Mission Areas

Promise of Additive Manufacturing

"Additive manufacturing will be a $5.2B industry by 2020" - *Terry Wohlers*

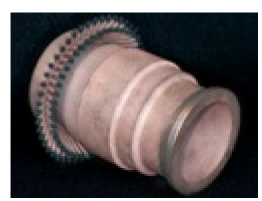
Low Cost Upper Stage-Class Propulsion System

Develop copper alloy design process, then build a 25K-class regen chamber and nozzle to be used with the previously tested DMLS injectors. This technology is also applicable to an NTP engine and small in-space applications. Infuse these technologies into industry to build competition and drive down the cost of future engines.

New material property database and proven techniques for processes copper via SLM and EBF^3

This program will lay the ground work for the beginning of a copper “allowables” database for flight certification processes

DMLS Injector



Cu Nozzle

Copper Alloy, Regeneratively Cooled Chamber and Nozzle

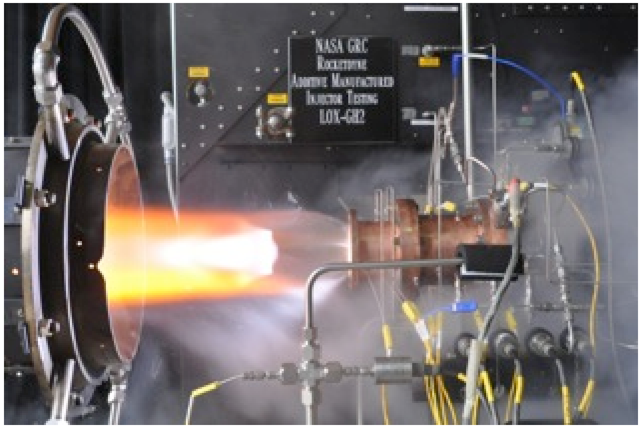
Project Snapshot:
Additively Manufactured Thrust Chamber Assembly

Objective

- Build on the investments, partnerships, and success stories from the July 2013 hot fire test sponsored by STMD's Manufacturing Innovation Project
- Extend the hot fire test duration (0.3 to 30 seconds)
- Characterize the performance of additively manufactured (AM) rocket engine components

Approach

- AR provides AM injector
- AR provides AM water cooled Thrust Chamber Assembly
    - Includes chamber and nozzle
- AR provides close coupled main valves
- GRC provides the support hardware, incorporates the main valves and performs the testing
- Full test matrix including performance mapping



Aerojet Rocketdyne additive manufactured injector test in RCL Cell 32, June 2013

Benefits to NASA and Industry

- Cost Savings
    - AR demonstrated 70% cost savings for the injector
- Direct infusion
    - NASA SMD and DOD use EELVs to launch payloads to orbit
    - RL-10 is the upper stage engine for the Atlas V and Delta IV
    - RL10 is the baseline engine for SLS ICPS and SLS 100t dual use upper stage
- NASA strengthens the partnership with AR and extends NASA influence on RL10
- TRL enhancement (3 to 5)
- Increases NASA knowledge base of RL10 and cultivates experience that can be passed on as RL10 continues to evolve

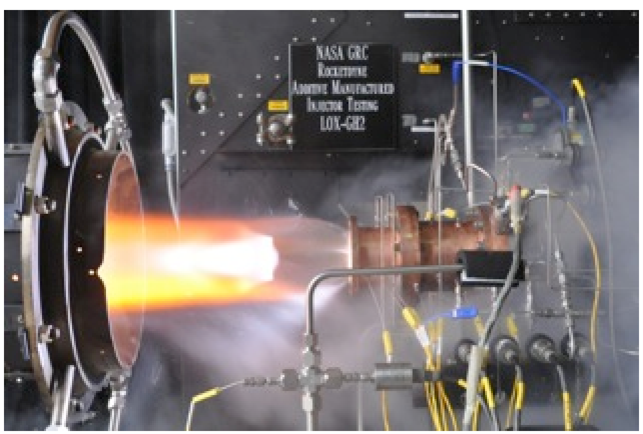
Key Milestones

- SAA signed 11/13
- AR Components Delivered to GRC 03/14
- GRC Support Hardware Complete 03/14
- Facility Modifications Complete 04/14
- Test Readiness Review 04/14
- Hot Fire Test Complete 08/14
- Final Report 09/14

Additively Manufactured Thrust Chamber Assembly Test

Building on the investments, partnerships, and success stories from the July 2013 hot fire test sponsored by STMD's Manufacturing Innovation Project, this effort

- Extend the hot fire test duration (0.3 to 30 seconds)
- Characterize the performance of additively manufactured (AM) rocket engine components
- Strengthens NASA's partnership with AR



Aerojet Rocketdyne additive manufactured injector test in RCL Cell 32, June 2013

Thrust Chamber Assembly (TCA)

AM Injector

Chamber

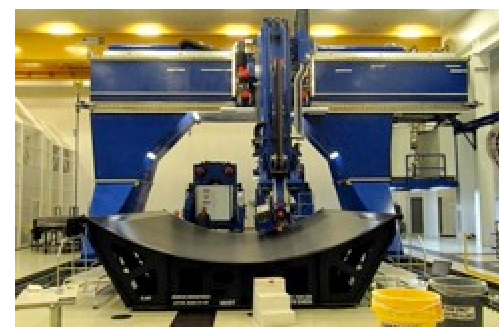
Nozzle

MIP Hot Fire Test Configuration

NASA Advanced Manufacturing Technology - Composites

- NASA's goal in large scale composite structures for Space is to develop low cost, lightweight, and thermally efficient structures, materials and manufacturing technologies for potential applications beneficial to the Space Launch System (SLS) launch vehicles.

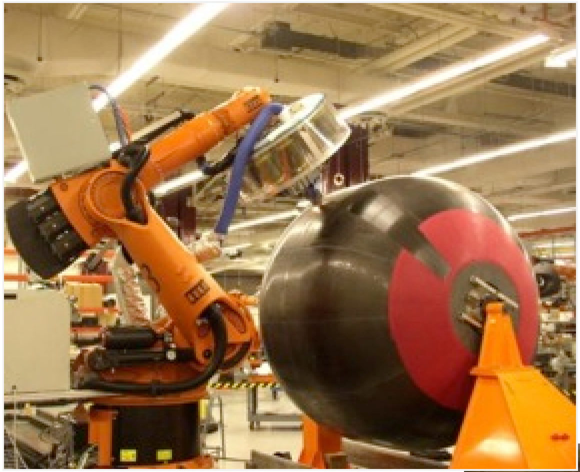
- NASA aims to gain better understanding of the entire trade space. Be a *smarter buyer* and a more effective, more relevant partner to the entire Aerospace Industry, in doing this we make smarter investments in advanced composite systems and leverage knowledge for future projects.



