Needs and opportunities in the development of advanced materials and manufacturing methods for future long-duration human space exploration

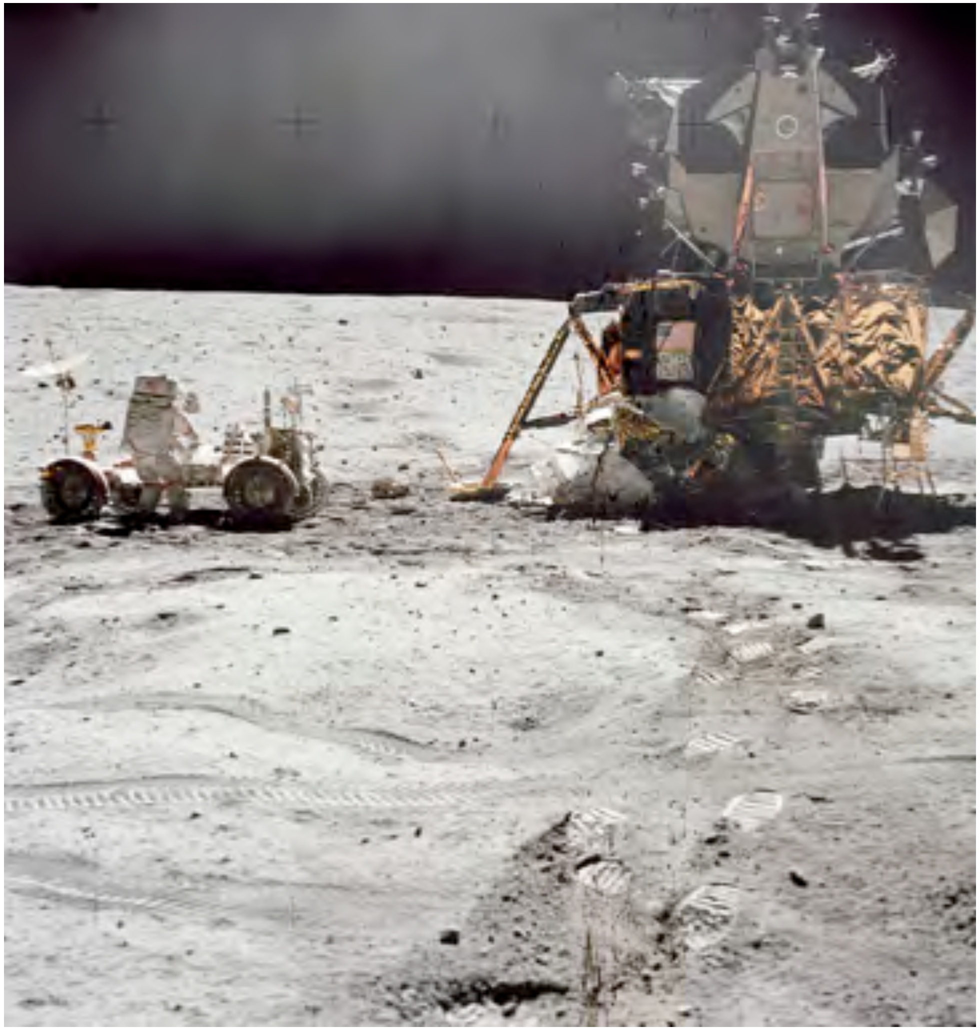
Michael A. Meador
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Apollo Missions

Apollo 15

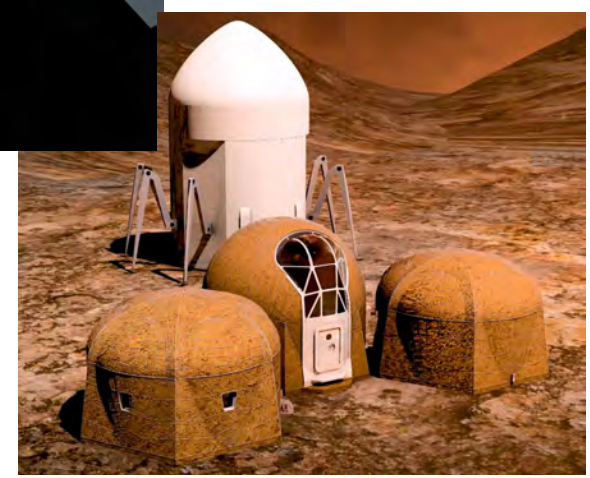
- 66.9 hours on Lunar surface
- 3 EVAs – 10 hours, 36 minutes
- Returned with 6.6 kg of Lunar materials

