



COSMIC Convergence: NASA In-Space Manufacturing (ISM)

Zachary S. Courtright | MSFC

In-Space Manufacturing Portfolio Manager



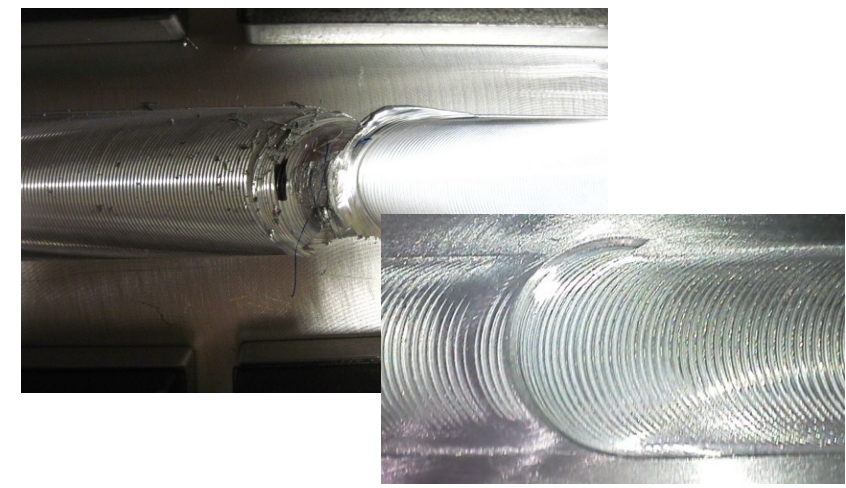
Why In-Space Manufacturing?



Reduce Launch Burden Related to Cargo Delivery to Space (image credit NASA)



Reduce launch mass through in-situ resource use (image credit ICON) Moon to Mars Objectives



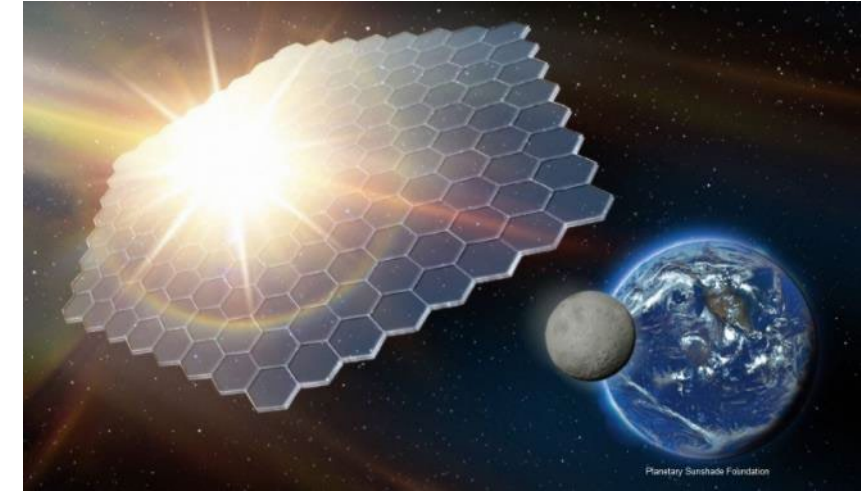
Weld Repair (structural damage, defective weld, damaged weld, etc.)



Recycling and Trash Management (image credit NASA)



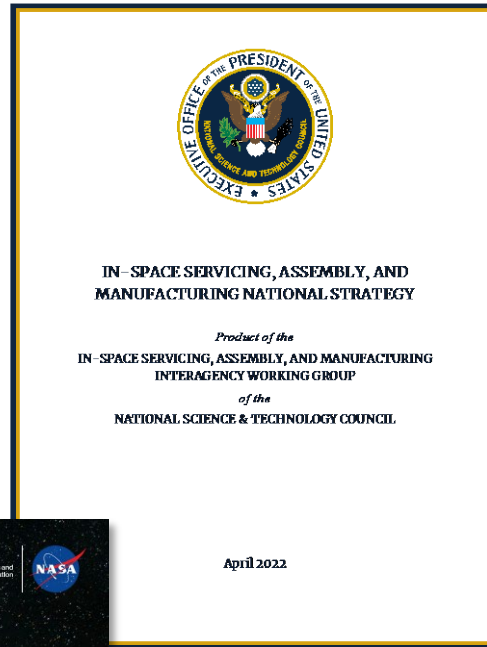
On-demand manufacturing of critical parts and tools (image credit NASA)



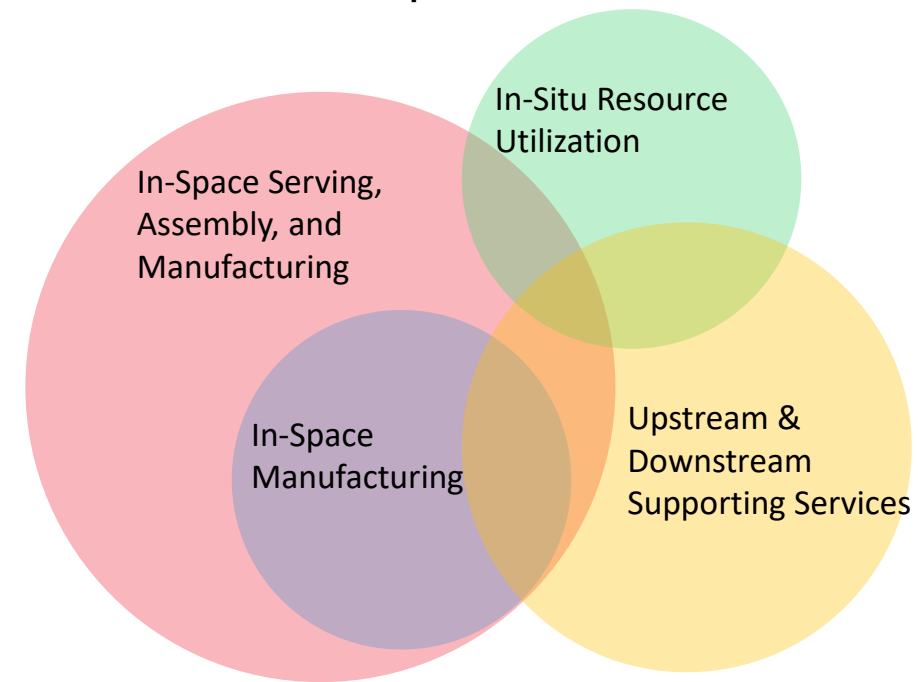
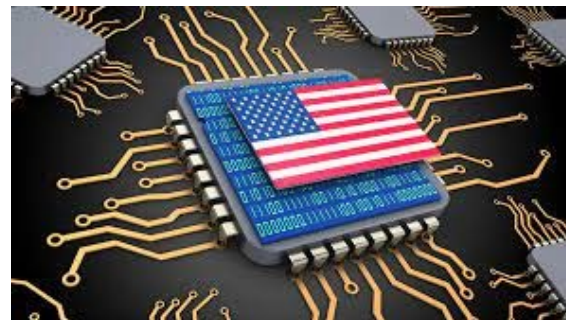
Build objects too big or fragile to launch

Bring  Recycle & Reuse  In-Situ Resource Utilization

Why?



“ISAM capabilities can create the foundation for sustainable operations and serve as a strategic enabler to spur U.S. scientific and technological innovation, ensure the freedom to operate, and preserve the use of space for future generations.”



Adapted from In-Space Manufacturing-2022 Industry Survey
Erik Kulu

M2M Architecture Definition Document: *Manufacture is mentioned 80 times, repair (43), and recycle (6)*

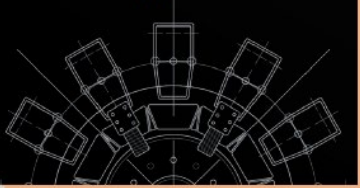
ISM Addresses STMD Advanced Manufacturing Technology Shortfalls (“Gaps”)

In-Space
Manufacturing
and Space Infrastructure



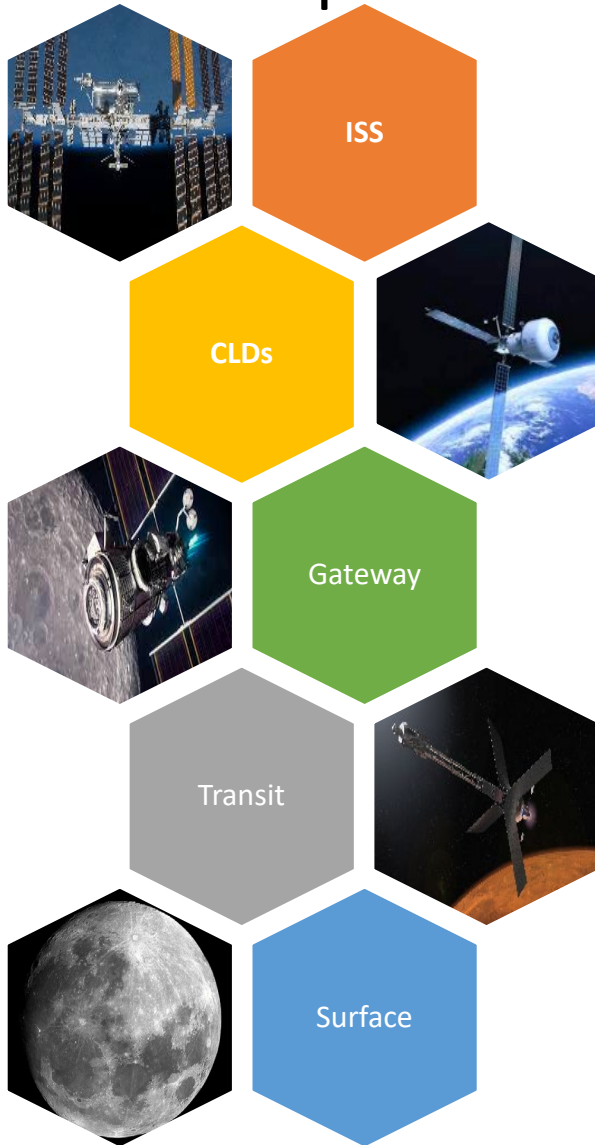
> 50% Mass reduction, > 99% 3D printer readiness. A catalyst for space infrastructure and economic opportunities

1



Gap ID	Gap Title	ISM Portfolio Approach
1485	In-Space Manufacturing of Metals, Electronics, and Polymers (Spares, Repairs, New Parts)	GCD-funded project On-Demand Manufacturing of Electronics (ODME) is currently pursuing in-space manufacturing of sensors for astronaut health and semiconductors for use in space and terrestrially. ISM anticipates resumption of in-space fabrication of metallic and hybrid material components and structures in future fiscal years.
1487	In Space Welding and Large-Scale Additive Manufacturing	MSFC TIP, proposed ECI, and a DARPA NOM4D collaboration are developing in-space laser-based processing (e.g. welding and bending) to enable critical repairs and construction of large articles such as lunar towers or space-based storage tanks.
1489	Recycling and Reuse for In-Space Manufacturing	ISM plans to reintroduce a focus on space-based material recycling in FY25, to be followed by recycling of metallics.
1486	In Situ Qualification, Verification & Validation of Components for Manufacturing, Assembly, and Construction	ISM is utilizing NDE, structured light, and various other inspection techniques to verify and validate form, fit, and function of space-fabricated electronics, components, and structures.

