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TECHNOLOGY DRIVES EXPLORATION

An Envisioned Future for Lunar Infrastructure – Technology Development Status & Needs

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Autonomous Lunar Excavation, Construction, & Outfitting

targeting towers, roads, landing pads, and habitable buildings utilizing in-situ resources

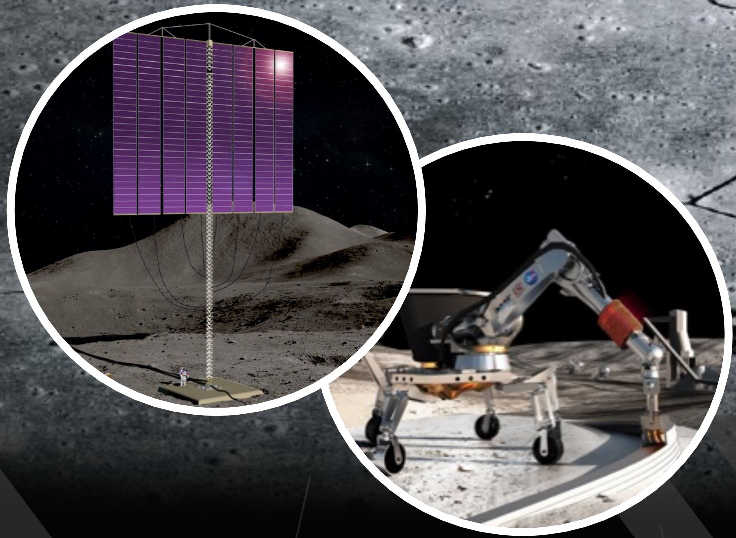
https://techport.nasa.gov/strategy

Excavation for ISRU-based Resource Production

- Ice mining, regolith extraction & delivery for 100s to 1000s metric tons of commodities per year
- Regolith for production of construction materials
    - 100s to 1000s metric tons of regolith-based feedstock for construction projects
    - 10s to 100s metric tons of metals and binders

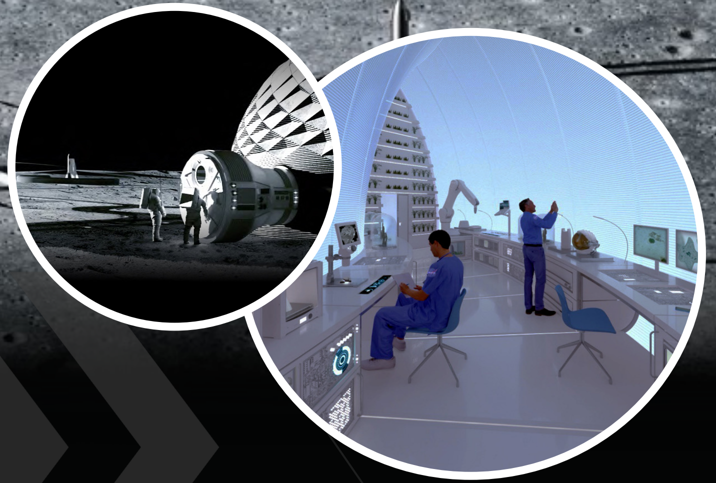
Regolith Manipulation & Site Preparation

- Site preparation: obstacle clearing, leveling, compacting & trenching
- Bulk regolith manipulation for berms and overburden
- Foundations for large infrastructure elements



Assembly & ISRU-based Construction

- Assembly of tall towers for solar power generation, communications, navigation
- Landing pad construction for CLPS and human lander systems
- Unpressurized structure evolving to single and then multi-level pressurized habitats
- 100-m-diameter landing pads, 100s km of roads, 1000s m^3 habitable pressurized volume



Outfitting

- Outfitting for data, power, fluid transfer & ECLSS systems
- Fully outfitted facilities and buildings to support a permanent lunar settlement and vibrant space economy

LIVE: Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources

Thrusts	Outcomes
Go Rapid, Safe, and Efficient Space Transportation	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.
Land Expanded Access to Diverse Surface Destinations	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.

Live
Sustainable Living and Working Farther from Earth
	• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
	  ◦ Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
	  ◦ Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
	  ◦ Technologies that enable surviving the extreme lunar and Mars environments.
	  ◦ Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
	• Enable long duration human exploration missions with Advanced Life Support & Human Performance technologies.

Explore Transformative Missions and Discoveries	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries. • Develop transformative technologies that enable future NASA or commercial missions and discoveries

TX 07.2 Mission Infrastructure, Sustainability, and Supportability – Provider of excavation and construction (E&C) services for cryogenic storage facilities

TX 07.2 Mission Infrastructure, Sustainability, and Supportability – Provider of landing sites, plume containment shields, landing aids.

TX 03 Advanced Power – Consumer of power; Provider of E&C services for power infrastructure

TX 07.1 In-Situ Resource Utilization – Provider of regolith for commodities and feedstock production; Consumer of construction feedstock.

TX 07.2.5 & TX 12.1 Advanced Materials and Dust Mitigation – Provider & consumer technologies for surviving extreme environments

TX4 Robotic Systems & TX 10 Autonomous Systems – Consumer of Autonomous Systems & Robotics technologies for Excavation, Construction, & Outfitting operations

TX07.2 Assembly, TX12.3 Mechanical Systems - Shared capability areas with Servicing & Assembly (SS&A/ISAM)

TX 12.4 Manufacturing – Consumer of manufactured parts for Lunar surface Construction and Outfitting

ECO Mapping to M2M Blueprint Objectives

M2M Obj.	Description DEMONSTRATE: Deploy an initial capability to enable system maturation and future industry growth in alignment with architecture objectives. DEVELOP: Design, build, and deploy a system, ready to be operated by the user, to fully meet architectural objectives.	Regolith Excavation /Delivery	Regolith Manipulation and Site Prep	Assembly, Construction, Outfitting
LI-1	Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels		x	x
LI-2	Develop a lunar surface, orbital, and Moon-to-Earth communications architecture capable of scaling to support long term science, exploration, and industrial needs		x	x
LI-4	Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy	x	x	x
LI-6	Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy		x	x
LI-7	Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.	x		
LI-8	Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.	x	x	x
MI-4	Develop Mars ISRU capabilities to support an initial human Mars exploration campaign.	x		
OP-11	Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.	x		x
TH-3	Develop system(s) to allow crew to explore, operate, and live on the lunar surface and in lunar orbit with scalability to continuous presence; conducting scientific and industrial utilization as well as Mars analog activities.	x	x	x
RT-2	Industry collaboration	x	x	x
RT-4	Crew Time: maximize crew time available for science and engineering activities			x
RT-9	Commerce and Space Development	x	x	x

Excavation for ISRU-based Resource Production

Capability Description, Outcomes, and Goals

Capability Description

- Autonomous resource excavation and delivery to ISRU plant – 1000s t/year
- Distance traveled with repeated trafficking – 1000s km/year
- Operational range between mine and ISRU plant - > 1km
- Operational Life – 5 years
- Reliability and Repair – MTBF = 10 lunar days, MTTR = <2 hrs

Outcomes

- Regolith for O_2
- Icy Regolith for H_2O and volatiles - hydrogen, carbon oxides, hydrocarbons, and ammonia
- Regolith for ISRU-based construction feedstocks and binders – Metals, Silicon, Slag

State of the Art: Current lunar excavation technologies can only dig into surface regolith, not deep or icy regolith.