Advanced Manufacturing is Critical to all NASA Mission Areas

Development of Composite Cryogenic Tanks

2.4m



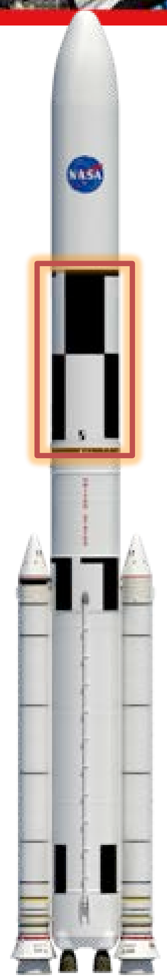
MSFC

5.5m

5.5m Tank Delivered to MSFC

NASA Super Guppy landing at
Army Redstone Arsenal

Maximum Infusion of Composite Opportunity



SLS Post Block 1
RSRMV + EUS *120t LEO*
40t Earth Departure
25t Trans Mars
8t Trans Jupiter

LH2 Forward Skirt:
Outer Mold Line Environment
Leverage CoEX Experience & Processes
Component Proof Test

LH2 Aft Skirt:
Outer Mold Line Environment
Leverage CoEX Experience & Processes
Component Proof Test

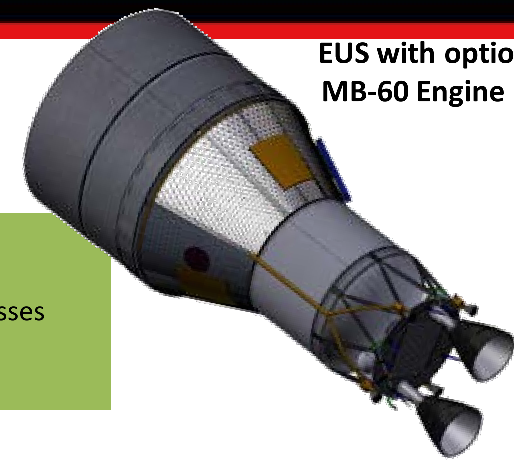
LH2 Tank:
Metallic Al-Li 2195
Leverage Core Stage
Tooling & Processes

LOX Tank:
Leverage Existing 5.5m CCTD
No Additional Testing

Intertank:
DUUS Centric Component
Leverage CoEX Experience & Processes
Component Proof Test

Interstage:
Outer Mold Line Environment
Leverage CoEX Experience & Processes
Component Proof Test

Thrust Structure:
Leverage CoEX Highly Loaded
Struts Development
Component Proof Test



EUS with optional MB-60 Engine Set

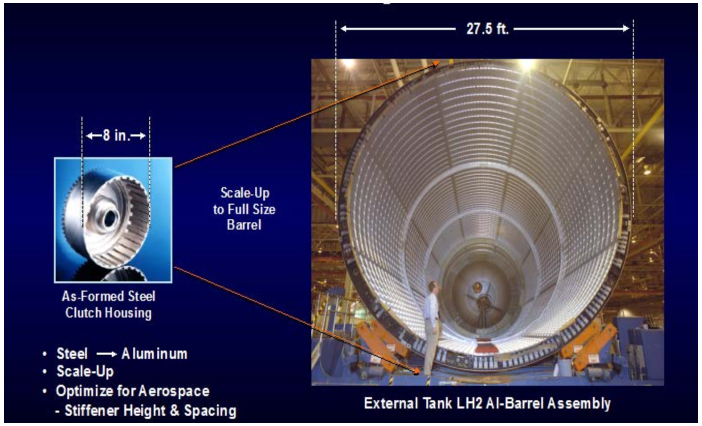
Outer Mold Line Environment
Potential Common Tooling w/Fairing

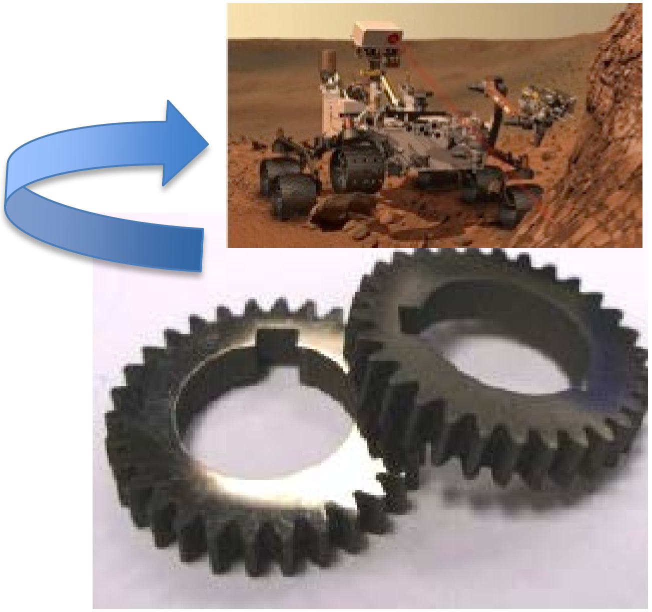
DUUS Centric Component

Existing CCTD Assests

Advanced Metallic Manufacturing

- NASA is currently investigating the use of Innovative Metals Manufacturing to Eliminate Integral Machining and Minimize Welds. Using a near net shape process, Integral Stiffened Cylinder Technology to Manufacturing of Launch Vehicle Cryogenic tanks.
- JPL is investigating the development of bulk metallic glasses (BMGs) for high-performance and extreme-environment applications such as cryogenic gearboxes on Mars rovers





Advanced Manufacturing is Critical to all NASA Mission Areas

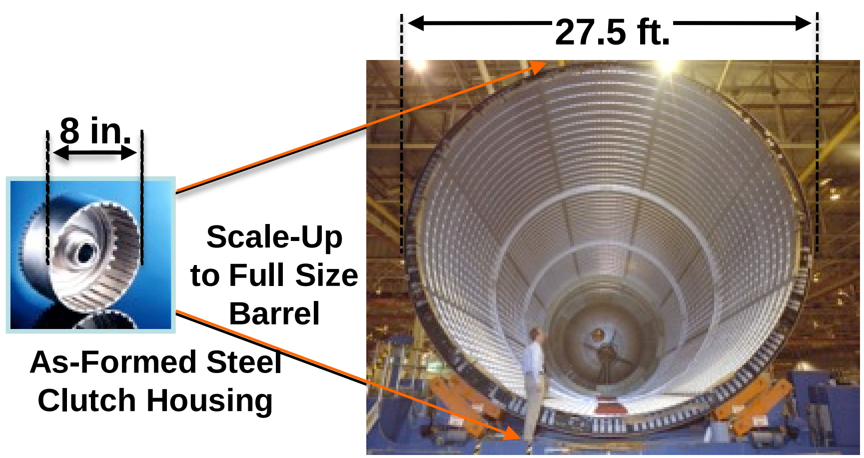
Advanced Near Net Shape

Develop net shape spin/flow forming technology to simultaneously form cryogenic tank stiffeners and cylindrical membrane using aluminum

Enable >30% weight reduction and dramatically reduced manufacturing costs of ultra-lightweight metallic tanks.