- Lunar Lander and Command Module constructed from:
  - Aluminum honeycomb with bonded aluminum facesheets
  - Stainless steel honeycomb filled with phenolic ablator for the heat shield



Going Back to the Moon and On to Mars

- **Structurally efficient launch vehicles and spacecraft**
  - Lightweight materials
  - Multifunctionality
  - Damage tolerant
- **Robust habitation and exploration systems**
  - Missions will be longer than Apollo with longer duration and more numerous sorties/EVAs
  - Environment is harsh – dust, radiation, temperature
  - In situ resource utilization, including recycling
  - In space manufacturing
- **Materials and chemistry are key to addressing these challenges**



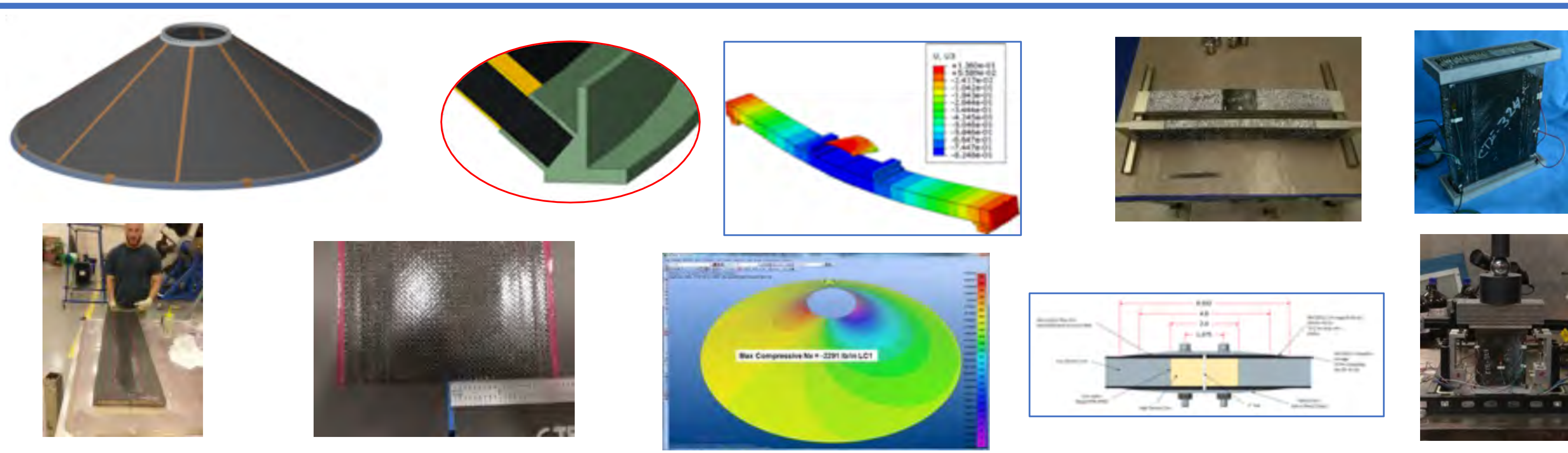
3D Printed Mars Habitat Challenge Winning Concept – Team Zopherus (Rogers, AR)

Examples of Ongoing Materials and Manufacturing R&D

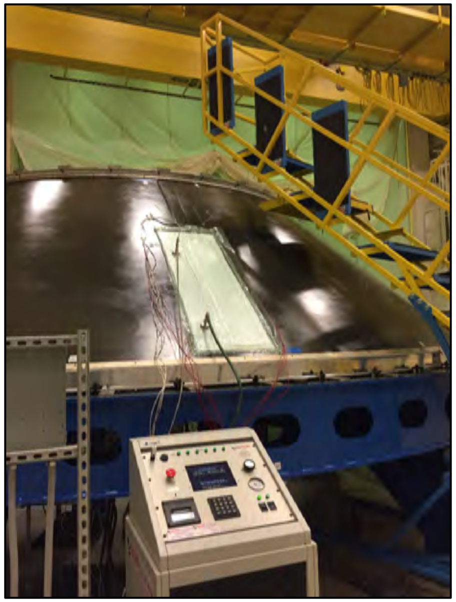
- Lightweight Materials
  - ✓Polymer Matrix Composites
  - ✓Carbon Nanotube Reinforced Composites
- Manufacturing Technologies
  - ✓ 3-D Printing of Habitat Structures
  - ✓ Autonomous Assembly/Configuration of Digital Materials
  - ✓ In-space Manufacturing