Capability or KPP	SoA	Threshold	Goal
Regolith Excavation and Delivery	Surveyor Scoop: < 10kg	100s t/year	1000s t/year
Dist. Traveled	Opportunity Rover: 46 km	100s km/year	1000s km/year
Repeated Trafficking	Apollo rover: 5X	100s X	1000s X
Operational Range between resource & delivery site	None	500 m	> 1 km
Operational Lifetime	Chinese Yutu Rover Many lunar day/night cycles	1 year	5 years
Reliability & Repair	None	MTBF: 2 lunar day MTTR: <24 hrs	MTBF: 10 lunar days MTTR: <2 hrs

ISRU resource prospecting and geotechnical characterization (ISRU dependency)

MTBF = Mean Time Between Failures

MTTR = Mean Time to Repair

Excavation for ISRU-based Resource Production

Capability State of the Art, Current Activities, and Technology Gaps

SoA & Current Activities

Granular Regolith Excavation – ISRU Pilot Excavator Flight System Development (TRL 5/6)

- 10mT excavated over a 15 day period, with limited autonomy, includes wireless recharging
- Not designed for lunar night survival, long-duration and long-distance operations, or repair
- Critical activity to inform next-generation design of lunar surface ECO systems

Icy/Consolidated Regolith Excavation – Proof of Concept Systems and Implements (TRL 2-5)

- Break the Ice Lunar Challenge Phase 2: develop/demonstrate icy regolith excavation and delivery system (TRL 3-4)
- Several excavation implements under development, e.g., hammer-chisels (TRL 2/3) and vibratory blades (TRL 4/5)
- Not flight rated, limited relevant environment testing of implements, not designed for lunar survival

Technology Gaps

- ➢ Modularity and interfaces for reconfigurability and repairability
- ➢ Autonomy for high throughput and cooperative operations
- ➢ Lunar survivability, reliability, and repair
  - ➢ Survive multiple lunar nights or shadowed regions
  - ➢ Wear-resistant materials and wear characterization
  - ➢ Long-life lubricants, motors, avionics
  - ➢ Dust mitigation for actuators, seals, joints, mechanisms; Dust-tolerant thermal control system
  - ➢ Autonomous maintenance and repair
  - ➢ Health and fault management
- ➢ Regolith flow/interaction with implements (simulation and test)
- ➢ Scale-up from pilot scale (10t) to initial commercial scale (1000 t/yr)

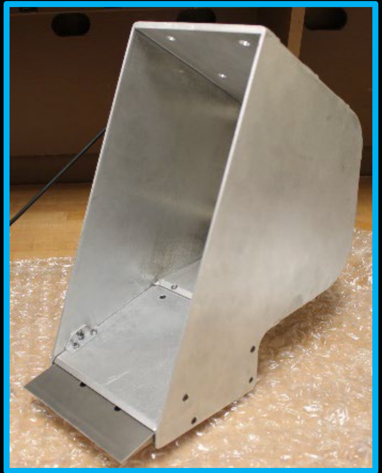
End-to-end system demonstrations that lead to lunar surface demo, need time on equipment

Many technology gaps are shared with **Regolith Manipulation and Site Preparation** capability area

ISRU Pilot Excavator (IPEx)