Net shape forming has the potential to reduce metal scrap rate (machining chips) in the production of launch vehicle structures from the current rate of 90% to 5% and eliminate welds (ET has >0.5 miles of welds)

Define process envelope, design, fabricate, and test a subscale, single-piece integrally stiffened cylinder.



External Tank LH2 Al-Barrel Assembly

- **Steel ⇨ Aluminum**
- **Scale-Up**
- **Optimize for Aerospace**
  - Stiffener Height & Spacing

Bulk Metallic Glass Technology

BMGs have a unique set of properties that makes them very appealing for many NASA applications (MMOD shielding, gears for extreme environments). However, current manufacturing technologies are insufficient for developing some of the best applications.

Next Generation Rovers

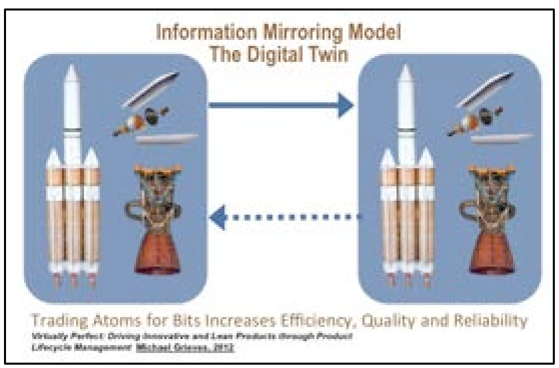
- The Mars Curiosity rover currently expends ~30% of the budgeted daily discretionary energy heating the actuators.
- The BMG gears have excellent wear loss under vacuum and in air
- New JPL BMG gears have demonstrated a ~3-times decrease in wear loss in gear-on-gear tests compared with the best steel gears

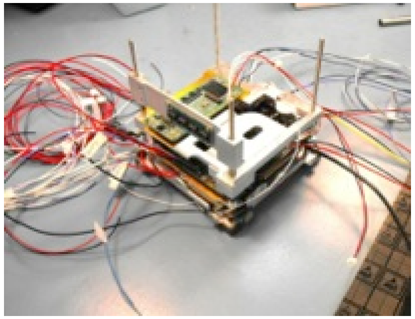
Alloy	Mass loss after 3 hrs		Total (mg)
	Driven gear	Drive gear	
DH1	33.9	113.1	147*
GHDT	50.8	100.5	151
Vascomax	28.3	20	48
CuZrAlY	10.4	15.9	26
CuZrAlBe	8.8	9.2	18

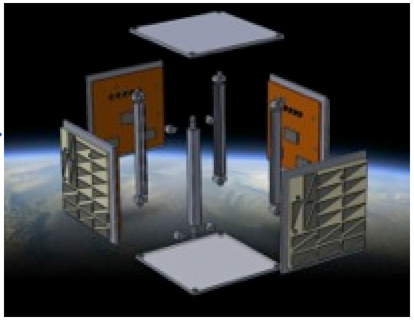
*test stopped after 1.5 hours

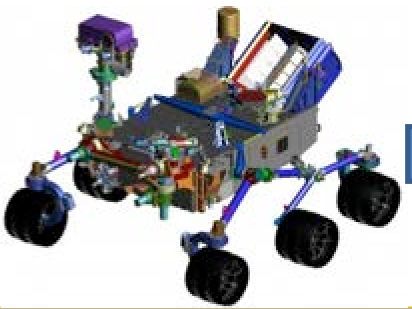
NASA Digital Materials and Manufacturing

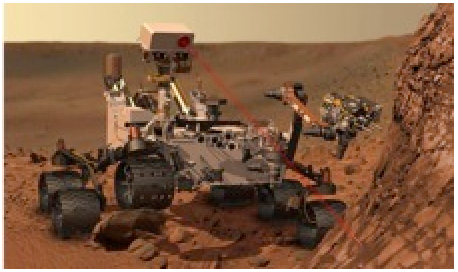
- The overall integrated digital environment will lead the way in innovation for a broad range of NASA mission capabilities. The digital twin concept, the physical vs. the virtual product is an important factor in NASA product lifecycle phases.
- NASA partnered with industry to model the systems integration and landing of Curiosity.
- NASA STMD is pursuing technology development in our SmallSat in a Day effort, Materials Genome Initiative which has a foundation in digital materials (discrete building blocks).









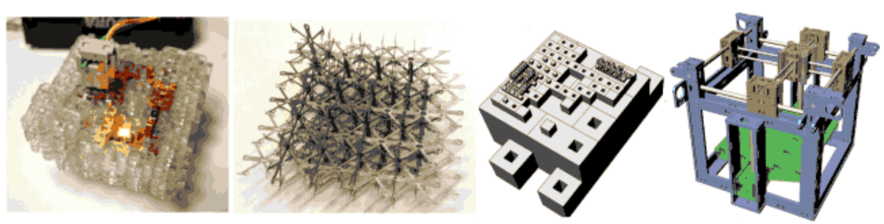


Advanced Manufacturing is Critical to all NASA Mission Areas

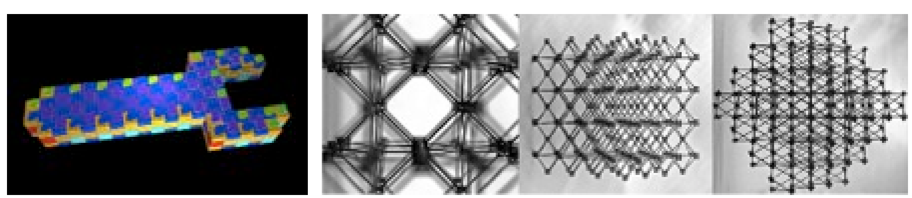
Modular Rapidly Manufactured Small Sat

The Modular Rapidly Manufactured Small Sat (MRMSS) project aims to develop and demonstrate digital materials and fabrication workflows for in-space and for-space manufacturing by assembly of building blocks (digital manufacturing and materials).

As an alternative approach to continuous materials manufacturing, this work will develop discretely assembled digital materials for space applications, with a focus on a small satellite demonstration.