In-Space Manufacturing Goals & Objectives



1) Develop a Space Economy

Applications: Manufacture goods for Government and Industry

- Leverage the microgravity environment
- Enable Outfitting of Habitats
- Manufacturing goods in space for Earth

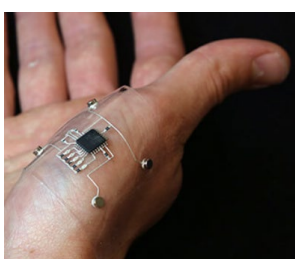
Focus: AM/Welding of Metals, Polymers, Electronics, Logistics Reduction, Biomanufacturing, and Computational Modeling/Digital Twins

2) Enable Sustainable Deep Space Missions

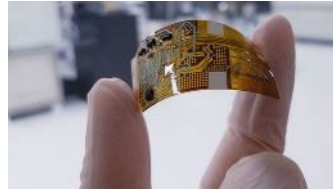
Applications: Living Sustainably on the Lunar and Martian Surfaces

- Medical Devices
- Crew Tools & Engagement
- Habitats Outfitting & Infrastructure
- EVA Aids (ex. modular excursion devices)

Focus: Enabling living and working in space to be **sustainable** → reducing **operations** cost.



Wearable Disposable Flexible Sensors



Printed Electronics



Multi-material printer for ISS Demo



Fasteners and Tools



On Demand Cast



Heat Exchangers

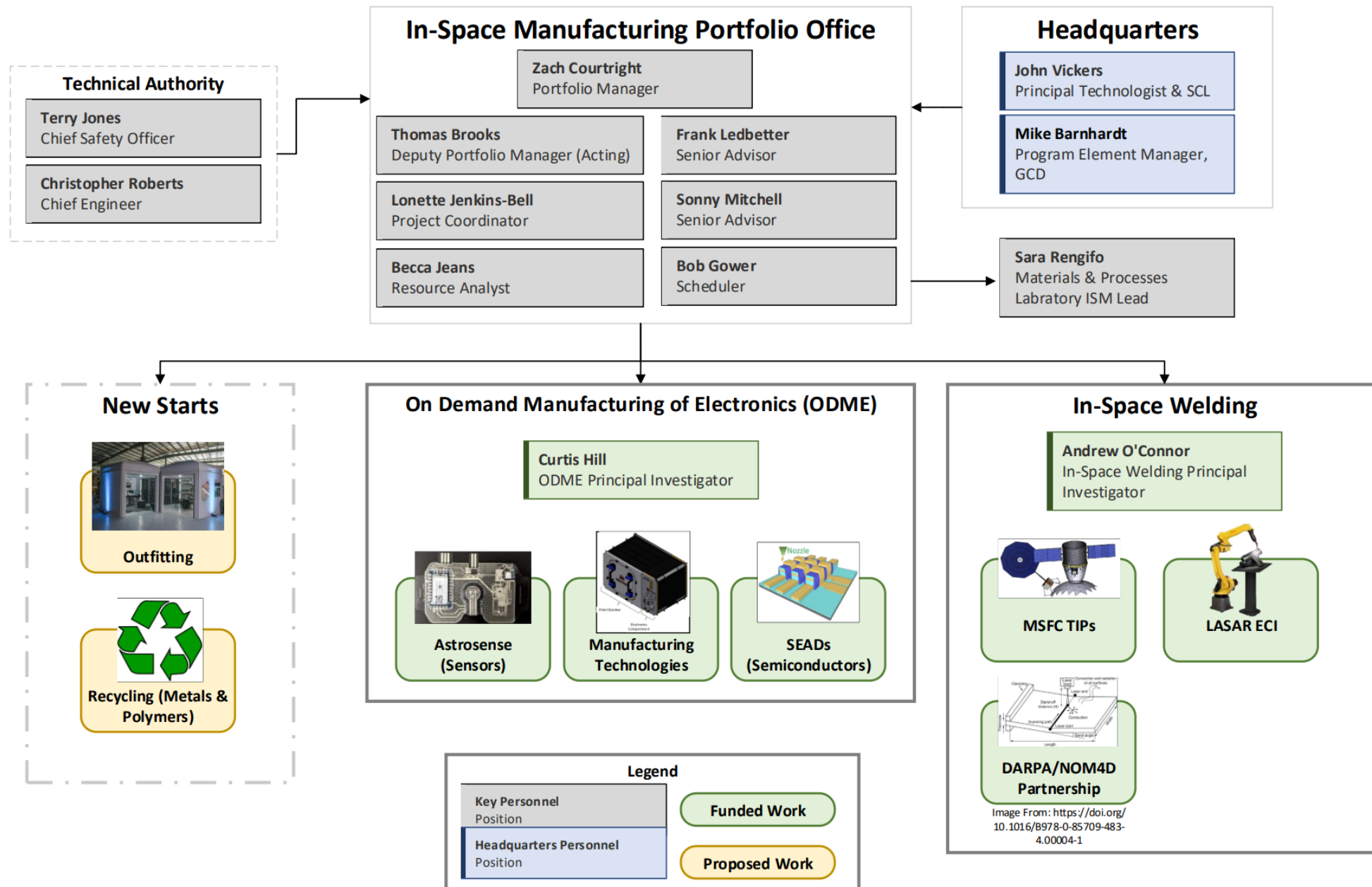


Modular Excursion Devices



On Demand Farming Tools

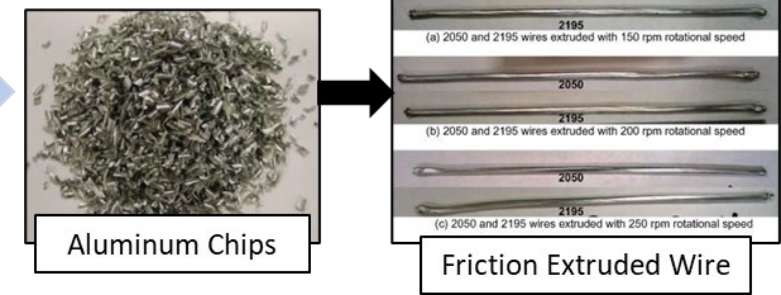
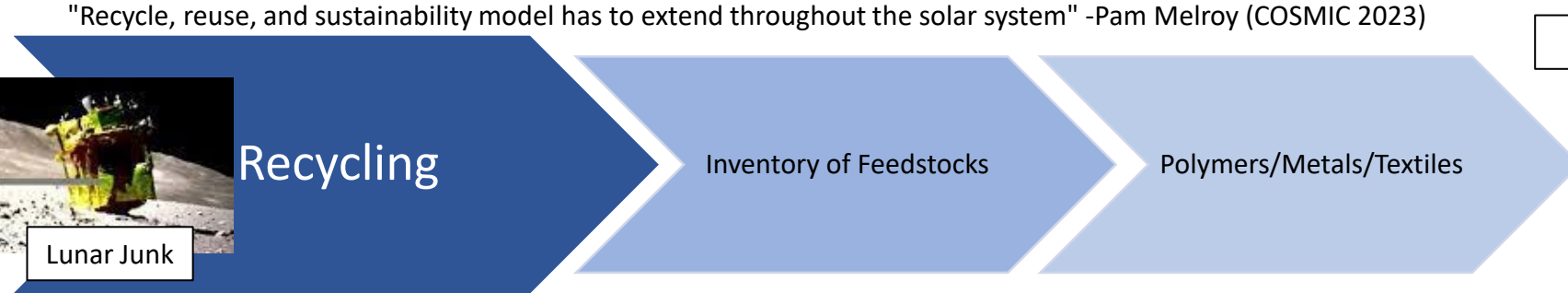
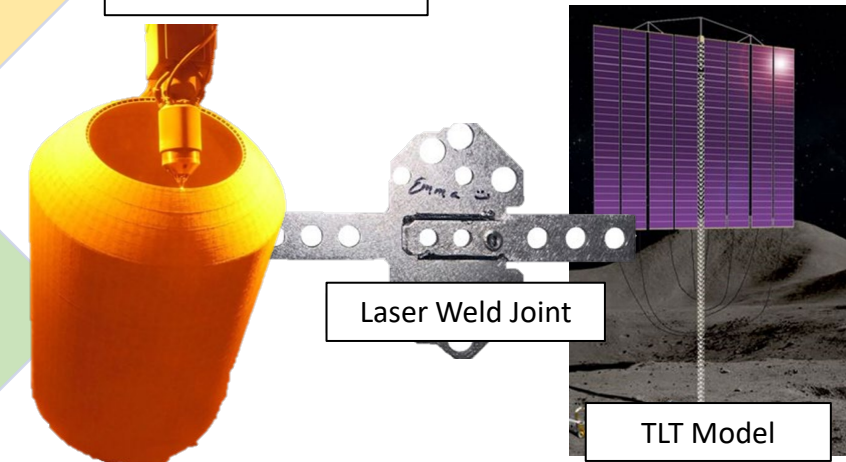
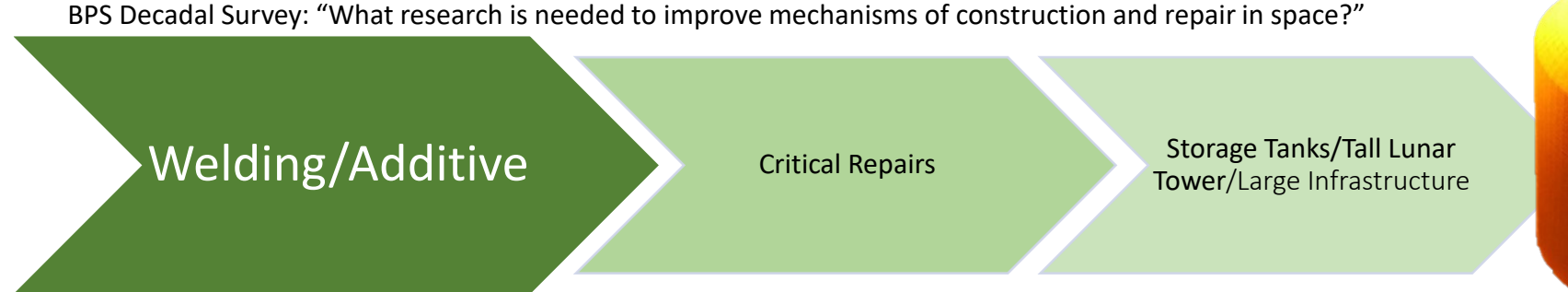
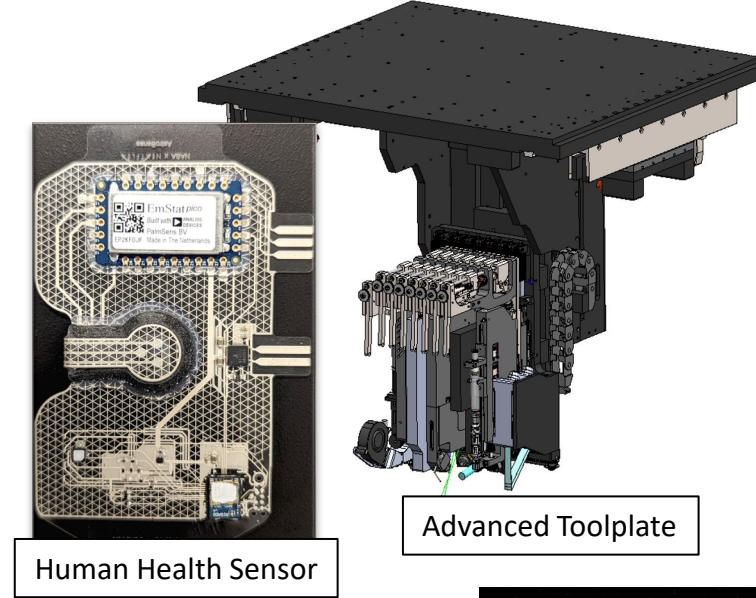
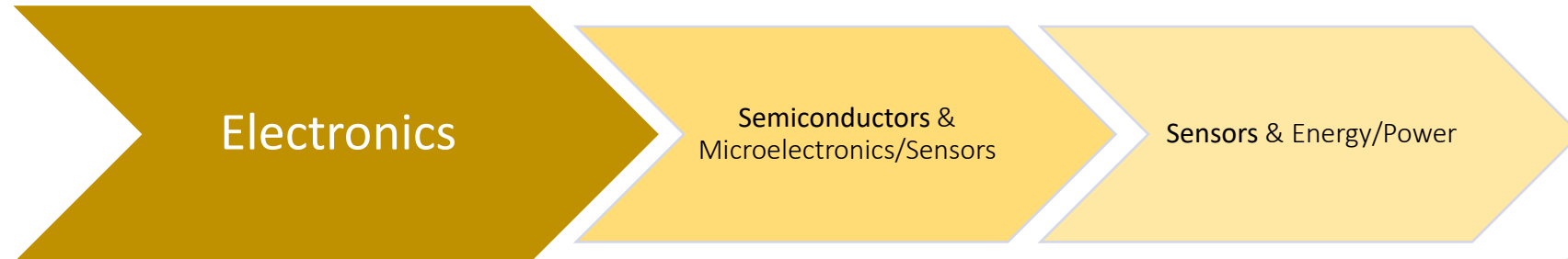
Takeaway: NASA is investing in the development of enabling manufacturing technologies for use in space.