Composite Technology for Exploration (CTE)

- Develop and demonstrate critical composites technologies with a focus on weight-saving, performance-enhancing bonded joint technology for Space Launch System (SLS)-scale composite hardware to support future NASA exploration missions.
  - ✓ Improve the analytical capabilities required to predict failure modes in composite structures.
  - ✓ Support SLS payload adapters and fittings by maturing composite bonded joint technology and analytical tools to enable risk reduction.
- Focus on Payload Attach Fitting. Potential for significant reduction in joint mass, part count, assembly time and cost over bonded metallic joints
  - ✓ Reduce longitudinal joint mass by 87% (from 927 to 42 lb) and part count by 98% (from 2116 to 40)
  - ✓ Reduce circumferential joint mass by 62% (from 927 tp 358 lb) and part count by 98% (from 1673 to 40)



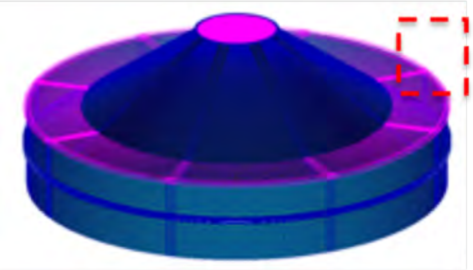
CTE Project Activities



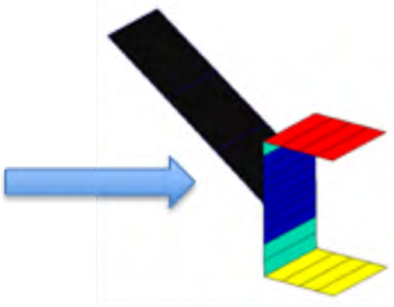
Fabrication of composite bonded joints for Payload Adapter Manufacturing Demonstration Article

Materials Production

Composite Testing



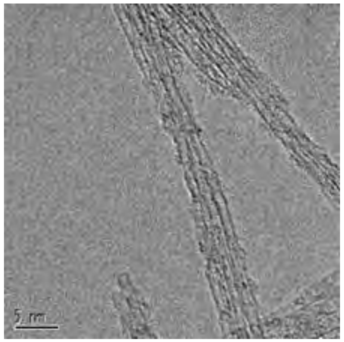
CTE Point Design



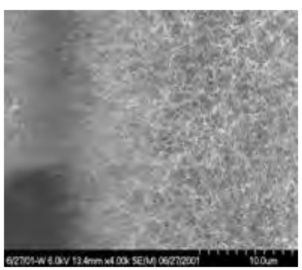
Design Optimization

Project Manager: John Fikes, NASA Marshall

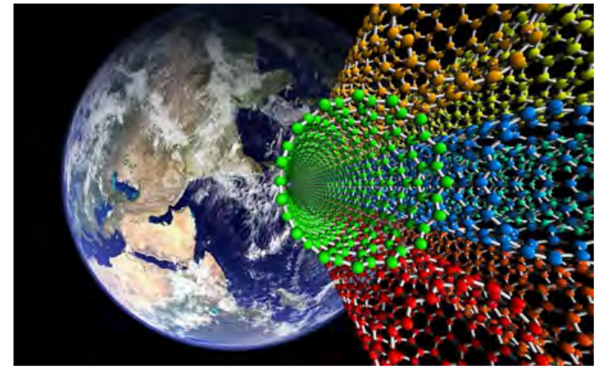
Lightweight, Multifunctional Materials- Carbon Nanotubes



Purified Single Wall Carbon Nanotubes



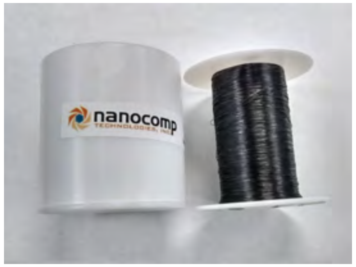
Nanotube Modified Substrates



Carbon Nanotube Space Elevator

- Carbon nanotubes (CNTs) have remarkable properties-
  - ➤ Specific strength 150X that of conventional carbon fibers, 100X aluminum
  - ➤ Elongation 10X that of conventional carbon fibers
  - ➤ Electrical and thermal conductivities ~10X that of high conductivity carbon fibers
- Because of these properties, carbon nanotubes have been proposed for disruptive applications such as a space elevator cable
- Widespread use of CNTs in aerospace hampered by inability to uniformly and reliably disperse them into polymers and other host materials