Break the Ice Lunar Challenge (BTIL)
Phase 1 Concept Hauler

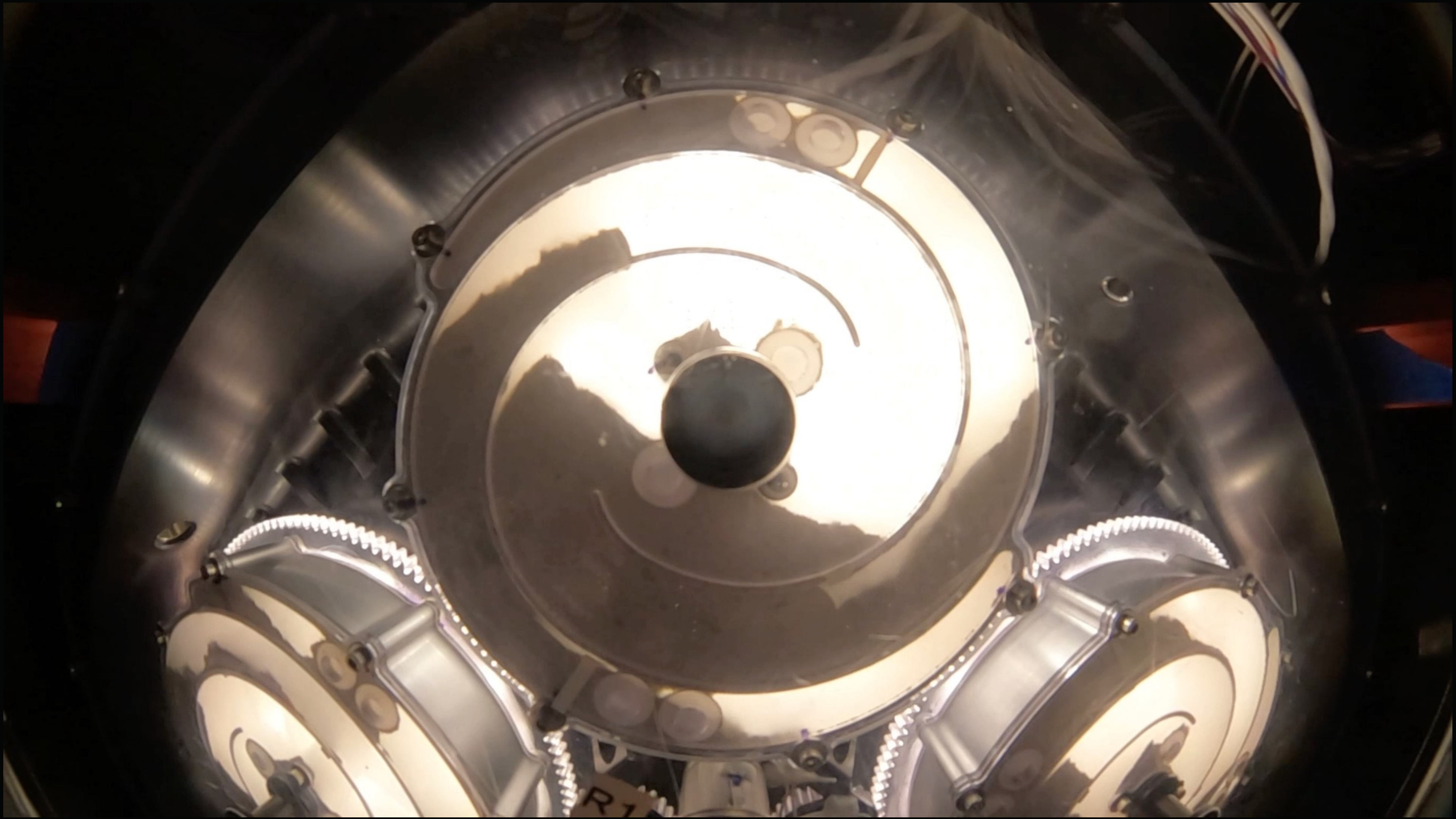
FLEET
Ultrasonic
Blade
Bucket
Prototype



ISRU Pilot Excavator Development Highlights - Capabilities

https://www.nasa.gov/gallery/isru-pilot-excavator/

ISRU Pilot Excavator Development Highlights – Regolith Flow Experiment



https://www.nasa.gov/gallery/isru-pilot-excavator/

Regolith Manipulation and Site Preparation

Capability Description, Outcomes, and State of the Art

Capability Description - Similar Capabilities as Excavation for ISRU, plus…

- Site survey – geotechnical, topography
- Load, Haul, Dump
- Bulk regolith manipulation – berms, piles, overburden, and gravel surfaces
- Level, grade, and compact
- Rock removal and gathering
- Trenching and burying

Outcomes

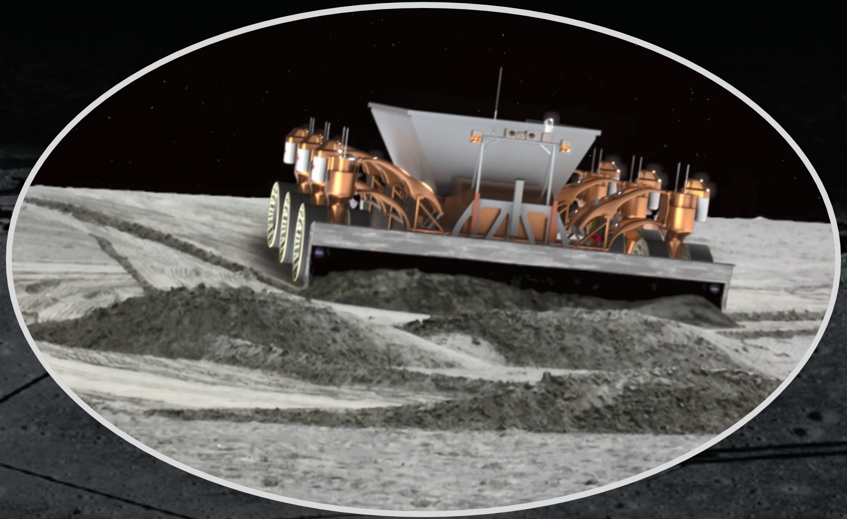
- Site preparation for construction - 1000s of m^2 of prepared surface
- Provide bulk regolith berms and overburden for shielding
- Compacted or gravel surfaces for dust mitigation

SoA: Excavation for construction has never been attempted on an extraterrestrial body. Prototypes have been built at low TRL.

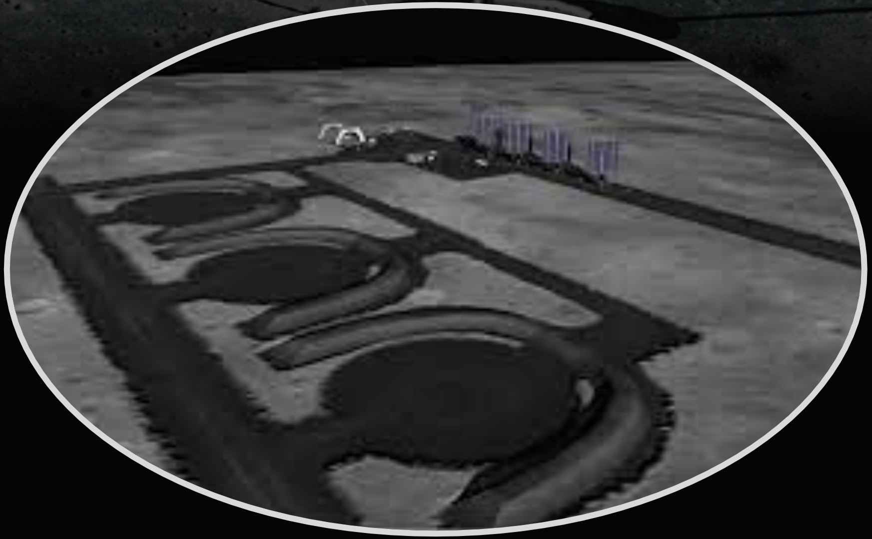
Similar KPPs as Excavation for ISRU, plus the following:

Capability or KPP	SoA	Threshold	Goal
Bulk density and bearing and shear strength measurement of regolith	cone penetrometer, shear vane, coring	1 measurement per 100 m^2	10 autonomous measurements per 100 m^2
Topology characterization	LIDAR, Photogrammetry	10mm resolution	5mm resolution
Bulk Regolith Manipulation – berm building and piling	None	3 m tall	7 m tall
Site Level, Grade & Compact (1.9 g/cc)	None	25 m radius (~2000 m^2)	50 m radius (~8000 m^2)
Rock Removal and Gathering	Rake (Apollo): 1-10 cm	<10 cm	<50 cm
Trenching	Apollo & lunar surveyor scoop: several cm's deep	1.0 m deep	3.0 m deep

Leveling and grading



Early-phase infrastructure



Not all activities depicted are currently funded or approved. Depicts "notional future" to guide technology development vision.

Regolith Manipulation and Site Preparation

Capability State of the Art, Current Activities, and Technology Gaps

SoA & Current Activities

Site Preparation Systems – Proof of Concept (TRL 3-4)

- LuSTR project - Autonomous Site Preparation: Excavation, Compaction, and Testing (ASPECT) (TRL 3-4)
  - 10m-diam area, moving/manipulating ~4t of loose regolith and small rocks
- Four STTR Ph1/2 to develop site prep systems, TRL 3/4 systems, ConOps, and analytical tools for site design

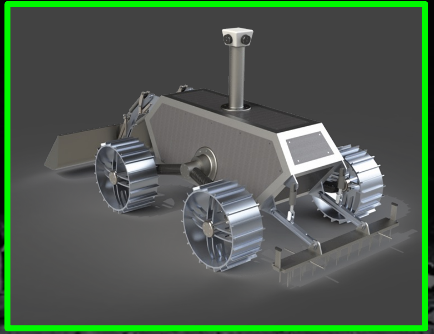
Site Preparation Implements – Proof of Concept (TRL 2-5)

- Several lab-scale studies on regolith compaction (TRL 3/4)
- Several grader and compactor implements under development, e.g., vibrating plates/rollers (TRL 2/3) and grading blades/buckets (TRL 4/5)
- Not flight rated, limited relevant environment testing of implements

Technology Gaps

- Site survey – geotechnical, topography
- Implements and Systems: excavation, haul, dump, rock handling, grading, leveling, compaction, berm building, trenching
- Site prep inspection techniques and sensor systems
- Feasibility testing for regolith manipulation and system development leading to lunar surface demo
- System scale-up to initial commercial scale; **1000's m^2 areas, 10,000's mT regolith moved**
- *Additional shared gaps listed for Excavation for ISRU*

Autonomous Site Preparation: Excavation, Compaction, and Testing (ASPECT) – Colorado School of Mines



STTR Ph1 Site Prep System Study – Astroport Space Technologies, Inc.