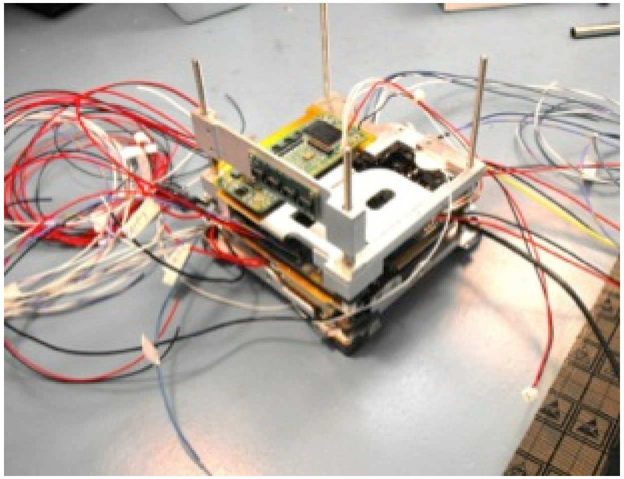


(Ward 2011, MIT CBA)

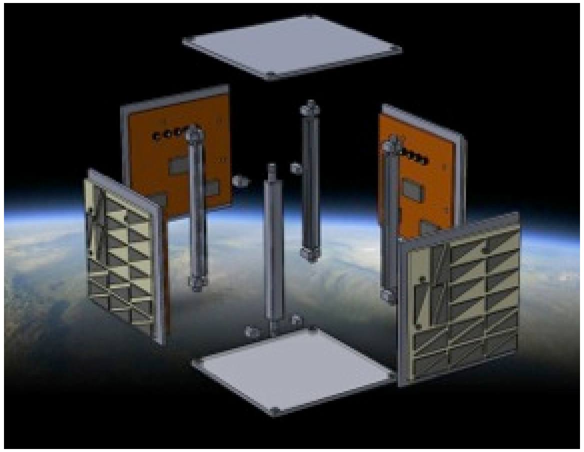


(Cheung ETAL 2013, NASA ARC, MIT CBA)

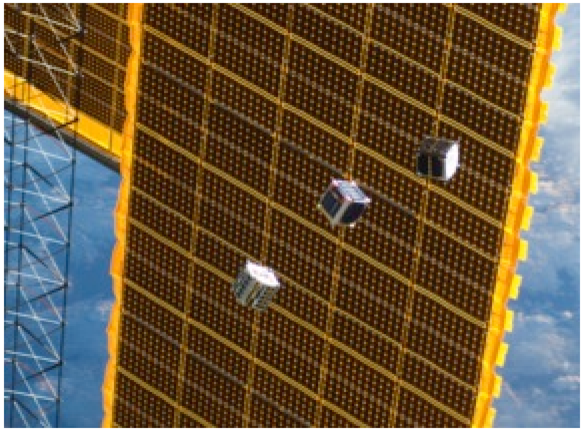
Modular Rapidly Manufactured SmallSat



Complex, labor/time intensive



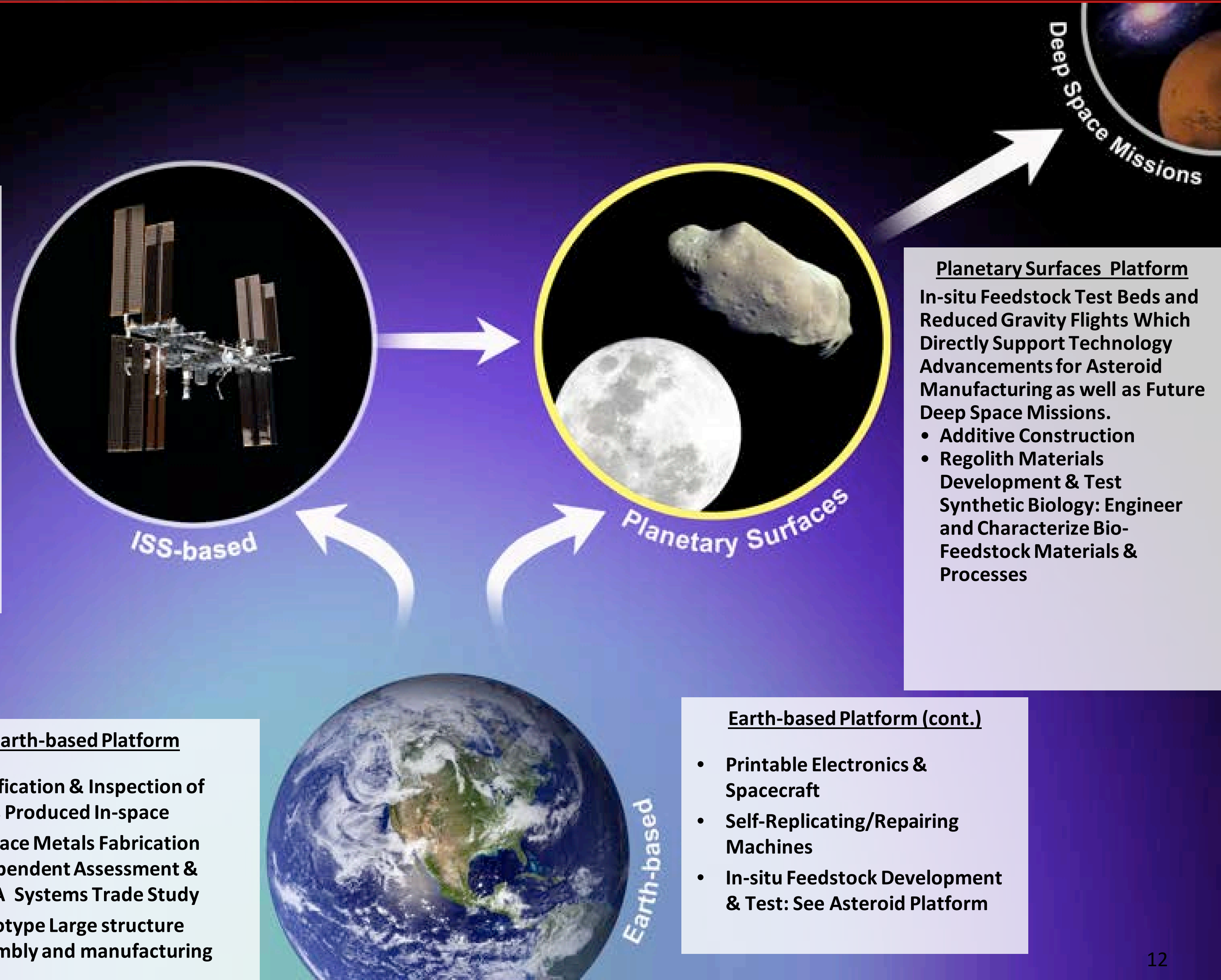
Simple, modular, rapid



In-Space Manufacturing Platforms

ISS Platform

- In-space Fab & Repair Plastics Demonstration via 3D Printing in Zero-G
- Qualification/Inspection of On-orbit Parts using Optical Scanner
- Printable SmallSat Technologies
- On-orbit Plastic Feedstock Recycling Demonstration
- In-space Metals Manufacturing Process Demonstration



Planetary Surfaces Platform

In-situ Feedstock Test Beds and Reduced Gravity Flights Which Directly Support Technology Advancements for Asteroid Manufacturing as well as Future Deep Space Missions.

- Additive Construction
- Regolith Materials Development & Test
  Synthetic Biology: Engineer and Characterize Bio-Feedstock Materials & Processes

Earth-based Platform

- Certification & Inspection of Parts Produced In-space
- In-space Metals Fabrication Independent Assessment & NASA Systems Trade Study
- Prototype Large structure assembly and manufacturing

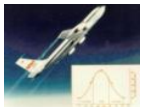
Earth-based Platform (cont.)