This chart represents a fraction of the team members that make the ISM vision possible.

5 Year ISM Portfolio Plan

Associated Verification Technology



ISM Enables Moon to Mars Objectives (e.g. Foundational Exploration, Sustained Lunar Evolution, Humans to Mars)

ISM Maturation using ISS NL, Integration Partners, and CLDs



Ground Development



Parabolic Flights - Test



ISS - Demonstrate



Lunar Habitat – Use

ISM is maturing advanced manufacturing capabilities through microgravity demonstrations on STMD Flight Opportunities enabled Parabolic Flights.

- Three parabolic flight campaigns prior to FY24, with five more planned in 2024.
- Working with ISS NL and multiple Integration Partners for planned microgravity demonstrations of semiconductor technologies.
- Working with CLDs partners Axiom and Sierra Space to mature semiconductor technology with plans for eventual demo on their platforms.



CLDs– Commercialize

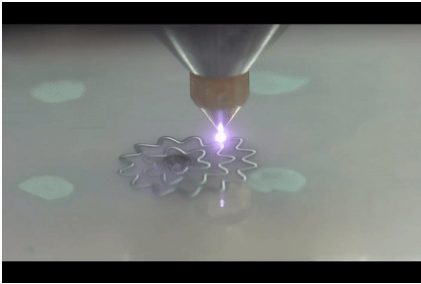
Takeaway: CLDs and the ISS provide platforms to demonstrate, mature, and commercialize ISM technology.

Current Projects



On-Demand Manufacturing Of Electronics

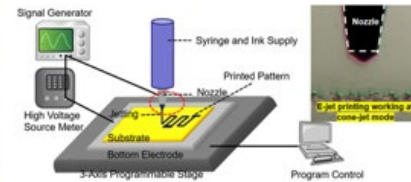
Goal: Develop and demonstrate on-demand printing of electronics in microgravity and characterize the impact of microgravity.



Dual Laser Ablation



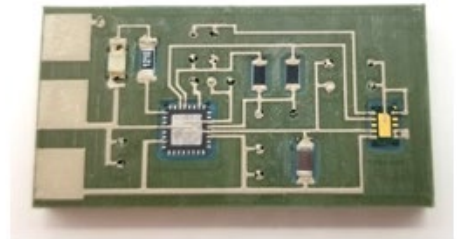
Faraday Electrodeposition of
Covetic Copper



Electrohydrodynamic Ink Jet Printer



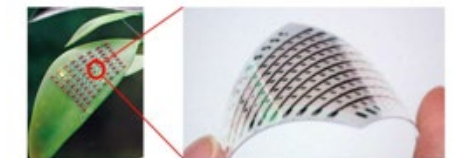
Iowa State Parabolic Flight



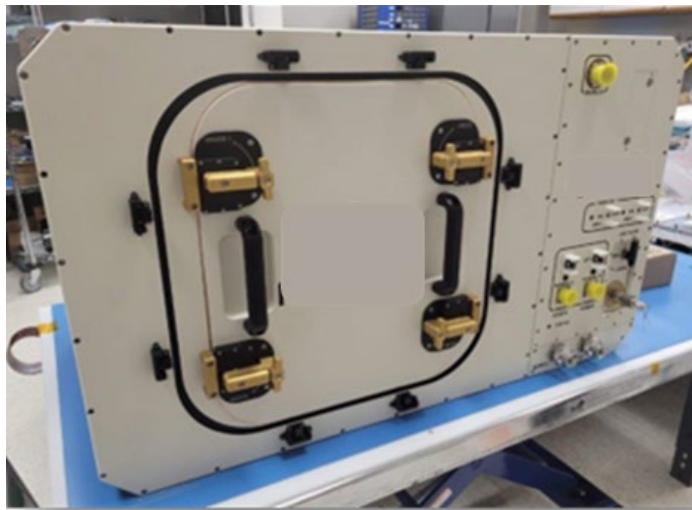
Printed CO₂ Sensor (ODME ISS Demo)



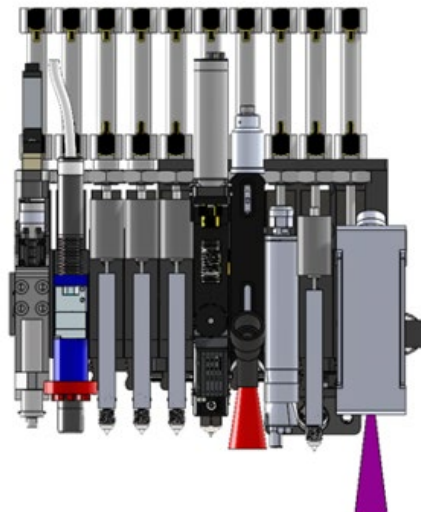
RF Power Harvesting Antennas- UAH



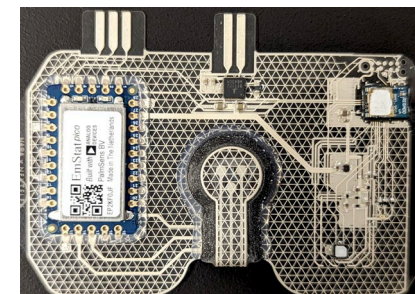
University of Illinois Plant Growth Sensor



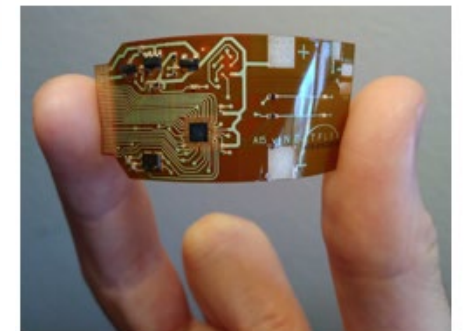
Electronics Printer Module Engineering Development Unit
Image Credit: Redwire



Advanced Toolplate with Newly
Developed Deposition Tech



AstroSense FTE Beta Crew Health
Biosensor



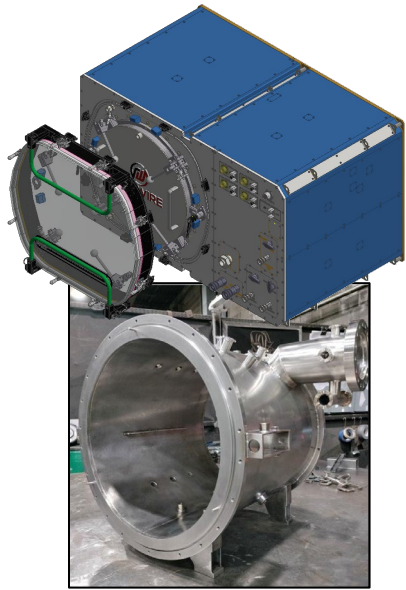
NextFlex Wireless Flexible Sensor Board

Recently Closed: On Demand Manufacturing Of Multi-materials Project

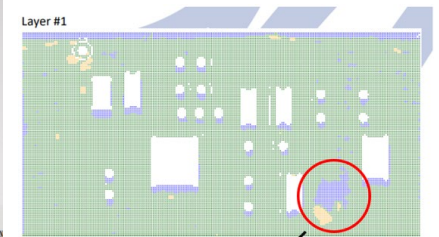
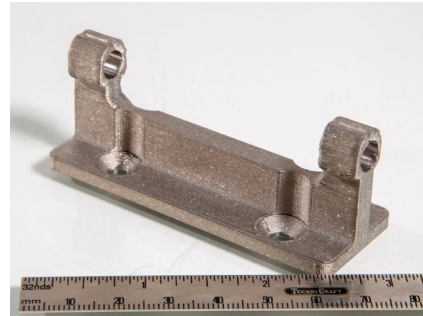
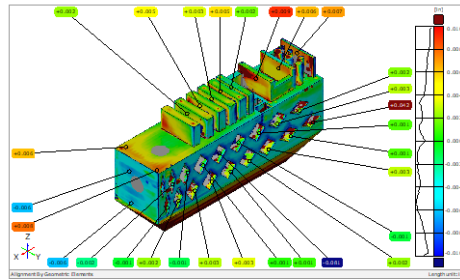
Goal: Demonstrate metals additive manufacturing in microgravity and characterize the impact of microgravity.

Sub Projects:

1. **Outfitting:** Develop the capability to manufacture on-demand utilities, furnishings, tools, etc. for off-earth habitation including the use of In-Situ Resources.
2. **Recycling and Reuse:** Develop the capability to recycle and reuse materials into useable feedstocks for in-space, on-demand manufacturing.



CAD of Revised furnace module (top). Furnace module hotzone during manufacturing.
Image courtesy of Techshot a Redwire company (bottom).