NASA Chariot with LANCE dozer blade

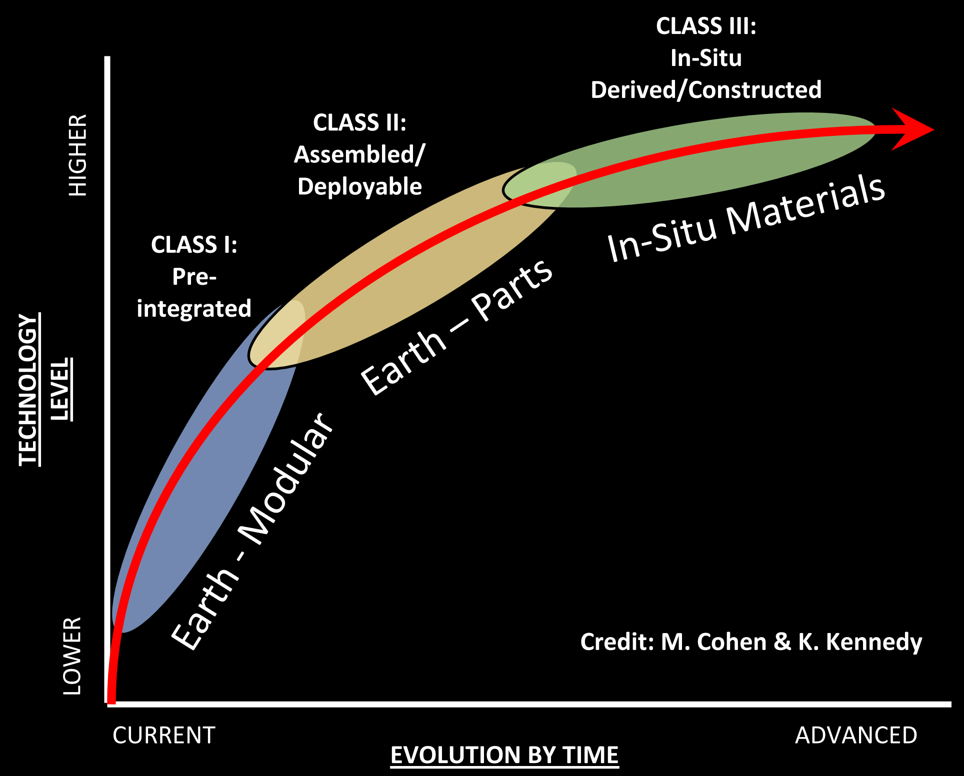
Autonomous Site Preparation: Excavation, Compaction, and Testing (ASPECT) – Credit Dr. Chris Dryer, Colorado School of Mines

Autonomous Site Preparation: Excavation, Compaction, and Testing (ASPECT) – Credit Dr. Chris Dryer, Colorado School of Mines

Surface Construction Classifications

Delivery of large habitable volumes will require a different approach from the "cans on landers" concepts that have been depicted for decades

- **How can we build?**



Classification	Key Characteristics
CLASS I **Pre-integrated module** 	• Earth Manufactured • Pre-Integrated & Tested Prior to Launch • Space Delivered with Immediate Habitation Capability • Volume and Mass Constrained by Launch Vehicle Capability
CLASS II **Surface Deployed or Assembled** 	• Requires Surface Deployment, Assembly & Outfitting • May Include Partial Integration of Subsystems • Critical Subsystems are Earth Based and Tested Prior to Launch • Requires Checkout Prior to Human Occupancy • Larger Volumes/Sizes Capable (e.g.., Transhab ~3X the Volume of a Standard ISS Module) • Reduced Restriction on Volume Due to Launch Vehicle Shroud Size • Restricted to Launch Mass Capability. Deliver on Multiple Vehicles • Earth-sourced elements for assembly can transition to ISRU-based elements
CLASS III **In-Situ Derived and Constructed** 	• Constructed In-situ, Derived from Local Resources (Lunar or Mars) • On-surface Construction and Outfitting (Integration of Subsystems) • Critical Subsystems are Earth Based and Tested Prior to Launch • Requires Assembly & Checkout Prior to Human Occupancy • Larger Volumes Capable, Constrained by Limitations of Construction Equipment and ISRU materials • Construction Equipment Constrained to Launch Vehicle Mass and Volume.

Notes:
- Hybrid Class II/III structures: ISRU-derived components for Class II assembly, premanufactured/precision components for Class III integration
- Shared capability areas with Servicing & Assembly, e.g., autonomous assembly, docking interfaces, outfitting, V&V

Surface Construction

Capability Description, Outcomes, and State of the Art

Capability Description:

- <u>*Class II*:</u> Assembly of components into built-up structures (e.g., Earth-sourced or ISRU-based truss, panel, paver, bricks); deployment of human-rated preassembled or inflatable structures
- <u>*Class III*:</u> In-situ construction (e.g., 3D printed regolith-based construction)
- In-situ testing and inspection techniques for certification (material and structural)
- Structural enhancement and repair
- Construction Systems: design for lunar survivability, reliability, and maintenance

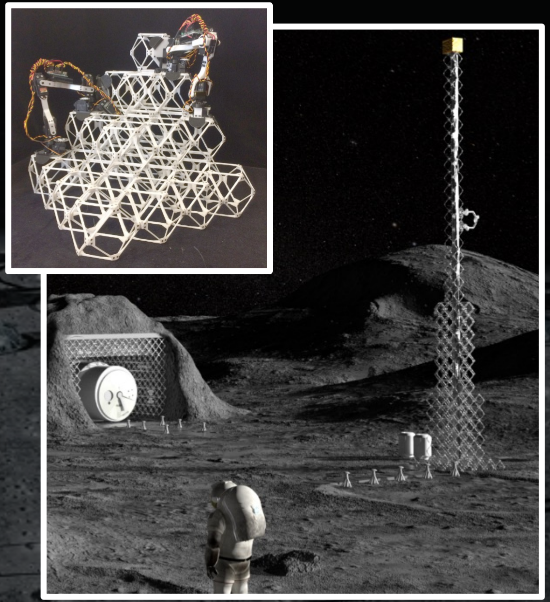
Outcomes

- Towers (50+ m tall for Power and Communication), scaffolding
- 10s km of roads
- 100-m-diameter launch/landing pads (LLPs)
- Lander plume containment shield (LPCS) – 7m-tall, 100s m long
- Shelters & habitats (1000s m^3 volume) to provide asset and crew protection (thermal, radiation, etc.)