- Printable Electronics & Spacecraft
- Self-Replicating/Repairing Machines
- In-situ Feedstock Development & Test: See Asteroid Platform

NASA In-space Manufacturing Technology Development Vision

International Space Station (ISS)

Parabolic



WE ARE HERE!

3D Print Tech Demo

Printable Electronics

Metal Printing

SmallSats

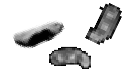
Add Mfctr. Facility

Optical Scanner

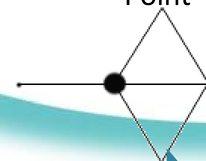
Recycler

Self-repair/ replicate

Asteroids



Lagrange Point



Lunar

Mars

Pre-2012 | **2015** | **2016** | **2017** | **2018** | **2020-25** | **2025** | **2030 - 40**

Pre-2012

Ground & Parabolic centric:

- Multiple FDM Zero-G parabolic flights
- Trade/System Studies for Metals
- Ground-based Printable Electronics/Spacecraft
- Verification & Certification Processes under development
- Materials Database
- Cubesat Design & Development

We are here

- POC 3D Print: First Plastic Printer on ISS Tech Demo
- NIAC Contour Crafting
- NIAC Printable Spacecraft
- NIAC SpiderFab
- Small Sat in a Day
- NRC Study
- Center In-house work in additive, synbio, ISRU,robotics

2015

- Next Generation 3DPrint
- SmallSat in a Day ISS Demo
- Recycler Demo: : recycle plastic

ISS: *Utilization/Facility Focus*

- Integrated Facility Systems for Stronger types of extrusion materials for multiple uses including metals & various plastics
- Printable Electronics Tech Demo
- Smallsat Build & Deploy

Lunar, Lagrange FabLabs

- Initial Robotic/Remote Missions
- Provision some feedstock
- Evolve to utilizing in situ materials (natural resources, synthetic biology)
- Product: Ability to produce multiple spares, parts, tools, etc. "living off the land"
- Autonomous final milling to specification

Planetary Surfaces Points Fab

- Transport vehicle and sites would need Fab capability
- Additive Construction

Mars Multi-Material Fab Lab

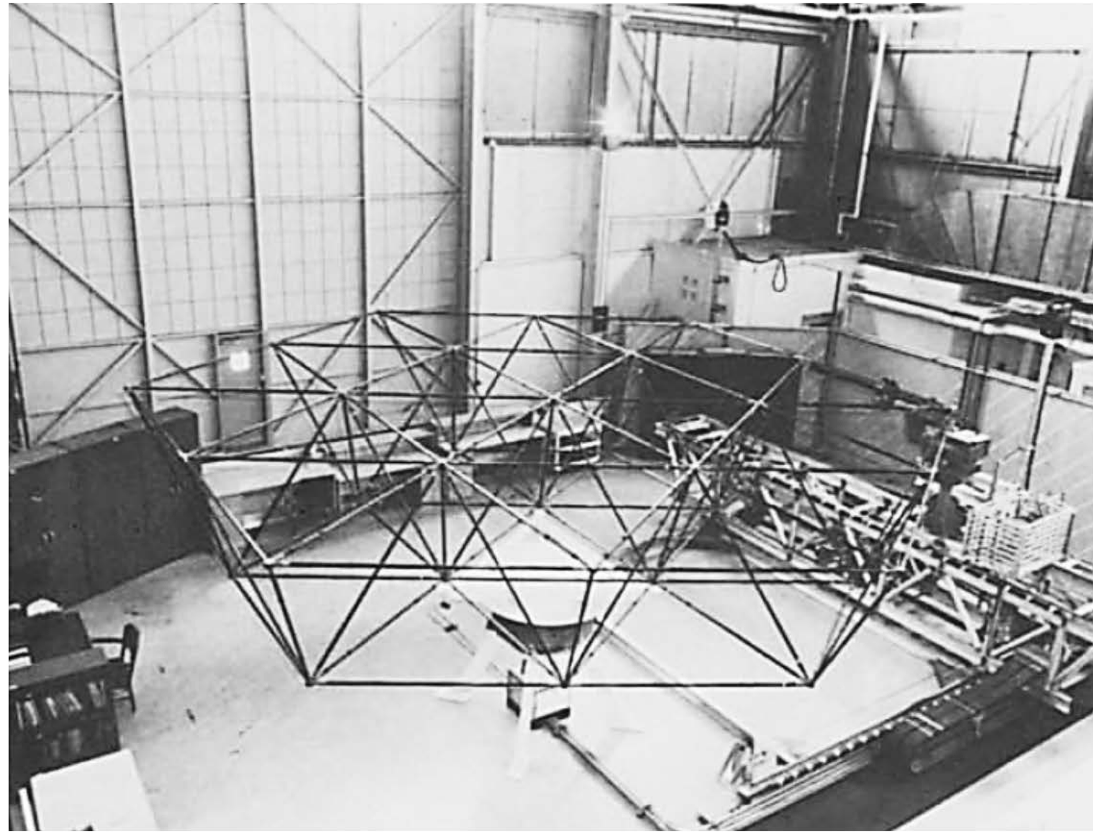
- Utilize in situ resources for feedstock
- Build various items from multiple types of materials (metal, plastic, composite, ceramic, etc.)
- Product: Fab Lab providing self-sustainment at remote destination

All dates and plans beyond 2014 are notional and do not imply planned investments

ISS Technology Demonstrations are Key in 'Bridging' Technology Development to Full Implementation of this Critical Exploration Technology. We believe this design is the right one for taking the very first step toward manufacturing in space!