Hole Gouged in Print

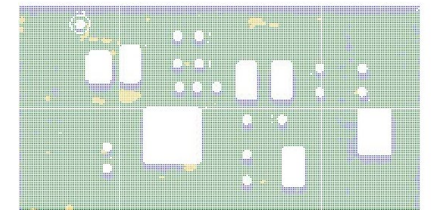
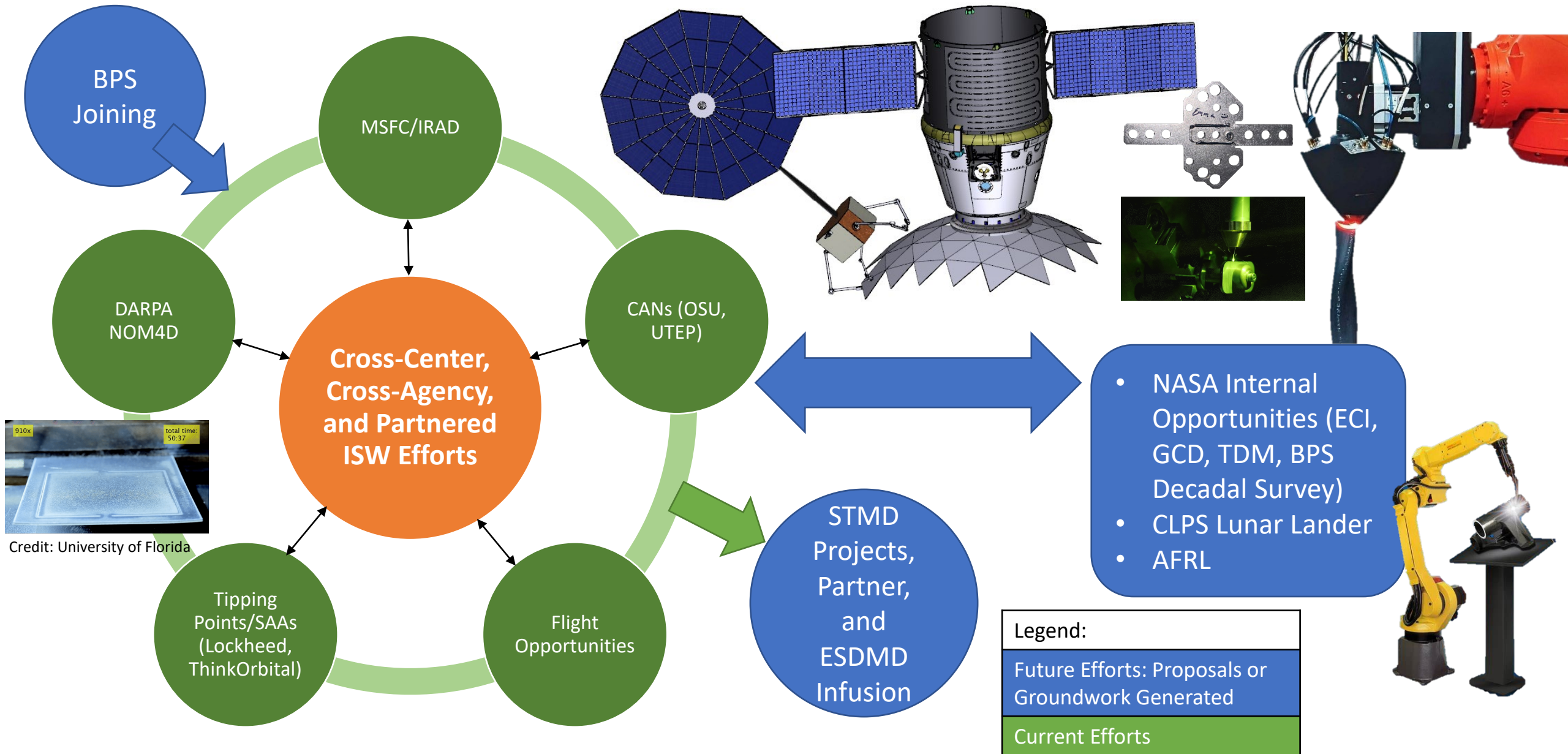


Illustration of inspection and remediation. Image courtesy of Techshot a Redwire company.



Space Suit Wrist Disconnect manufactured by FabLab. Image courtesy of Techshot a Redwire company.

Ecosystem for In-Space Welding (ISW) at NASA



Ground Experiment

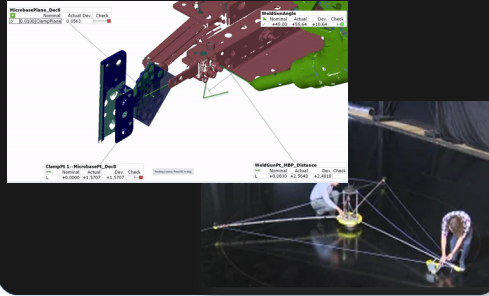
IPG LightWeld



- COTS, handheld laser beam welder with cleaning and cutting modes
- Demonstrated welding of aerospace-grade aluminum joints in lab

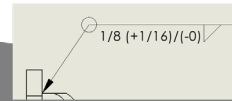
Develop and Integrate a 3-DOF Laser Welding System

- Integrate portable laser welder onto robotic fixturing.
- First demonstration of laser welding in 3 degrees-of-freedom space simulator
- Augment Digital Twin model development.



Digital Twin Modeling

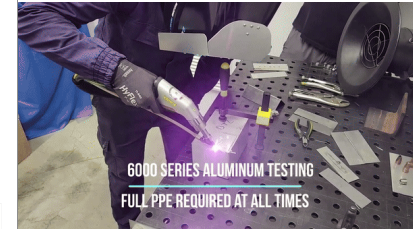
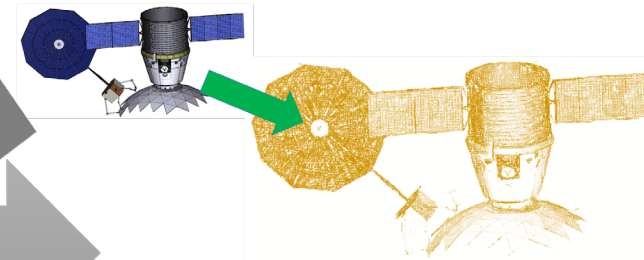
- UTEP is funded by MUREP through a CAN to build virtual counterpart of in-space weld.
- Determine tolerances to inform ISW requirements



End Goals. Leverage 2 Concurrent CANs.

- 1) Use two-pronged experimental approach to develop MSFC modeling (ICME and Digital Twin) capability for in-space welding. TRL 2 → TRL 4.
- 2) Demonstrate laser beam welding technology as viable approach for ISAM. TRL 3 → TRL 5.

Digital Twin of Space Welding



Suborbital Flight Experiment (FO Request Pending)



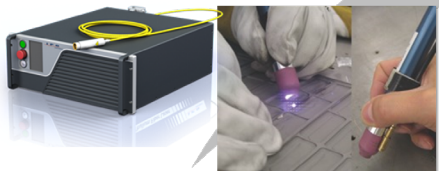
- Proven flight system used to demonstrate electron beam AM on NASA C-9B parabolic flights

LaRC Vacuum Chamber

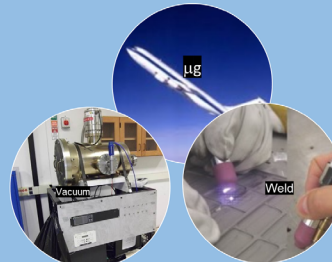
Parabolic Flight Experiment

MSFC Laser Beam Welding

- Cycle times of fiber LBW are fast
- Tremendous data collection potential on 15 to 25 s parabolic arcs



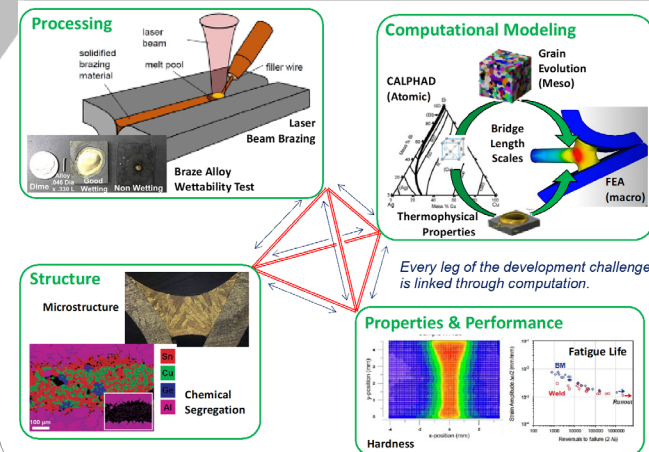
OSU-NASA CAN Partnership



- Integrates MSFC laser with LaRC flight chamber
- Incorporates instrumentation to collect data for model calibration and validation
- Funded by ISM, BPS, SNP, CAN

Manifested on Zero-G 727 for flights in August 2024

Integrated Computational Materials Engineering workflow of Laser Welding



Substantial NASA investment has enabled this work to create a pathway to Lunar demonstrations.

Lunar Assembly and Service by Autonomous Robotics (LASAR)

NASA Core Team Members

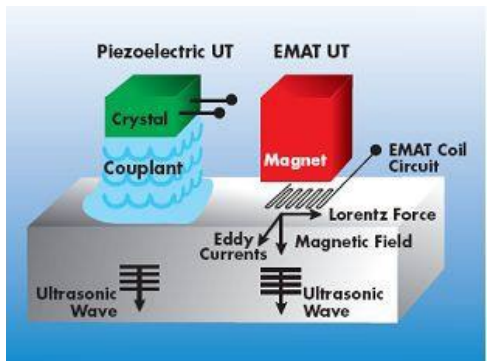
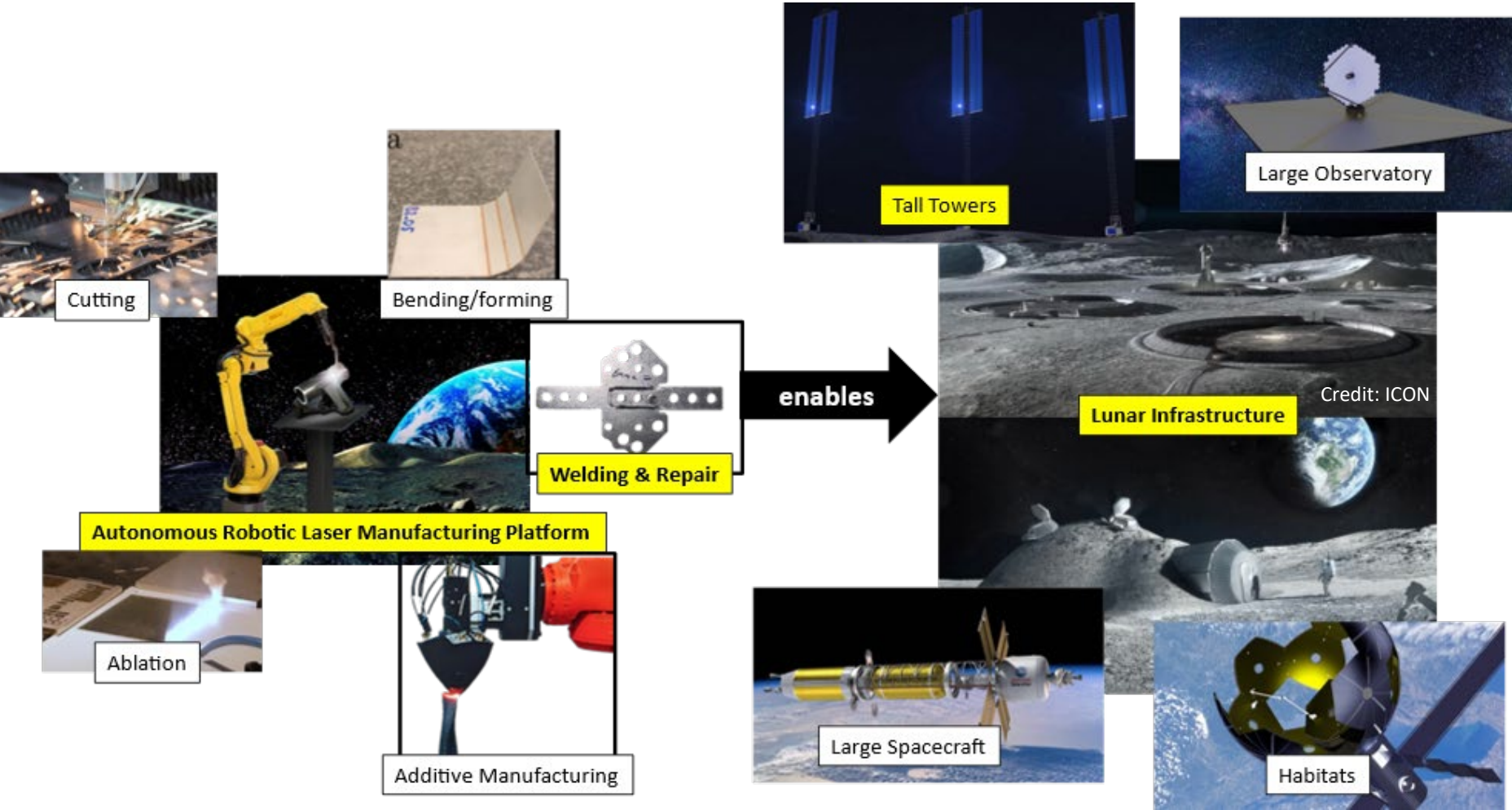
Name	Center
Emma Jaynes	NASA/MSFC
Alex Sowell	NASA/JSC
Raju Subedi	NASA/MSFC
Brace White	NASA/LaRC
Supported by:	
William Evans	NASA/MSFC
Matthew Mahlin	NASA/LaRC
Parker Shake	NASA/MSFC