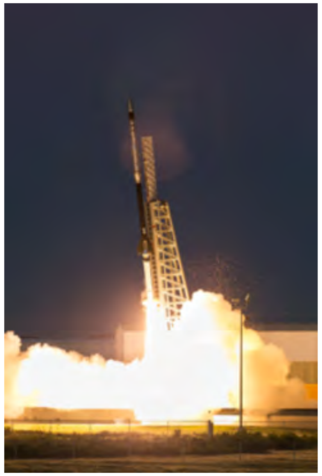
CNT Reinforced Composites Demonstrated in a Structural Component



Carbon Nanotube (CNT) Fiber

Filament Winding of Composite Overwrap Pressure Vessel (COPV)

COPV Installed in Sounding Rocket Cold Gas Thruster System

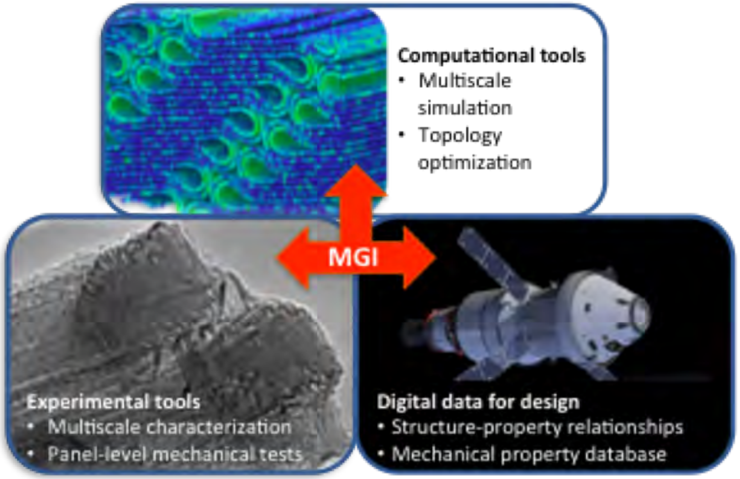


Successful Flight Test on May 16. 2017

- First ever demonstration of CNT reinforced composites in a load-bearing component (including flight testing)
- Significantly improved the mechanical properties of CNT fibers and fiber reinforced composites
- Further work is needed to develop composites that more fully exploit the unique properties of CNTs

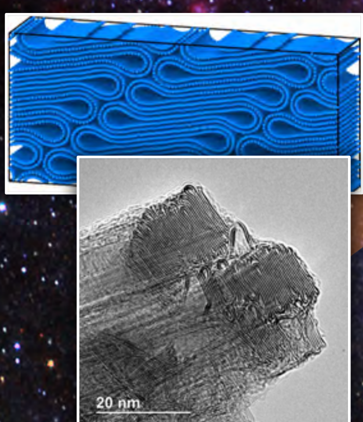
Institute for Ultrastrong Composites by Design (US-COMP)

- Develop integrated multiscale modeling and simulation, experimental tools, and design methods for carbon nanotube reinforced composites and enable the development of composites with:
  - ✓ 300% increase in tensile properties
  - ✓ 50% increase in fracture toughness
- Consortium of 11 universities, industry, Government labs
  - ✓ Michigan Tech (lead), MIT, Florida State, U of Utah, U of Minnesota, Ga Tech, Florida A&M, Johns Hopkins, Virginia Commonwealth, U of Colorado, Penn State
  - ✓ Solvay and Nanocomp
  - ✓ AFRL and NASA
- Funded by the STMD Space Technology Research Institute Program



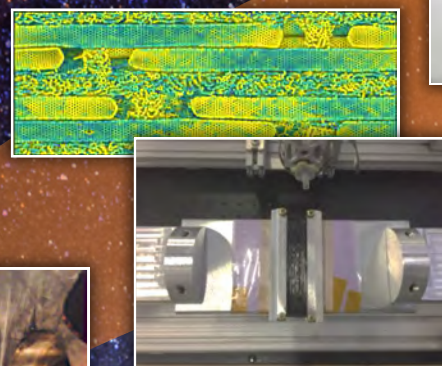
Technical Monitor: Emilie J. Siochi, NASA Langely