SoA: Extraterrestrial surface construction has never been attempted. Terrestrial prototypes at low TRL.

Capability or KPP	SoA	Threshold	Goal
Class II: Deployable and assembled structures	ISS: deployable trusses for solar arrays and radiators; inflatable volumes (not human-rated).	Assembly of tower and blast cont. shield (BCS) with 50% ISRU-based components	Autonomous Construction of most major infrastructure elements with 100% ISRU based components and materials. Towers, roads, LLPs, LPCS, shelters, and habitats
Class III: In-situ construction	Low TRL development work	ISRU-based roads, LLPs, BCS with limited Earth-sourced materials (20%)	
In-situ testing & inspection for Class II & Class III construction	ISS inspection: visual, thermography, eddy current, ultra-sound, strain gage, accels.	Voids & cracks, material strength and stiffness. Material degradation	full volumetric inspection of material and structural properties w/ real-time corrective actions
Structural enhancement & repair	ISS enhancement: swap-out of modular components and orbital replacement units ISS structural repair: none	Manual repair; post-construction enhancement/modification	Selected autonomous robotic repair and post-construction enhancement
System Operational Lifetime	None	2 year	10 years
Reliability & Repair	None	MTBF: 2 lunar days, MTTR: <24 hrs	MTBF: 10 lunar days, MTTR: <2 hrs

Class II: Assembly & Deployables



Class III: In-situ Construction

MTBF = Mean Time Between Failures

MTTR = Mean Time to Repair

Class II Surface Construction – Assembly and Deployment

Capability State of the Art, Current Activities, and Technology Gaps

SoA & Current Activities

Deployable Surface Solar Arrays – (TRL 2-6)

- Vertical Solar Array Technology (VSAT) Flight system development (TRL 6)
- Several activities to develop deployable 50kWe array concepts (TRL 2/3)

Inflatable Structures – Proof of Concept (TRL 2-6)

- Multiple activities developed inflatable habitat concepts (TRL 6); Ex. Bigelow Expandable Activity Module (BEAM)
- Inflatable airlocks and crew transfer tunnels (TRL 4)
- Several activities on material testing (TRL 2/3) and Structural Health Monitoring (TRL 2/3)
- Proof of concept, limited long-term relevant environment testing of materials

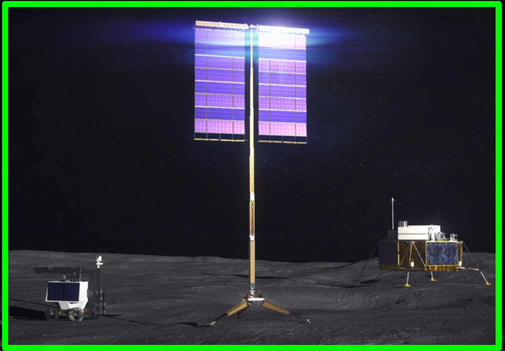
On-Surface Assembly of Structures – Proof of Concept (TRL 2-5)

- Demonstrations of autonomous robotic assembly of precision truss and voxel-based structures, mechanical joining, non-flight rated, no outfitting; Ex. ARMADAS (TRL 5), PASS (TRL 4)
- Robotic assembly of a tall Power/Comm tower, not flight rated, no outfitting (TRL 4)
- Concepts for assembly of Lander Plume Containment Shields and Shelters (truss and panel assemblies) (TRL 2/3)

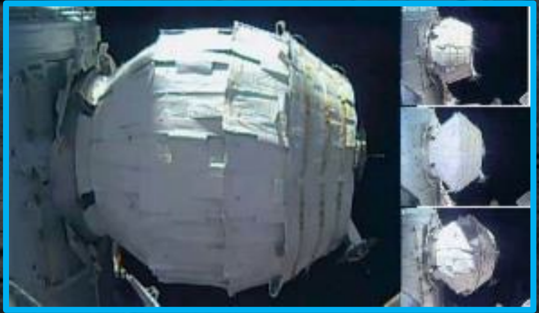
Technology Gaps

- ➢ Advanced joining methods for assembly (e.g., in-space welding, reversable joining)
- ➢ Autonomy and Robotics and specialized tools for structural assembly and repair
- ➢ Pressure sealing for pressurized assembled structures
- ➢ In-situ V&V and Certification methods
- ➢ Structural health monitoring of structures
- ➢ Production of ISRU-based structural elements for Assembly

Deployable Vertical Solar Array (VSAT)

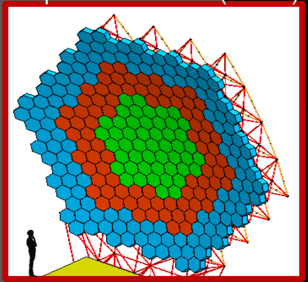


Bigelow Expandable Activity Module (BEAM)

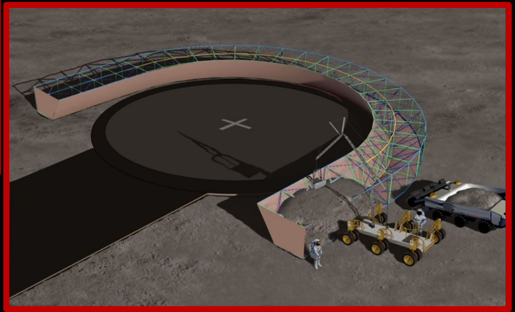


Inflatable crew transfer tunnel concept

Precision Assembled Space Structures (PASS)