External Partners

Name	Role
Laserline	Laser Processing Partner
Motiv Space Systems	Robotics Hardware Partner
PickNik Robotics	Robotics Software & Autonomy Partner

Mentors

Name	Role
Shaun Azimi	JSC Robotics SME
Bill Doggett, PhD	LaRC In-Space Assembly SME
John Fikes	MSFC Management SME
Jeffrey Sowards, PhD	MSFC Laser Welding SME

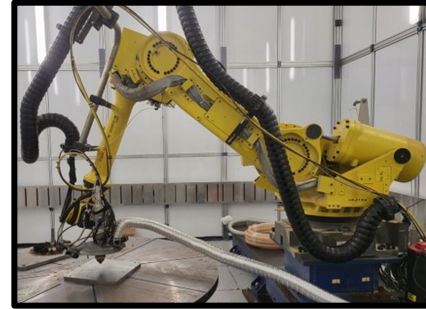
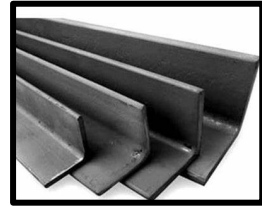
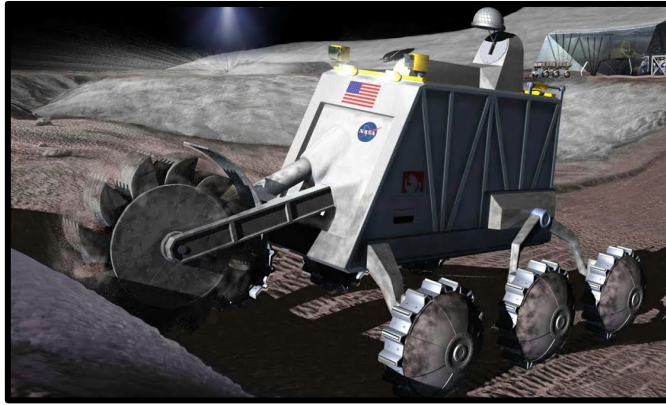


Credit: ThinkOrbital/Vojtech Holub

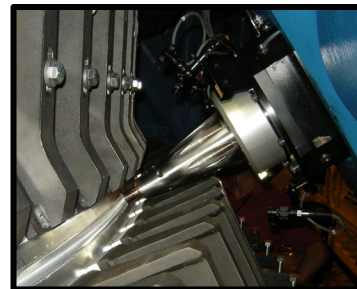
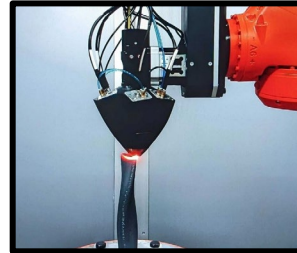
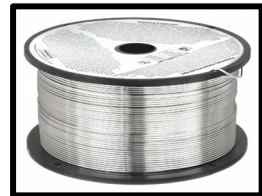
Future In-Space Manufacturing



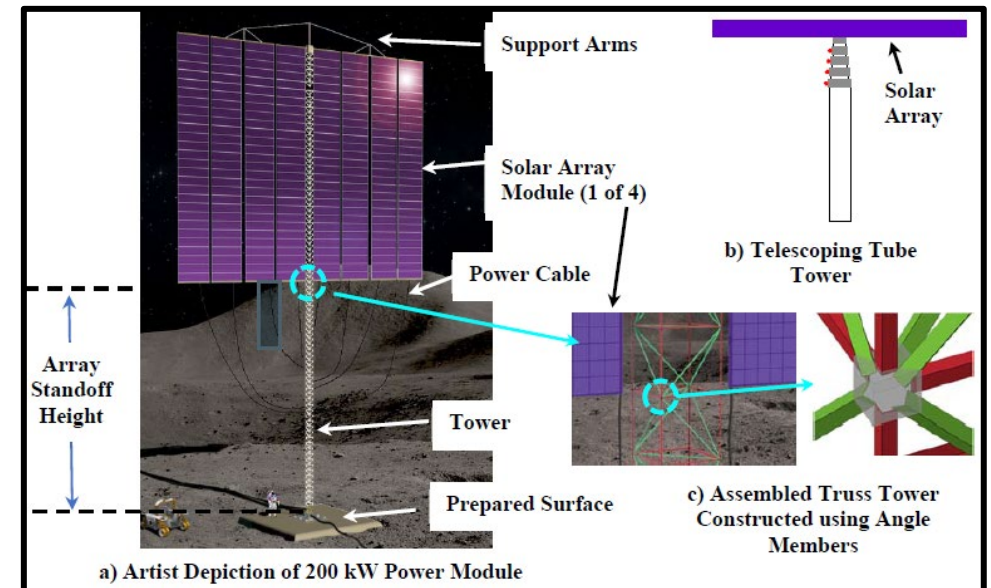
Future: In-situ Resource Utilization and Manufacturing

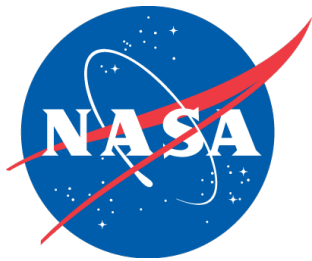


LuSTR ISRU Grant: [MAGMA: Molten Aluminum Generation for Manufacturing Additively - NASA](#)



Computational Modeling, AI/ML and Digital Twins Enable All Steps of this Process

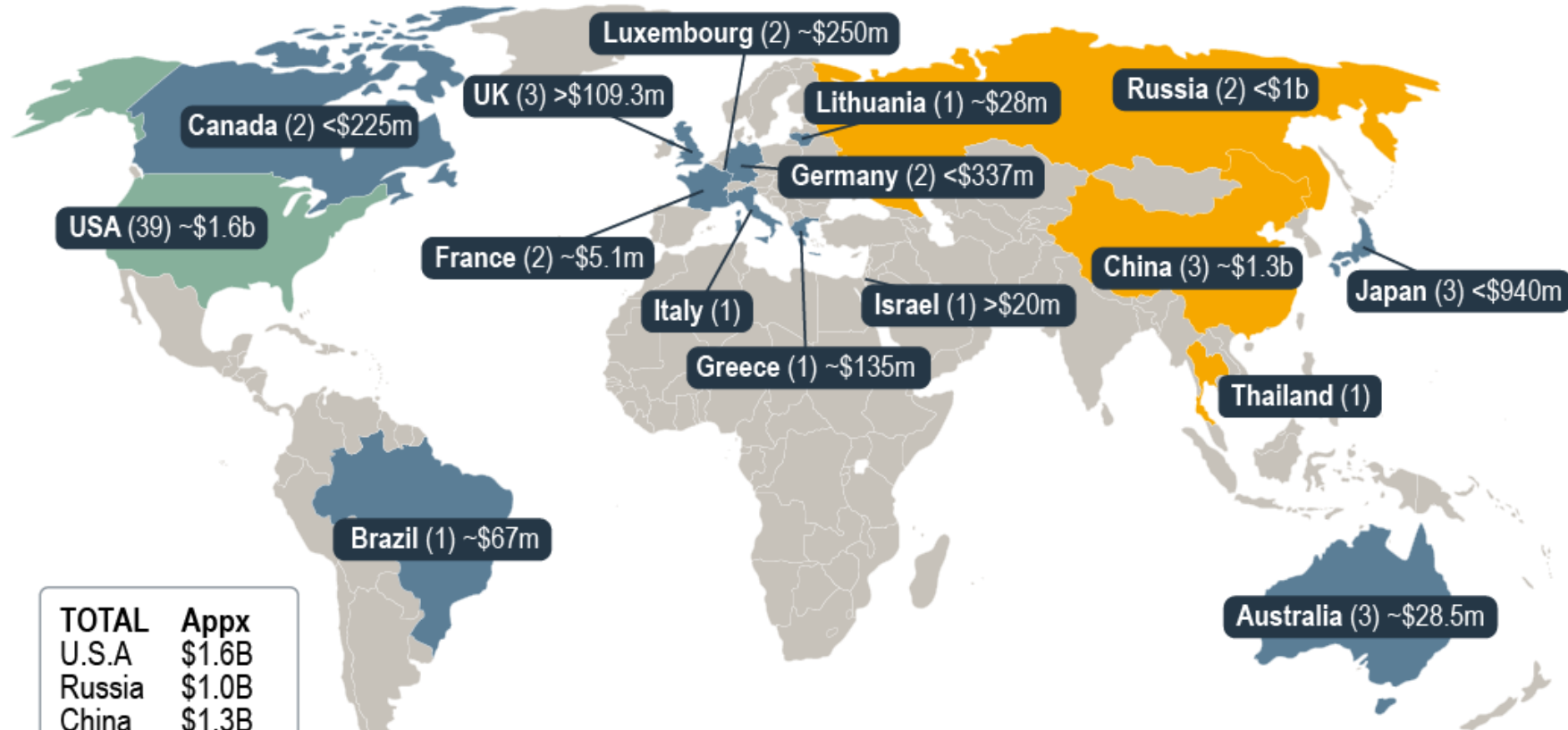




Backup



ISM Investment by Country



TOTAL	Appx
U.S.A	\$1.6B
Russia	\$1.0B
China	\$1.3B
EU	+\$780M
Japan	+\$940M

Russia and China have joint collaboration for the space race in human exploration, doubling resources to advance quickly in comparison to the USA. Also, note that commercial funding seems to be concentrated in a handful of companies for China and Russia, which could indicate an effort to mature specific technology areas.