In-Space Deployment, Fabrication, or Assembly

NASA JSC 1985 Construction of Erectable Space Structures

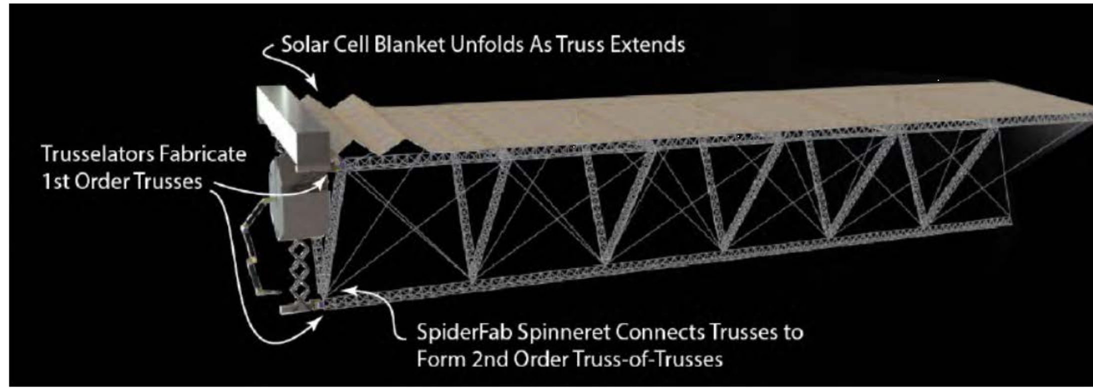


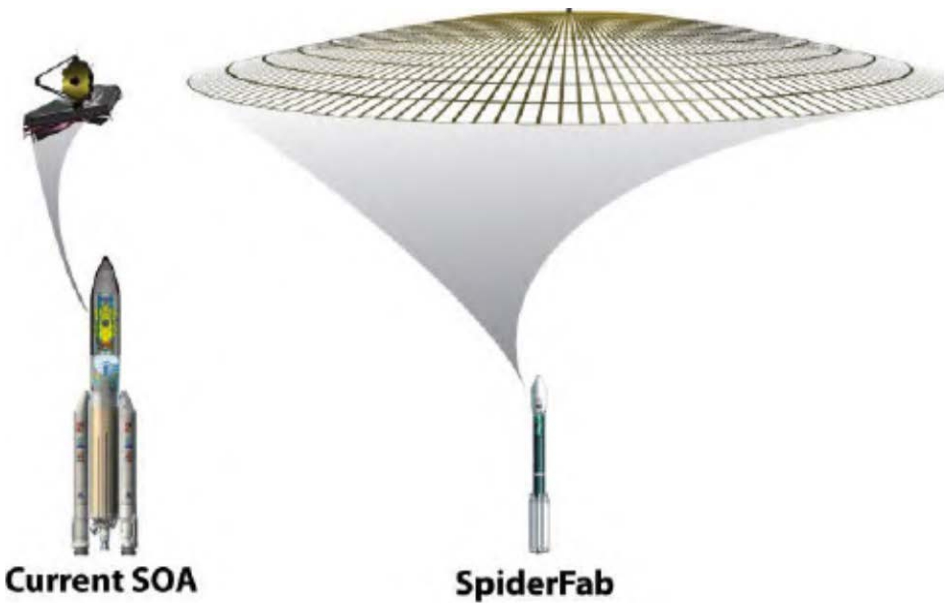
NASA LaRC 1991 Automated Structural Assembly Laboratory

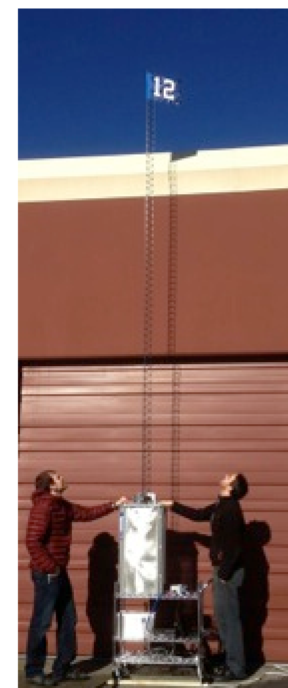
Assembling Large Structures in Orbit

- Trusselator: NIAC Phase II
  - R. Hoyt, Tethers Unlimited

    http://youtu.be/3pYWuypTBOc







A significant fraction of the engineering cost and launch mass of space systems is required exclusively to enable the system to survive launch.

Scalable Automated Lattice Structure Assembly System (SALSAS)

Concept illustration:

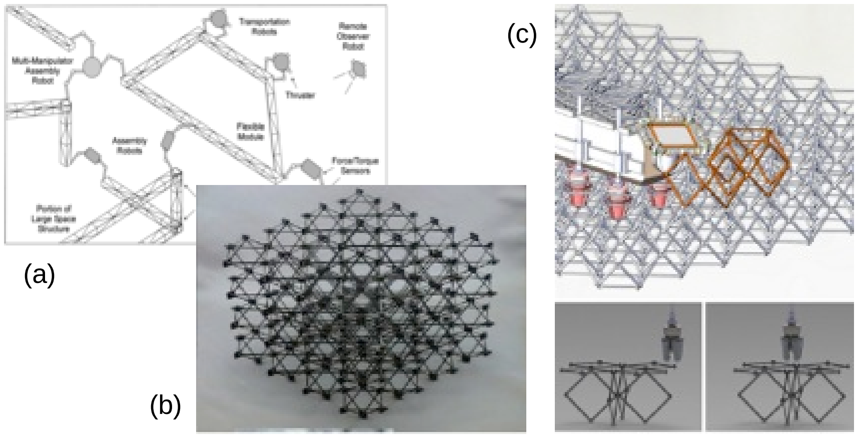


Figure: (a) notional multi-agent in-space assembly [11] (b) 3D reversibly assembled lattice material [10] (c) simpler robotic assembler concept [11]

Operational Capability:

- The overall mission objective is to develop and demonstrate scalable structures manufacturing technology.
- This system will require a feedstock of building block components, which reduces the ISRU of materials problem (just have to produce many of a few different types of discrete and easy-to-qualify building blocks)
- The focus on lattice structures reduces the In-space Assembly problem (periodic robot environment)
- The technology could be critical to NASA's In-space Reliance and "mass-less" exploration efforts, as well as broadly benefiting DARPA and DHS efforts in infrastructure supply chain, NSF's efforts in digital materials research, and national interest in leading manufacturing technologies.

Proposed Technical Approach:

- The robotic assemblers will be comprised of modular locomotion and end-effector subsystems.
- Major subsystem component technologies are all available as COTS assemblies/subassemblies with 'plug-and-play' utility (servos, drivers, mainboard).
- The integration of COTS components into the physical systems and robotic end-effectors will require custom hardware development, appropriate as an in-house activity.
- Ongoing development at ARC in collaboration with MIT-CBA can be continued with additional engagement with other University partners.
- Once working hardware systems are established, there is potential for a SBIR engagement to speed development of control/organization algorithms

Proposal Team Information:

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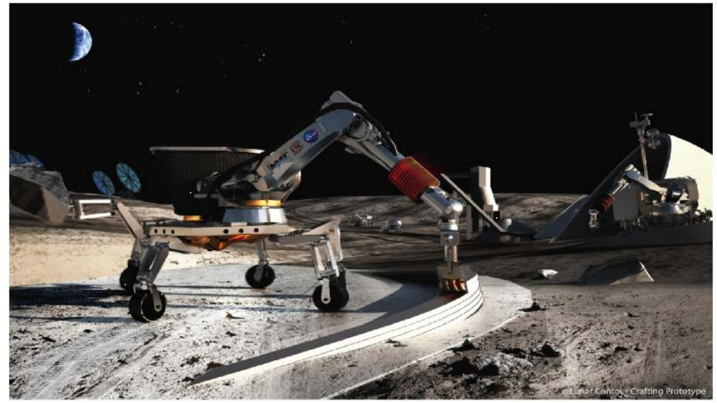
Living off of the Land – Additive Construction

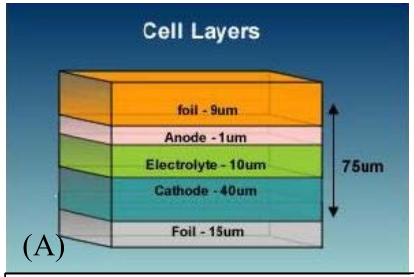
- Contour Crafting
  - Khoshnevis @ USC
  - SwampWorks