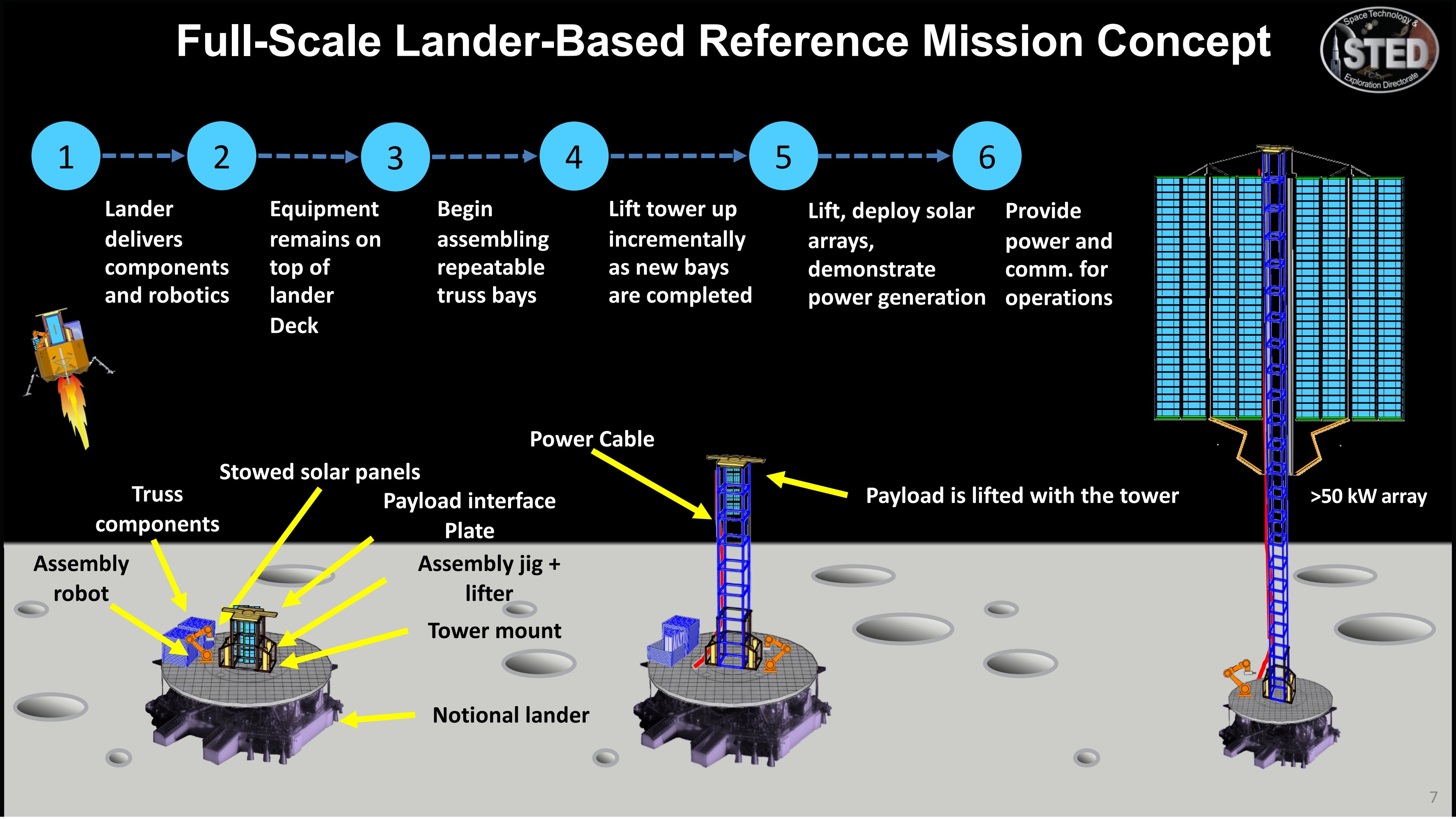


Assembled Lander Plume Containment Shield (LPCS) concept



Tall Lunar Tower (TLT) – Robotic Tower Assembly Project

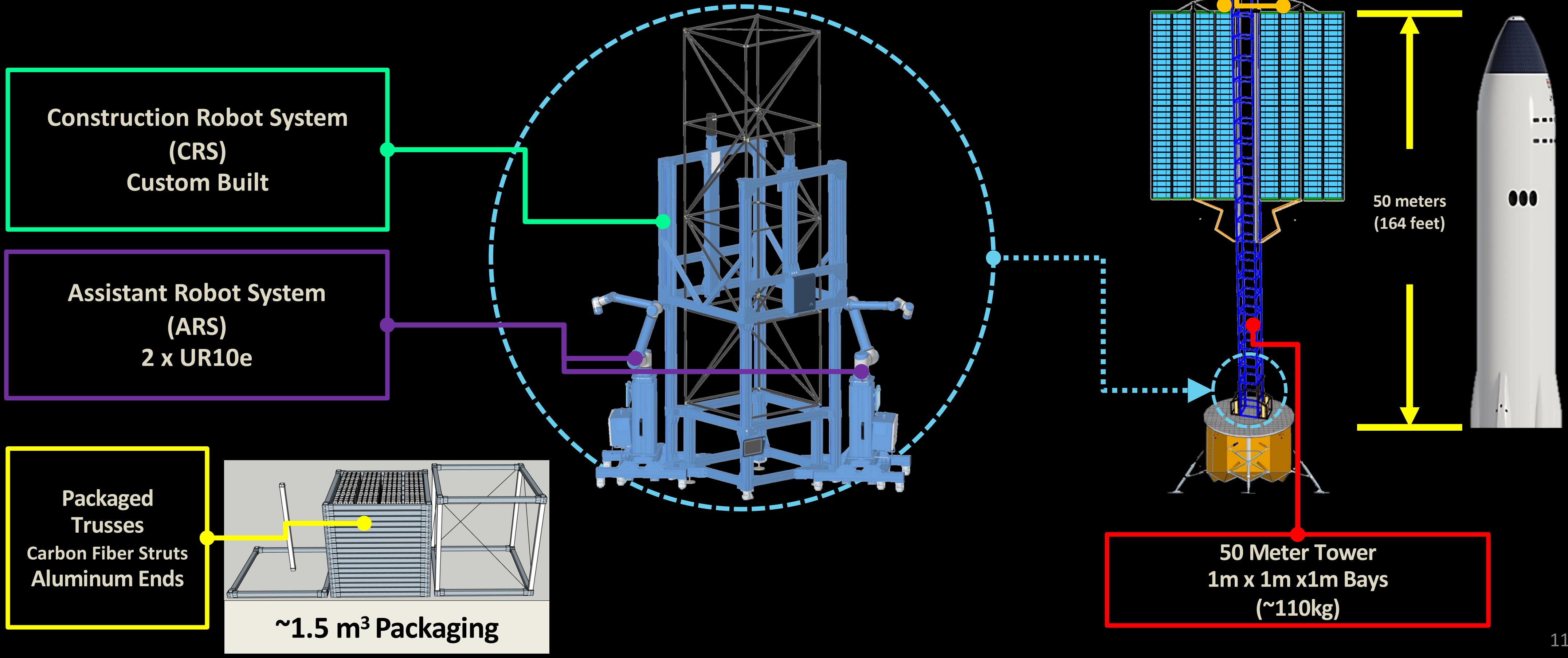
Goal: to design, manufacture, autonomously assemble, and characterize a TLT assembly engineering development unit (EDU). Cross-cutting truss assembly technology will be developed enabling construction of infrastructure in the lunar environment.