The number in the parenthesis () indicates the number of companies contributing

**Provided by Booz Allen Hamilton*

Pathway to Sustainability through ISM

**DEMONSTRATIONS &
COMMERCIAL MANUFACTURING
IN LEO (E.G. DARPA NOM4D
BENDING AND ELECTRONICS)**

Currently working Strategic Planning, Tech Maturation,
and Roadmaps

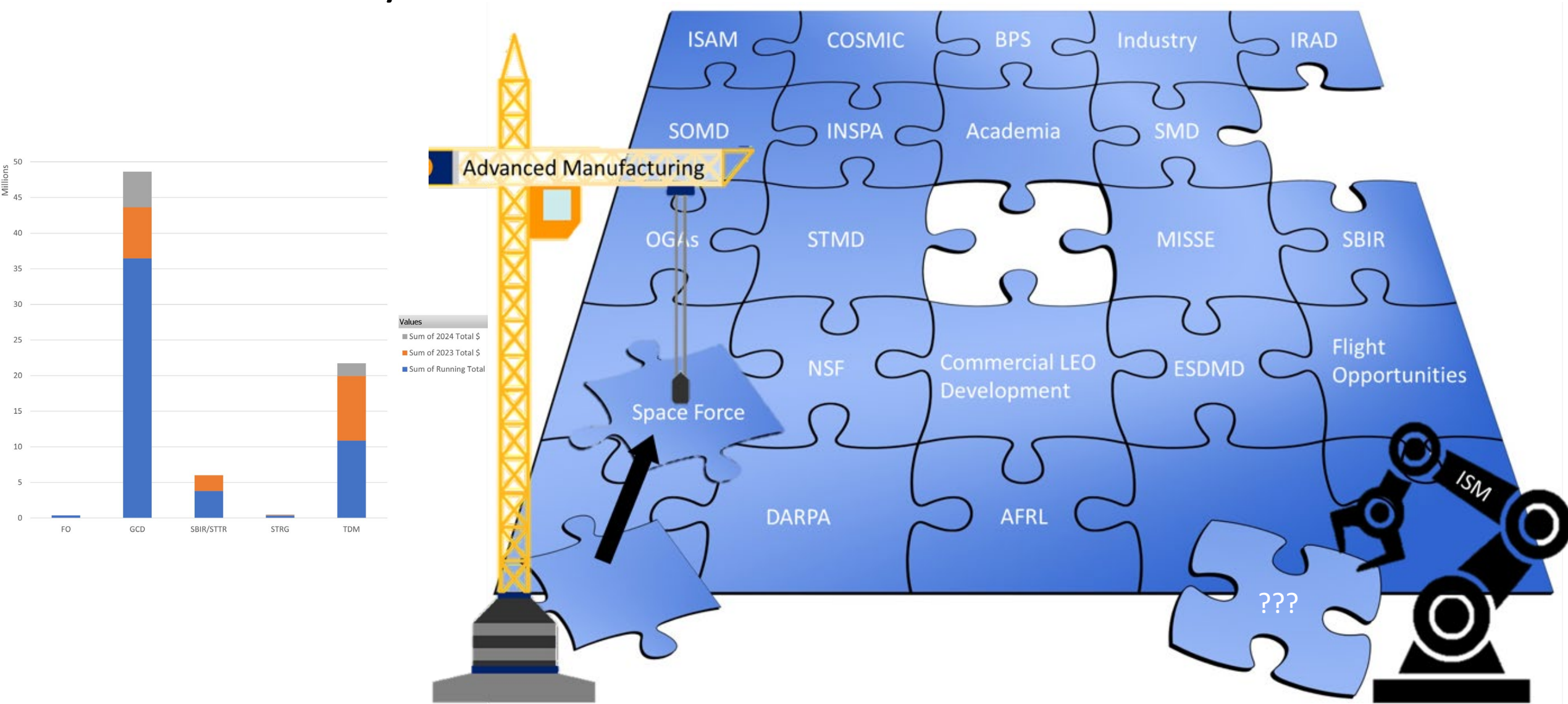
LOGISTICS REDUCTION

**SUSTAINING HABITATS &
OUTFITTING**

**EXPLORATION &
TRANSIT**

ISM Enables Moon to Mars Objectives (e.g. Foundational
Exploration, Sustained Lunar Evolution, Humans to Mars)

ISM Ecosystem



Moon to Mars Strategy

Objective-based Approach – Architect from the Right

LI-4: Lunar Surface Advanced Manufacturing and Construction

LI-8L: Cislunar Orbital/Surface Depots, Construction and Manufacturing

PPS-2: Understanding Physical Systems

AS-6: Understanding Environmental Effects

RT-5: Maintainability and Reuse

RT-6: Responsible Use and Behavior in Space

RT-9: Commerce and Space Development

OP-11: In-Space Resources to Reduce Mass

OP-12: Minimize the Disturbance to the Environment, Maximize Reuse/Recycling

TH-4: In-Space and Surface Habitation





In-Space Manufacturing (ISM) / On Demand Manufacturing of Electronics (ODME) Collaborations & Partnerships

Exploration & Science

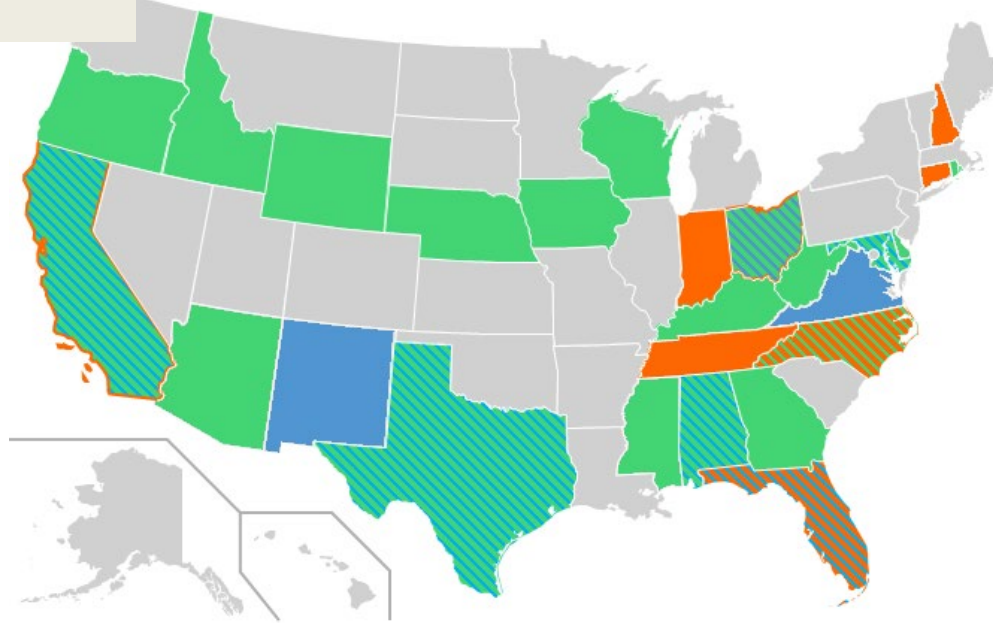
NASA Exploration and Support "In Space for Space" development

- ECLSS Sensors
- Wearable sensors
- Printed Power & Energy
- Logistics – spares and upgrades for missions

Commercialization

Support "In Space for Earth Applications" development

- Semiconductors



Academic

- University of Louisville
- University of Alabama Huntsville
- Appalachian State
- Auburn University
- Boise State
- Georgia Institute of Technology
- CalTech
- Iowa State University
- Florida A&M University
- Oregon State University
- West Virginia University
- Youngstown State University
- University of Wisconsin
- University of Wyoming
- University of Delaware
- University of Texas El Paso
- Mississippi State
- Arizona State University
- University of Delaware
- Stanford University
- The Ohio State University
- University of Texas at El Paso

NASA Centers

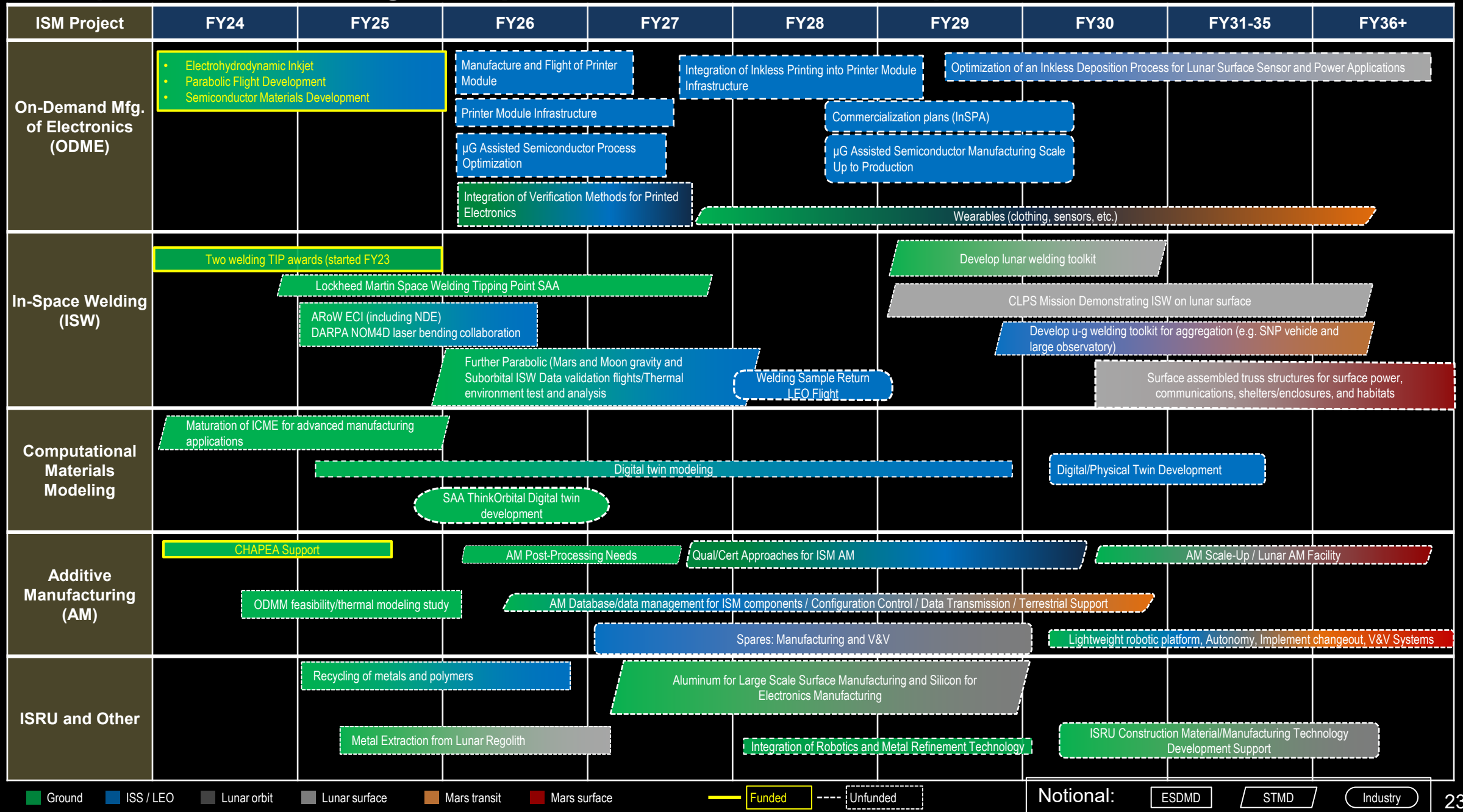
- Marshall Space Flight Center
- Ames Research Center
- Johnson Space Center
- Kennedy Space Center
- Goddard Space Flight Center
- Jet Propulsion Laboratory
- Glenn Research Center
- Langley Research Center
- Armstrong Flight Research Center

Industry/Government

- Redwire Space
- Cornerstone Research Group
- LambdaVision
- Faraday Incorporated
- Laboratory for Physical Sciences
- Intel
- Lockheed Martin
- ThinkOrbital
- IPG
- Fujifilm
- Axiom Space
- ISS National Lab
- Goeppert
- NextFlex
- nScript
- Multi3D

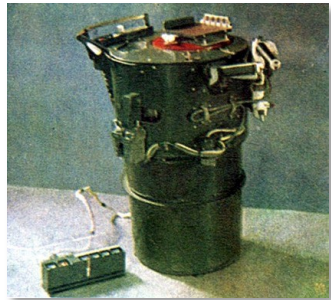
Note: Some of these official partnerships have concluded and we have maintained contacts and relationships for future opportunities.

In Space Manufacturing and Space Infrastructure Roadmap



History of Space Welding and Joining

The first and last
completed US Space
Welding Experiment



Progress in Space Stagnated and Moved to Parabolic Flights



It has been over 50 years since NASA
has performed a weld in space.