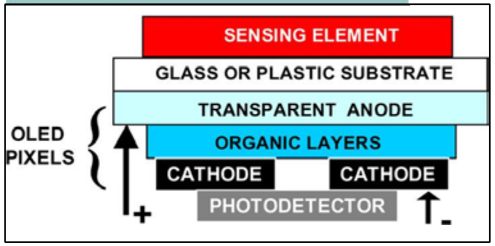


Rendering courtesy of Behnaz Farahi and Connor Wingfield

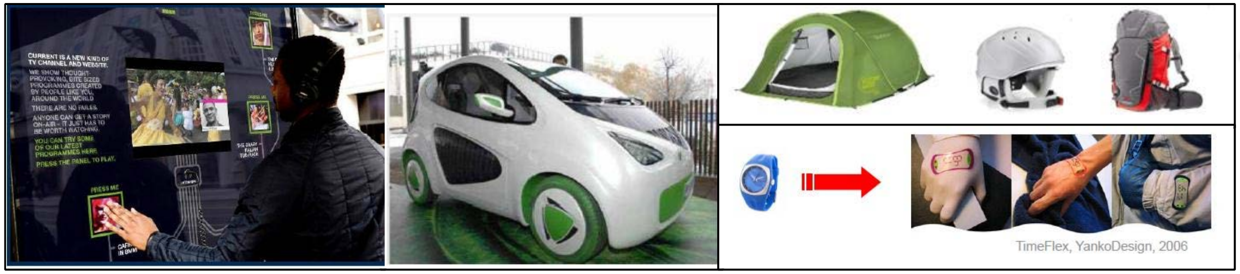
Printing Spacecraft

- Printable electronics
- Additive manufacturing in-orbit
- Print spacecraft on-demand in-space





Credit: (A) Planar Energy; (B) IDTech Ex; (C) SPIE; (D) ID Tech Ex



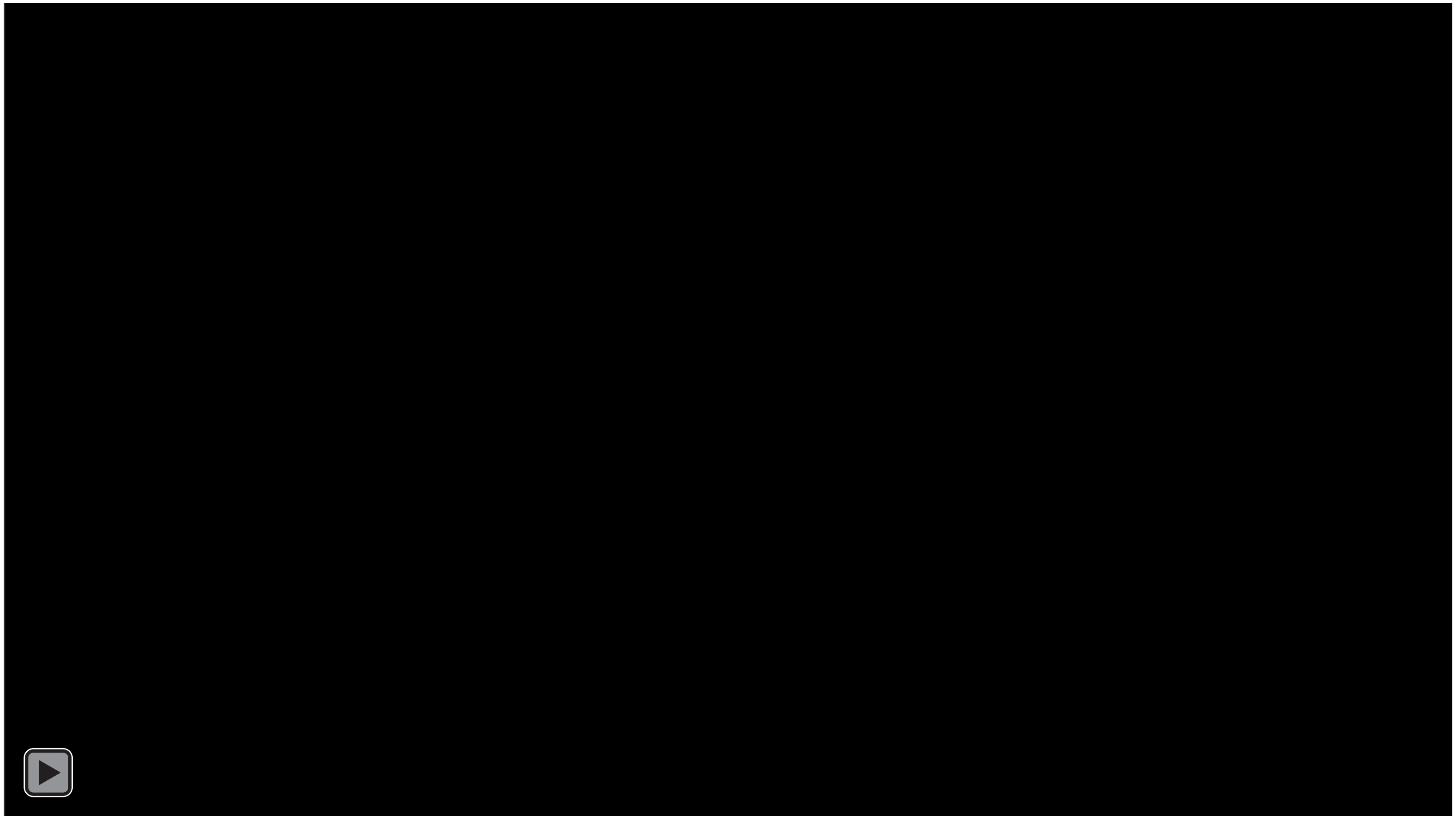
Credit: ID Tech Ex, Solar Print, Time Flex

Lessons Learned

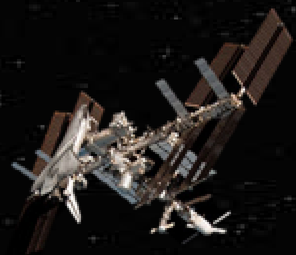
Lessons Learned

[>>Kendra Short NASA JPL<<]

3D Printing on ISS



For transcript, please visit http://www.youtube.com/watch?v=AZlsJb9AWPs



3D Printing in Zero-G ("3D Print") ISS Technology

Scheduled to launch on Space X-5 in October 2014 to the International Space Station

http://www.youtube.com/watch?v=NwGnRGTIx5g

Vision of the National Advanced Manufacturing Initiative


June 2011

REPORT TO THE PRESIDENT ON ENSURING AMERICAN LEADERSHIP IN ADVANCED MANUFACTURING

Executive Office of the President
President's Council of Advisors on Science and Technology