NASA Carbon Nanotube Structural Materials R&D



Computationally Guided CNT Reinforcement Optimization – STRI, ESI, GCD
(US-COMP STRI, NASA, Nanocomp, U of Minnesota, U of Virginia)

CNT Reinforcement Scale-up - GCD
(Nanocomp)



Computationally Guided CNT Composite Development – STRI, GCD
(NASA, US-COMP STRI)

CNT Component Prototyping and Testing - GCD
(NASA + Industry)

Component Demo - TBD
(NASA + Industry)

ISM Project Overview

Why is this project important?

- *The operations & logistics approach utilized for ISS is not feasible for long-duration missions.
- ISM provides a “pioneering” approach which will help to enable sustainable, affordable Exploration mission operations and logistics.
- ISM is key to addressing significant logistics challenges for long-duration missions by reducing mass, providing flexible risk coverage, and enabling new capabilities that are required for Exploration missions.

Objectives

- Develop and enable the technologies and processes required to provide affordable, sustainable on-demand manufacturing, recycling, and repair during Exploration missions.

Current activities

- ISS Refabricator Tech Demo, NextSTEP FabLab contracts with Techshot Inc., Interlog Corp., Tethers Unlimited, Inc. (TUI), ISS AMF Ops, 3D Print Tech Demo Results, Printable Electronics Dev, 8 SBIRs underway, ISM Design Database Development with LSS, LR, and NextSTEP UTAS, Future Engineers STEM SAA, X-Hab Filament Development

ISS Additive Manufacturing Facility

ISS Refabricator

NextSTEP ‘FabLab’

Printable Electronics: LSS Pressure Switch (Left); UV Radiation Sensor (Right)

Design Database Development ISM LSS Retaining Plate (Left); LR Urine Funnels (Right)

* *Quantitative Benefit Analysis performed in 2016 for ISM Utilization study. The analysis used data from ISS maintenance and logistics tracking, as well as EMC Deep Space Habitat studies.*

ISM Primary Focus Areas

❖ ***In-Space Manufacturing Technology & Material Development: Work with industry and academia to develop on-demand manufacturing and repair technologies for in-space applications.***

- **Two polymer printers are currently on ISS (3DP Tech Demo & AMF). Supporting STMD TDM Archinaut (Made In Space, Inc.) Tipping Point for External ISM.**
- **NextSTEP BAA for the 1st Generation Multi-Material "FabLab" capable of on-demand manufacturing of metallic & electronic components/parts during missions.**

Multi-Material FabLab BAA will result in 1st Generation Exploration System

❖ ***In-Space Recycling & Reuse Technology & Material Development: Work with Industry and academia to develop recycling & reuse capabilities to increase mission sustainability.***

- **Refabricator (Integrated 3D Printer/Recycler) Tech Demo launching to ISS in early 2018.**
- **ERASMUS Phase II SBIR with Tethers Unlimited, Inc. (TUI) developing Food & Medical Grade Recycling Capability.**
- **Common Use Materials Phase II SBIRs (TUI & Cornerstone Research Group, Inc. (CRG))**

ISS Refabricator developed via SBIRs with Tethers Unlimited, Inc.

❖ ***In-Space Manufacturing Digital Design & Verification Database (i.e. WHAT we need to make): ISM is working with Exploration System Designers to develop the ISM database of parts/systems to be manufactured on spaceflight missions.***

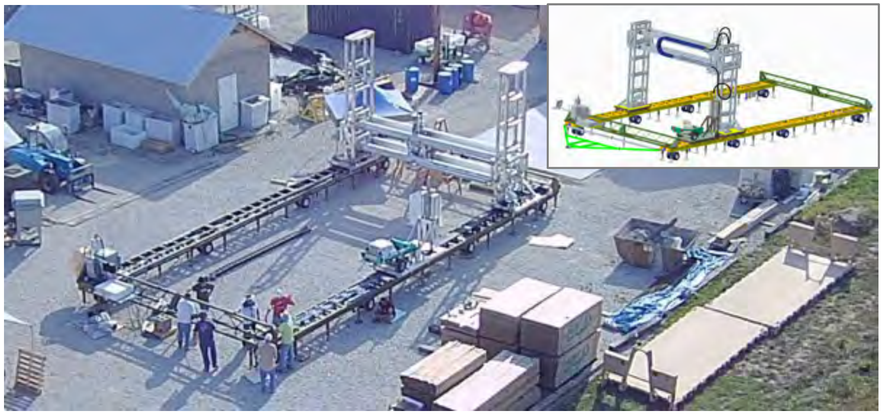
- **Includes material, verification, and design data.**
- **Ultimately, this will result in an ISM Utilization Catalog of approved parts for on-orbit use.**