FIRST SPACE WELD

FIRST AMERICAN SPACE WELD

FIRST MANUAL OPEN SPACE WELD

CANCELLED

1960s

US

1970s

1980s

1990s

2000s

2010s

2020s

Future

Parabolic Vulkan
Experiment (USSR) 1965

Parabolic Skylab Materials
station (USA) 1972



Parabolic LBW Experiment 1988/89

Parabolic UHT Experiment 1993

Parabolic ISWE Experiment 1994

Drop Tower GTA Weld Experiment 1998

Parabolic GHTA Weld Experiment 2001

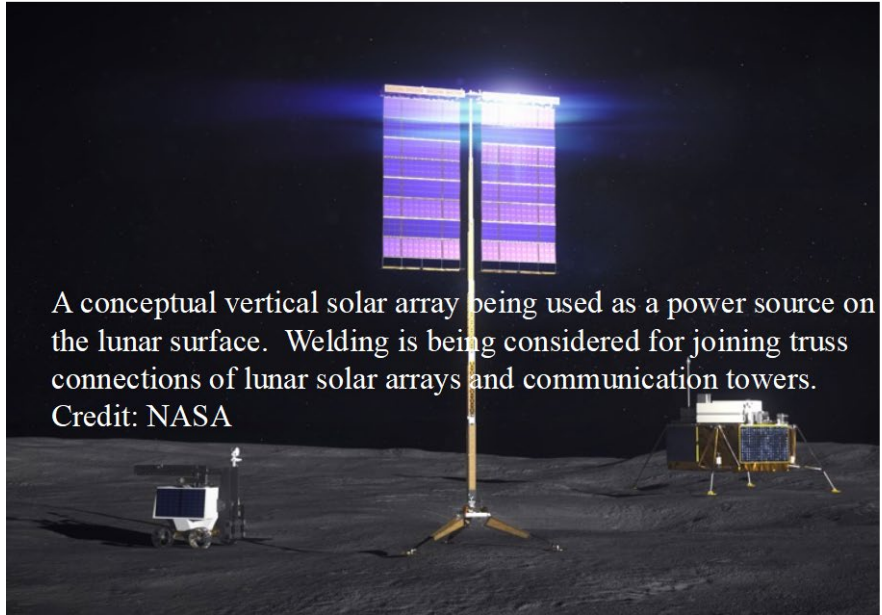
1999. ISWE went to MIR USA/UKRAINE

2018. New Ukrainian EBW Gun Patented

2021. SUBSA-BRAINS braze metal

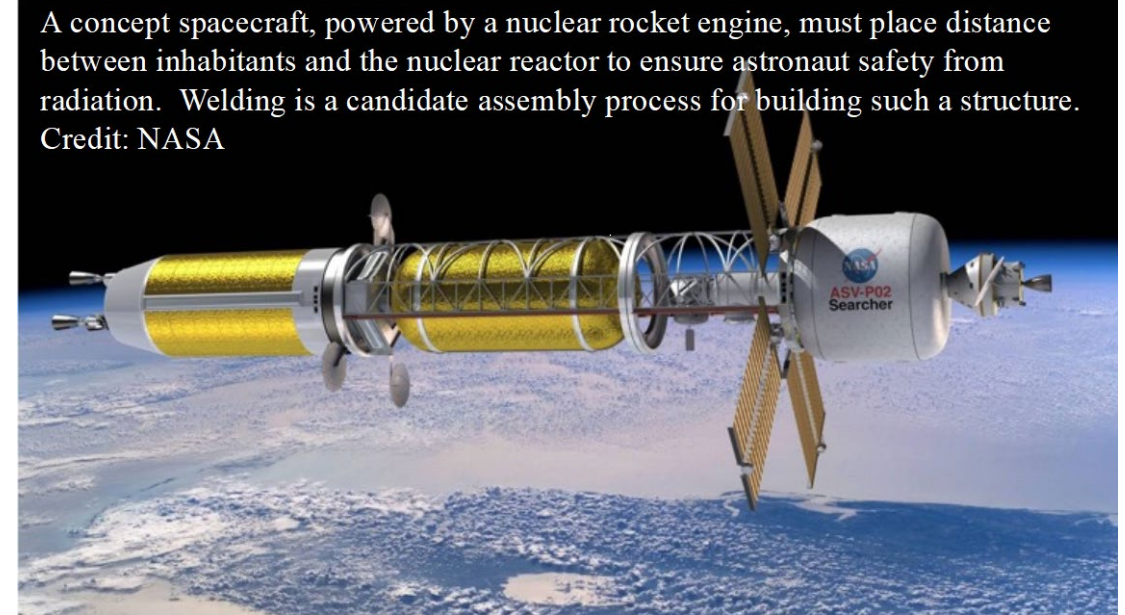
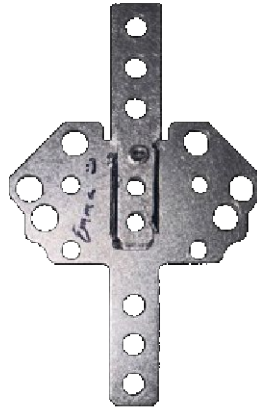
2023. NASA Public-private partners

Applications in Progress



A conceptual vertical solar array being used as a power source on the lunar surface. Welding is being considered for joining truss connections of lunar solar arrays and communication towers.
Credit: NASA

Tower truss connection made with handheld laser beam spot weld and lap welds. AA 6061 with 5183 filler metal.

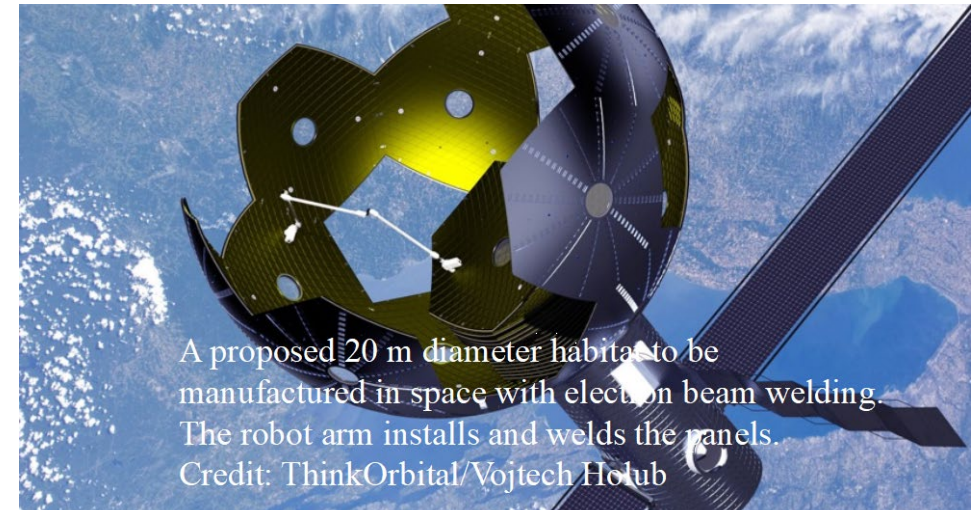


A concept spacecraft, powered by a nuclear rocket engine, must place distance between inhabitants and the nuclear reactor to ensure astronaut safety from radiation. Welding is a candidate assembly process for building such a structure.
Credit: NASA



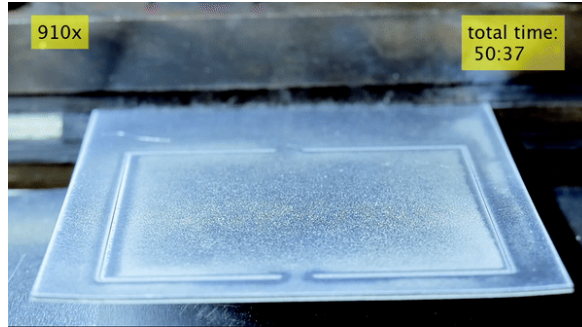
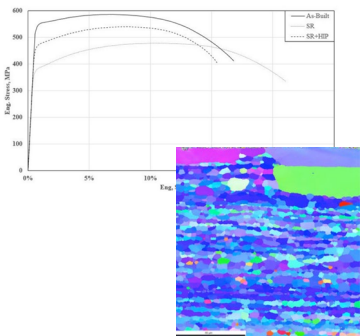
In-space joining demonstration will verify integrity for future space applications such as lunar surface infrastructure, orbital persistent platforms, and several space-system elements including antennas, solar arrays, sunshades, optical systems and radiators that will be essential to building out the lunar economy.

Credit: Lockheed Martin/Robert Biggs



A proposed 20 m diameter habitat to be manufactured in space with electron beam welding. The robot arm installs and welds the panels.
Credit: ThinkOrbital/Vojtech Holub

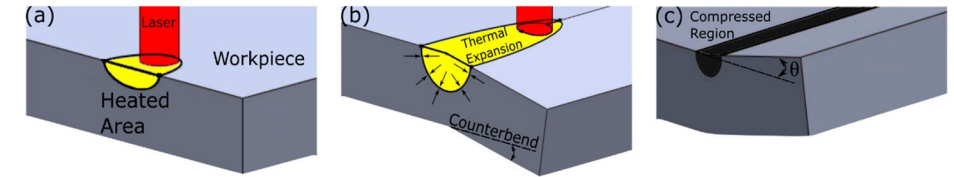
DARPA NOM4D partnership: Laser bending



Credit: University of Florida

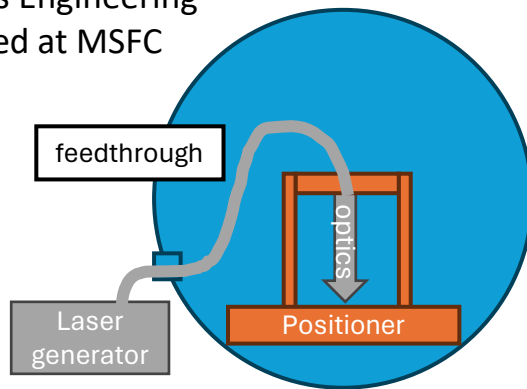
Must optimize:

- Laser beam profile
- Laser beam power
- Laser beam focus
- Laser beam position/scanning

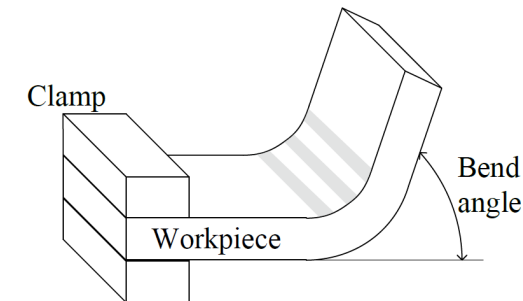
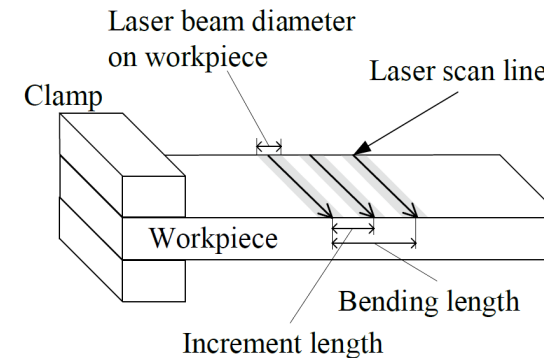
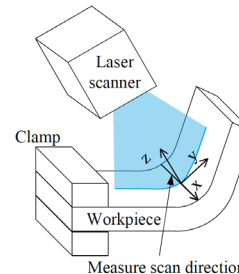
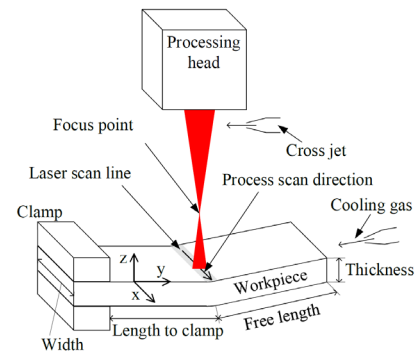


Thermal Gradient Mechanism (TGM) enables bending towards laser beam source

Integrated Computational Materials Engineering performed at MSFC



*notional TVAC schematic



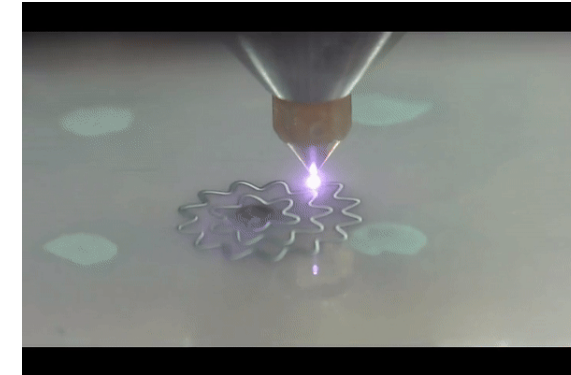
Minimal processing or workpiece setup required for laser bending

Mechanism dependent on thermophysical properties of workpiece (e.g. thermal conductivity at temperature) and thermal dissipation (affected by vacuum). Laser bending will be wholly different in space environments!