Tall Lunar Tower – Robotic Tower Assembly Project

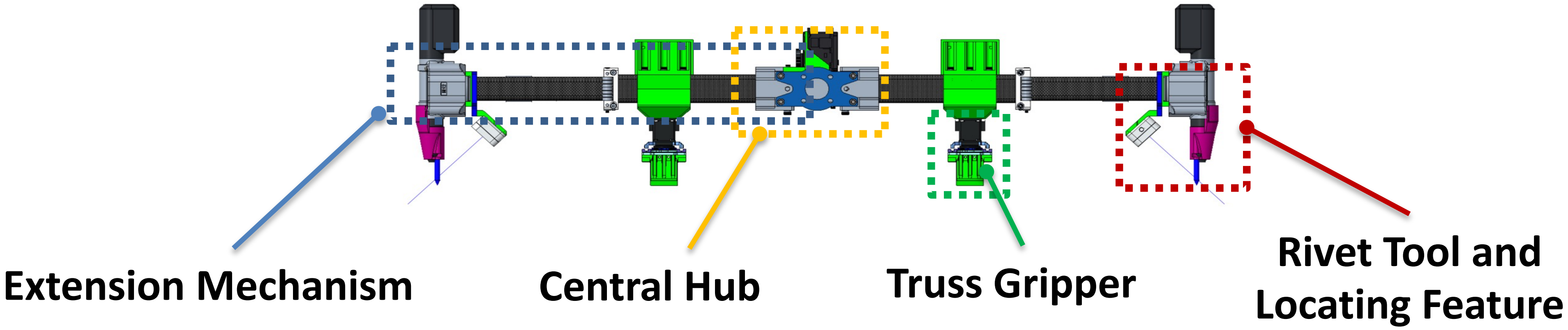
Engineering Development Unit (EDU)

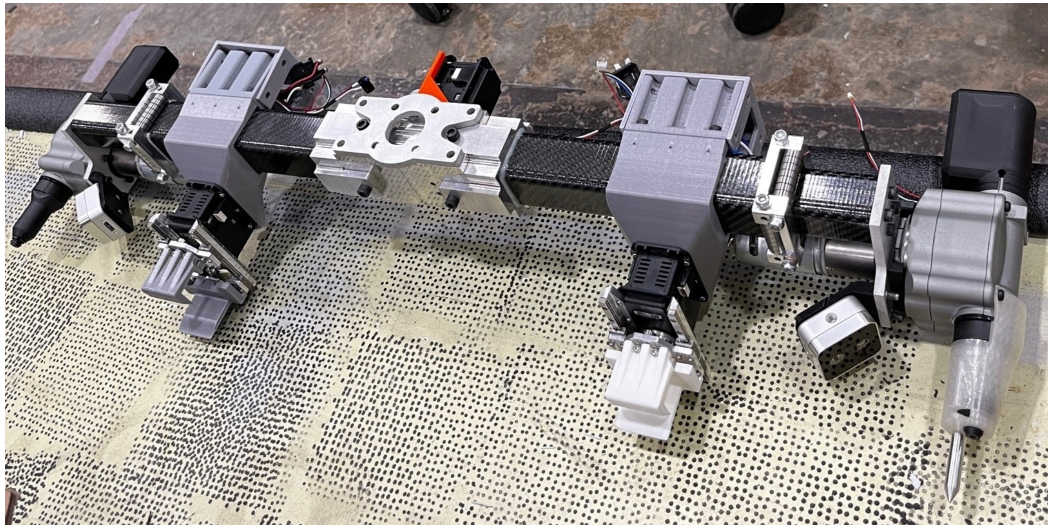
Goal: Demonstrate an EDU analogous to a lander-based system.
Hardware assembly in progress.



Tall Lunar Tower – Robotic Tower Assembly Project

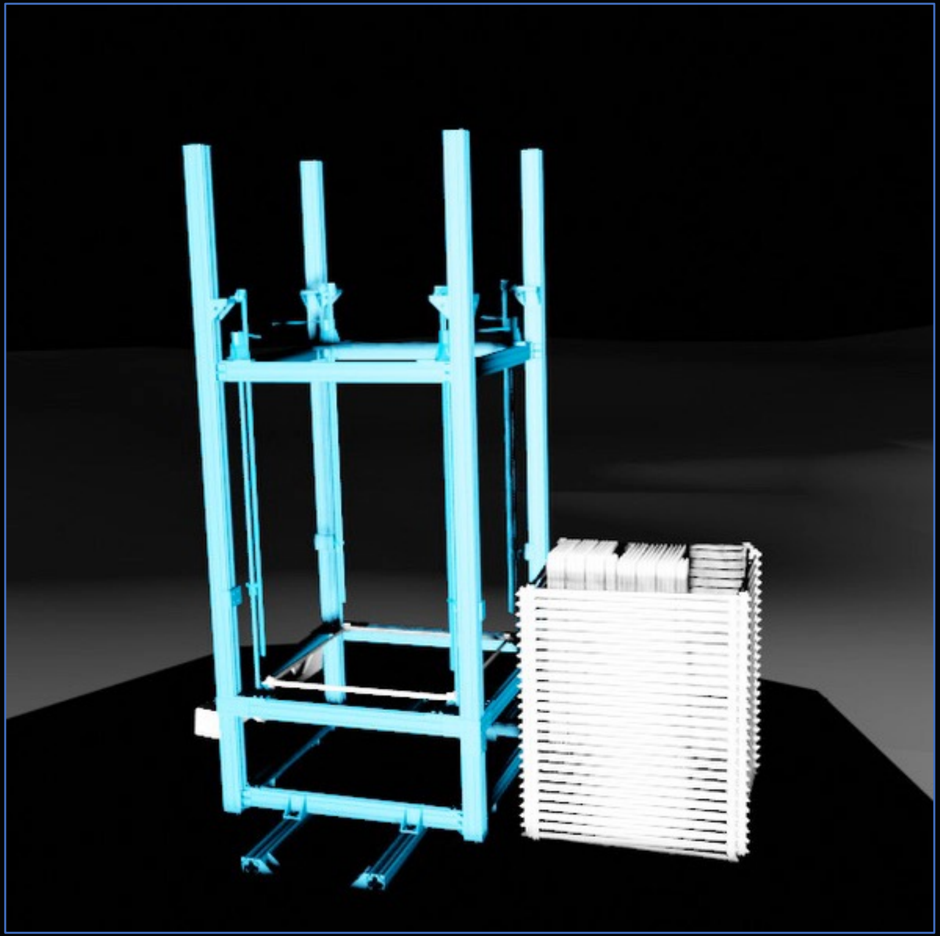
End Effector - Overview





Tall Lunar Tower – Robotic Tower Assembly Project

TLT Assembly Sequence



TLT Assembly Demo – 5m tall tower

Class III Surface Construction – In-situ Derived Structures

Capability State of the Art, Current Activities, and Technology Gaps

SoA & Current Activities

In-situ Construction – (TRL 2-5)

- Multiple processes in various stages of development; Most in the TRL 3/4 range of maturity
  - Laser melting TRL 3/4; Cementitious TRL 2-4; Microwave sintering TRL 3/4; Molten regolith extrusion TRL 4; Polymer/regolith extrusion TRL 4/5
- Challenges: deposition of material in a vacuum, process V&V, scale-up, power requirements, material uniformity

Surface Stabilization, Foundations, Anchors – Concepts formulated (TRL 2)

- Several NIAC activities funded in past on surface stabilization for landing pads

NDE, Modeling, Analysis – Proof of Concept (TRL 2-4)

- Several SBIR activities related to NDE and damage analysis; Laser ultrasonic testing for defects; smart optical spectroscopy for metal additive manufacturing