ISM works with Exploration designers to optimize parts/systems for on-orbit

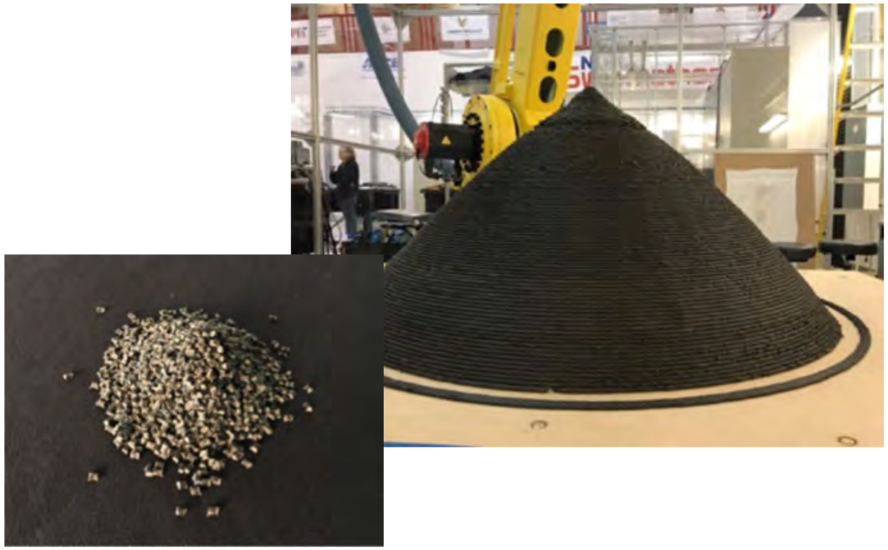
Additive Construction with Mobile Emplacement (ACME)

- Develop and demonstrate the capability for 2D and 3D printing on a large (structure) scale using in-situ resources as construction materials
  - Gantry, printer, and control system
  - Printing materials – composites from Mars Regolith Simulant and PE
- Habitats for Lunar and Mars exploration
- Structures (B-Huts, barricades) for terrestrial applications - Partnership with US Army Corps of Engineers

Project Manager: John Fikes, NASA Marshall



Gantry System Under Assembly at US Army Corps of Engineers

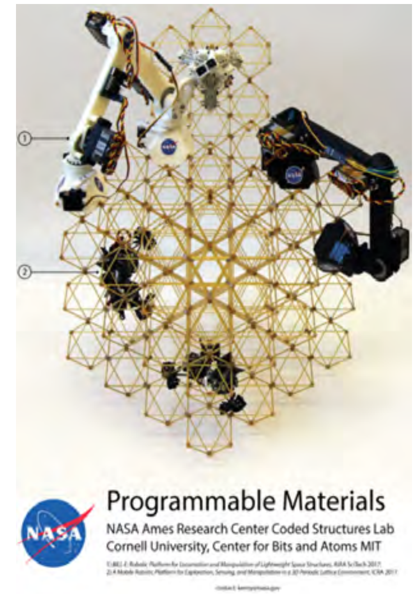


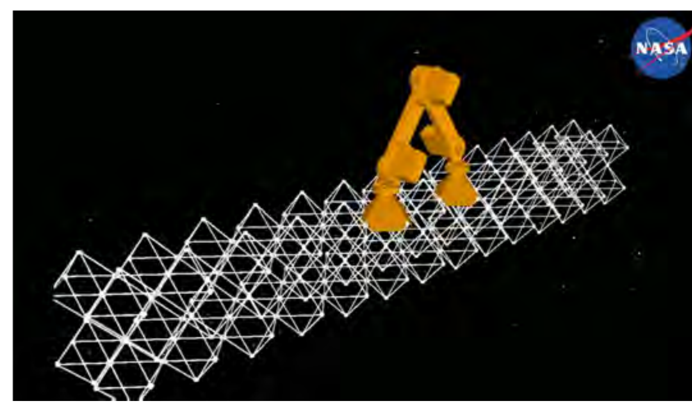
3-D Printed PE/Regolith 1m Ogive Dome Has a Flexural Strength of 26,2000 psi – 44X that of conventional concrete