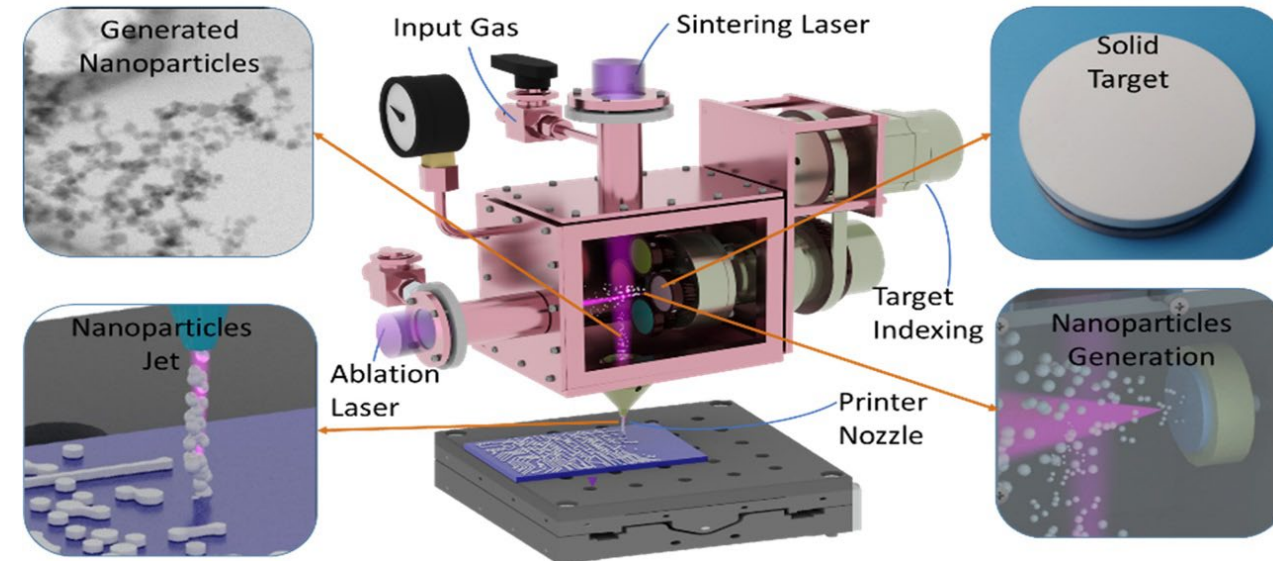
ODME Summary

- Progress toward completion of goals and objectives, TRL, and KPP
 - Parabolic flight testing completed in late February 2024 has already realized advancements in TRL for the Advanced Toolplate and SEADS semiconductors objectives. There is an additional parabolic flight campaign scheduled for August to advance the TRL on the EHD-Advanced Toolplate integration.
 - ODME sponsorship and management has helped Auburn University to win a large award from Flight Opportunities TechFlights for the dual laser ablation technology that will result in significant advancement in that technology and two parabolic flight campaigns.

Dual Laser Ablation



- Reiterate any major issues requiring help or anticipated help needed from GCD
 - No significant technical or programmatic issues for the remainder of FY24.
 - GCD alignment and support for new funding for ODME beyond FY24 is very important. Progress has been made with other funding sources for development funds, but additional labor funds are critical for FY25.



In-Space Manufacturing Advancement Center (ISMAC)



New collaborative workspace where ISM technologies can be advanced utilizing multidisciplinary teams. Equipment has been commissioned to explore ISM technologies related to electronics, welding, additive manufacturing, recycling, and metal extraction from Lunar or Martian regolith.

Robotic Swing Arm (RoSA) – Large robotic swing arm that with adaptable cube-sat to allow for AM under variable gravity environments.

In-Space Welding Development Hardware – Test cell dedicated to exploring and optimizing welds in a dusty regolith environment.

Regolith Pre/Post Processing via Acoustic Levitation – To study pre-processing of regolith for optimizing feedstock of direct regolith ISRU solutions, as well as post-processing extrusion.

M2M Regolith Laser Sintering Development Printer – M1 Metal Powder-bed printer for direct sintering of regolith.

Robotic Test Platforms

In-Space Welding

Powder Analysis

Regolith AM

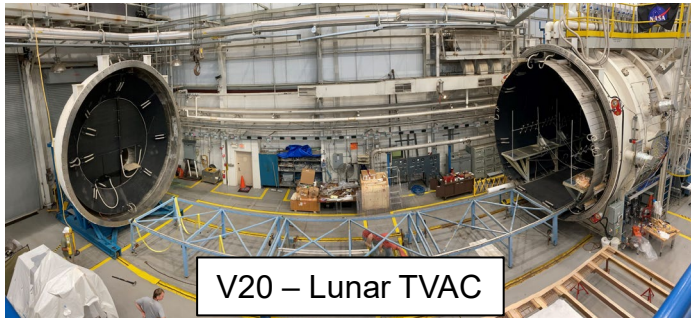
Variable Gravity Simulation

3D Lidar Scanning

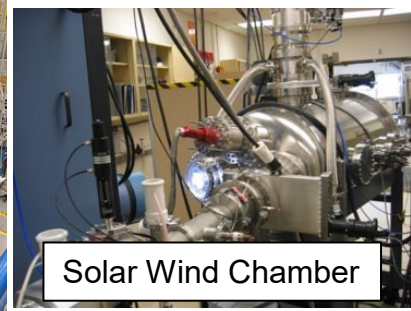
Acoustic Levitation



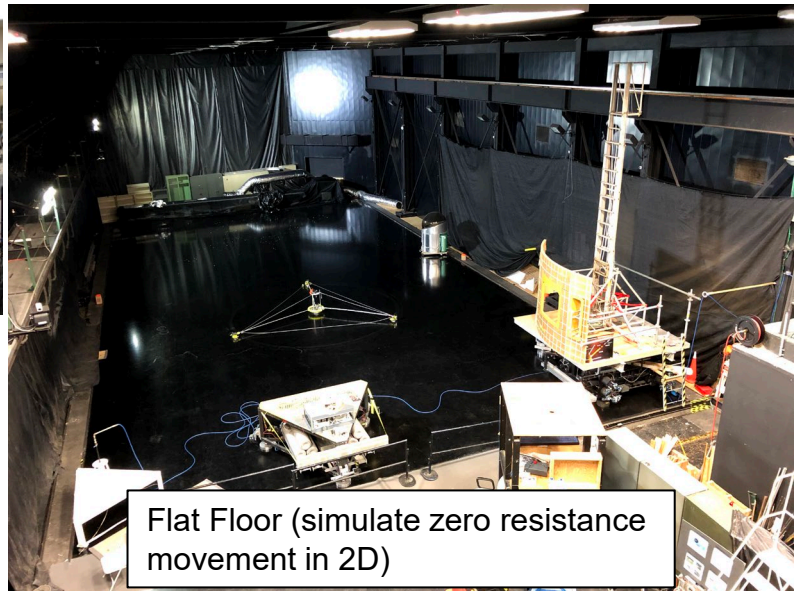
Leveraging Capabilities



V20 – Lunar TVAC



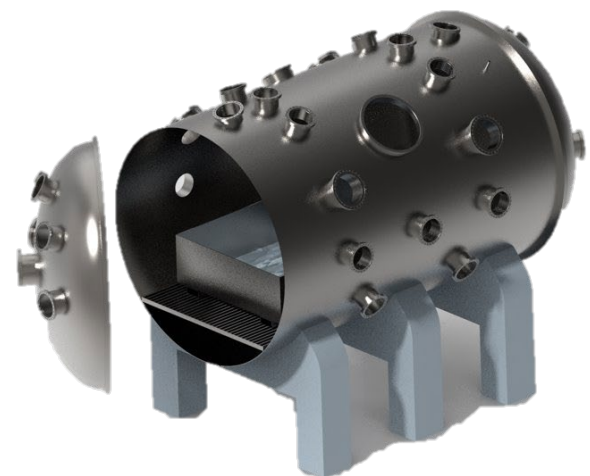
Solar Wind Chamber



Flat Floor (simulate zero resistance movement in 2D)



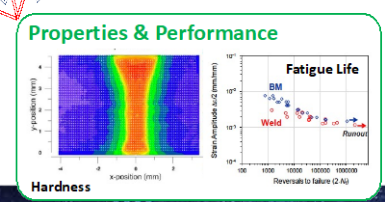
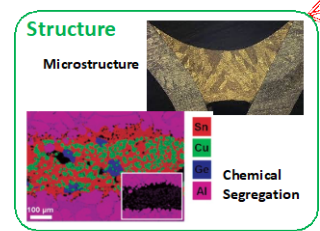
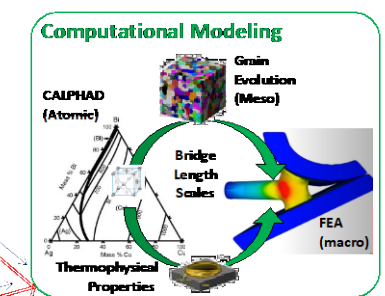
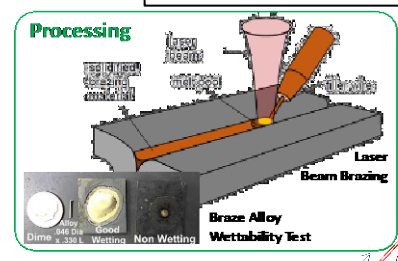
UV Radiation Test Chamber



Planet Chamber (combines multiple environments => atmosphere, radiation, temperature, regolith)



Charging from Plasma Environments Chamber

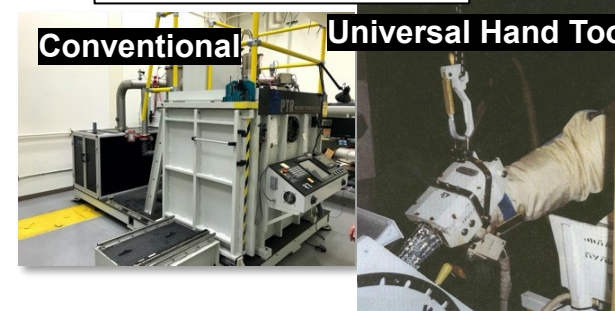


Every leg of the development challenge is linked through computation.

Weld/AM Development & Manufacturing Facilities

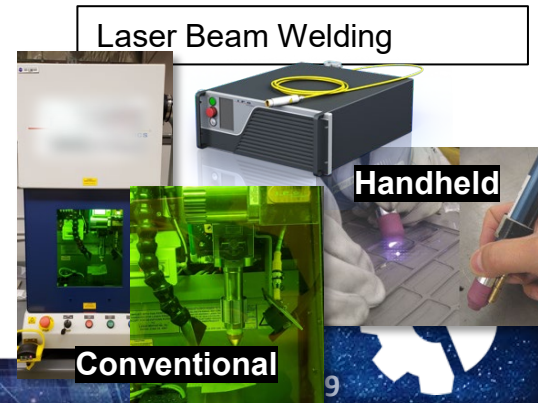


Electron Beam Welding



Conventional

Universal Hand Tool



Laser Beam Welding

Handheld

Conventional

High Fidelity Experiments Coupled with Computational Modeling, AI/ML, and Digital Twins Enable Sustainable ISM