JUNE 2011


February 2012

A NATIONAL STRATEGIC PLAN FOR ADVANCED MANUFACTURING

Executive Office of the President
National Science and Technology Council

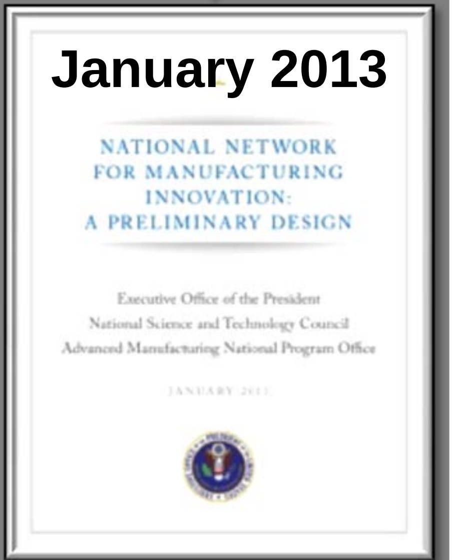
FEBRUARY 2012


July 2012

REPORT TO THE PRESIDENT ON CAPTURING DOMESTIC COMPETITIVE ADVANTAGE IN ADVANCED MANUFACTURING

Executive Office of the President
President's Council of Advisors on Science and Technology

JULY 2012


January 2013

NATIONAL NETWORK FOR MANUFACTURING INNOVATION: A PRELIMINARY DESIGN

Executive Office of the President
National Science and Technology Council
Advanced Manufacturing National Program Office

JANUARY 2013

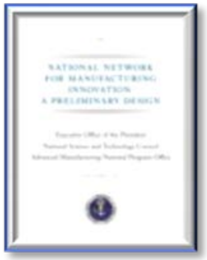
National Network for Manufacturing Innovation

- The proposed Network will be composed of up to 45 Institutes for Manufacturing Innovation (IMI's) around the country
- NNMI managed by the interagency Advanced Manufacturing National Program Office(AMNPO), with participating agencies: the Department of Defense, Department of Energy, Department of Commerce's National Institute of Standard and Technology (NIST), NASA, the National Science Foundation, and other agencies.
- Four initial IMI's - National Additive Manufacturing Innovation Institute (NAMII)/August 2012; Two new DoD led institute's (1) Digital Manufacturing and Design Innovation (DMDI) and (2) Lightweight and Modern Metals Manufacturing Innovation (LM3I); DOE Clean Energy Institute, wideband gap and semiconductor devices.
- Future DOD/NASA IMI could focus on propulsion related manufacturing technology

BLUEPRINT FOR ACTION
WORKSHOP ON THE DESIGN OF THE
NATIONAL NETWORK FOR MANUFACTURING INNOVATION
USSRC - DAVIDSON CENTER,
HUNTSVILLE, ALABAMA
JANUARY 16, 2013

Advanced Manufacturing is Critical to all NASA Mission Areas

Manufacturing Innovation – Aligned with Federal Priorities



National Additive Manufacturing Innovation Institute (NAMII)

- NAMII's goal is to transition additive manufacturing technology to the mainstream U.S. manufacturing sector and create an adaptive workforce capable of not only meeting industry needs but also increasing domestic manufacturing competitiveness.

America Makes

Digital Manufacturing and Design Innovation or DMDI,

- Advanced design and manufacturing tools that are digitally integrated and networked with supply chains can lead to 'factories of the future' forming an agile U.S. industrial base with significant speed to market advantage.

Lightweight and Modern Metals Manufacturing Innovation, or LM3I Manufacturing

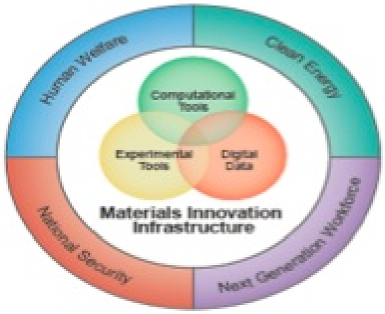
- Advanced lightweight metals possess mechanical and electrical properties comparable to traditional materials while enabling much lighter components and products.

Clean Energy Manufacturing Innovation Institute (Institute) Manufacturing

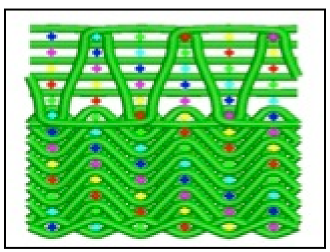
- Wide bandgap semiconductor based power electronic devices represent the next major platform beyond the silicon based devices that have driven major technological advances in our economy over the last several decades.

NASA and the Materials Genome Initiative

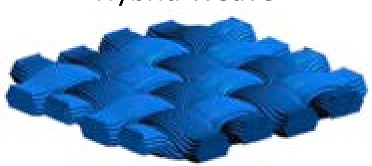
- The Space Technology Mission Directorate (STMD) is investing in the development of new materials and manufacturing technologies to enable more demanding mission requirements.
  - Multifunctional, lightweight materials/structures and advanced manufacturing identified as critical technologies in NASA Roadmaps.
- The Materials Genome Initiative (MGI) concept integrates computational methods, directed experimental interrogation at all relevant length scales, and data informatics for the entire manufacturing process. This concept is intended to reduce the time and cost to bring new materials to market.



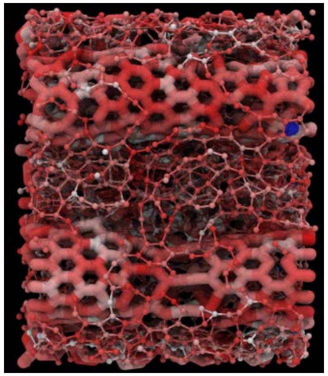
Materials Genome Initiative Overview [1]



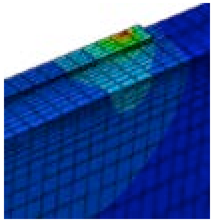
Hybrid Weave



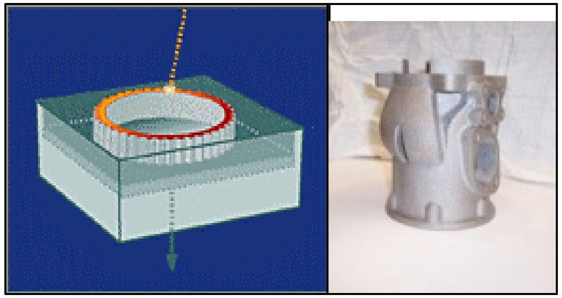
Digital chain representation of plain weave generated using VTMS 2.0



Simulation snapshot of CNT/amorphous carbon composite nearing failure point



Temperature at midpoint of first layer of deposit



Laser Sintering/E-beam Melting

[1] Materials Genome Initiative for Global Competitiveness, http://www.whitehouse.gov/sites/default/files/microsites/ostp/materials_genome_initiative-final.pdf

Space Technology Mission Directorate

www.nasa.gov/spacetech