Automated Reconfigurable Mission Adaptive Assembly Systems (ARMADAS)

- Develop and demonstrate autonomous assembly of building block-based digital materials and structures
  - ✓ Robotic assembler – autonomous unpacking and assembly of various
  - ✓ Digital materials building blocks (thermoplastic composites)
- Potential applications in habitats, antenna and solar array support structures, on-orbit space port structures, large aperture instrumentation

Project Manager: Kenny Cheung, NASA Ames





Space Technology Pipeline

Early Stage

- NASA Innovative Advanced Concepts
- Space Tech Research Grants
- Center Innovation Fund

Commercial Partnerships

- SBIR/STTR
- Flight Opportunities
  - Centennial Challenges
  - Regional Economic Development

Technology Demonstration Missions

TECHNOLOGY PIPELINE

Space Technology Research Grants
Opportunities to Propose

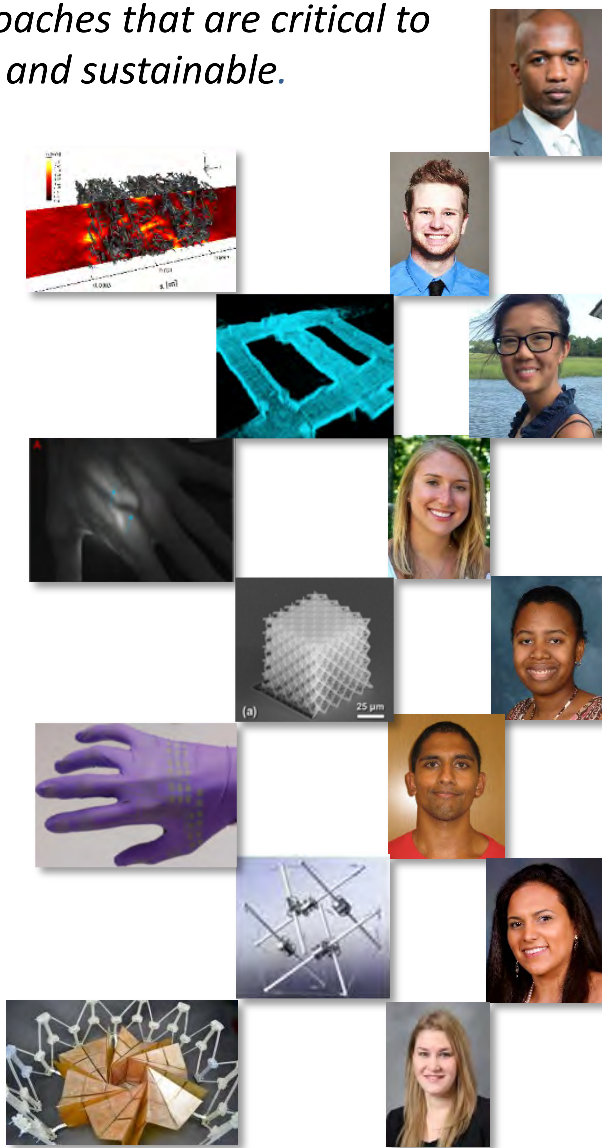
Engage Academia: *tap into* ***spectrum*** *of academic researchers, from graduate students to senior faculty members, to examine the theoretical feasibility of ideas and approaches that are critical to making science, space travel, and exploration more effective, affordable, and sustainable.*

NASA Space Technology Research Fellowships
- Graduate student research in space technology; research conducted on campuses and at NASA Centers and not-for-profit R&D labs

Early Career Faculty
- Focused on supporting outstanding faculty researchers early in their careers as they conduct space technology research of high priority to NASA's Mission Directorates

Early Stage Innovations
- University-led, possibly multiple investigator, efforts on early-stage space technology research of high priority to NASA's Mission Directorates
- Paid teaming with other universities, industry and non-profits permitted

Space Technology Research Institutes
- University-led, integrated, multidisciplinary teams focused on high-priority early-stage space technology research for several years



Accelerate development of groundbreaking high-risk/high-payoff low-TRL space technologies