Technology Gaps

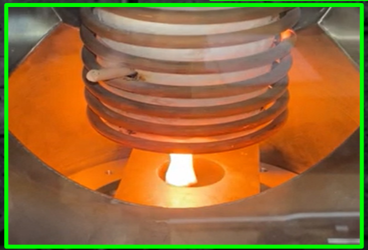
- ➢ Deposition of print material in low-pressure environment while controlling porosity
- ➢ High-temperature materials for LLPs
- ➢ In-situ polymer production
- ➢ LLP Paver joining
- ➢ Surface stabilization, Foundations, and Anchors
- ➢ Repair technologies
- ➢ Process inspection and control
- ➢ In-situ V&V of construction materials

Process Development

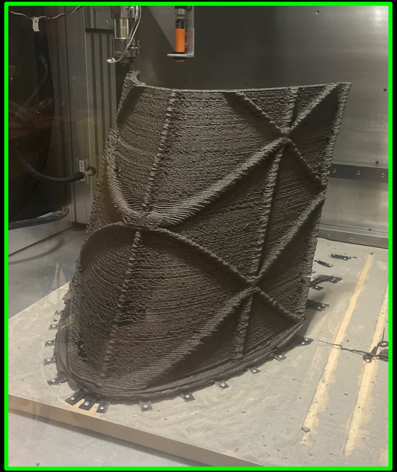
Laser melting in vacuum

Microwave sintering in vacuum

Molten extrusion in vacuum



Additive Construction

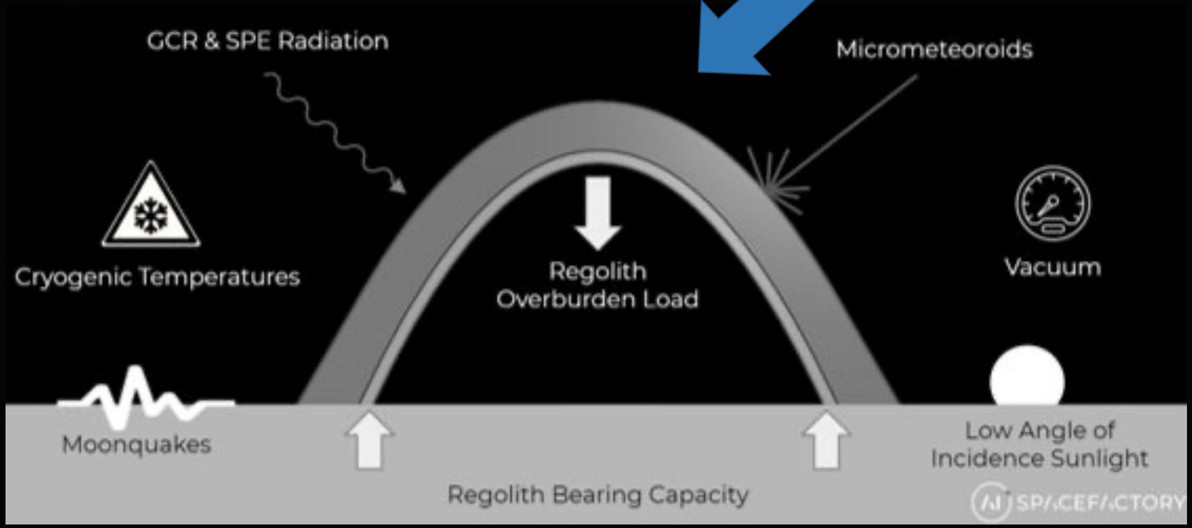


Polymer-regolith printing in a vacuum

Relevant Environment Additive Construction Technology (REACT)

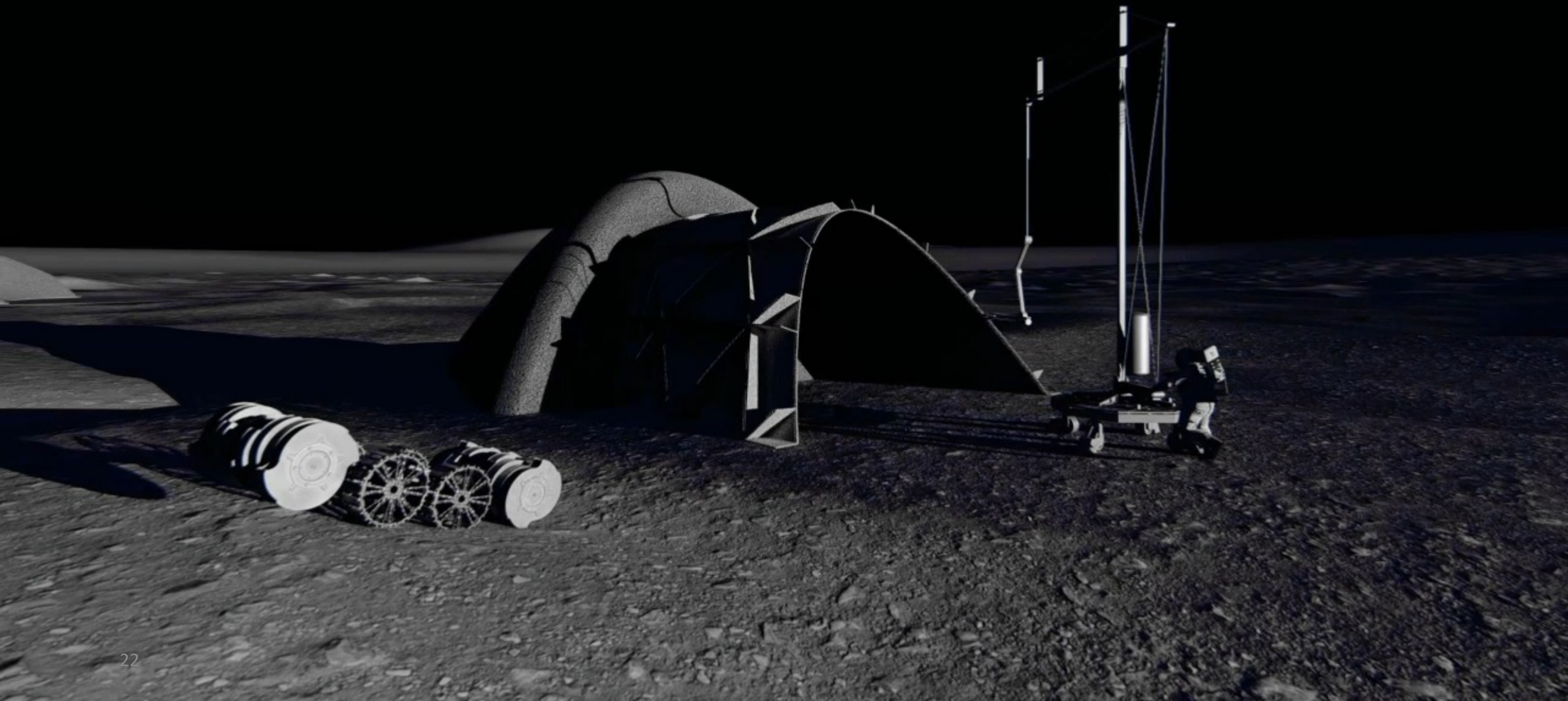
NASA ACO with AI SpaceFactory and LERA

AI SpaceFactory won NASA' 3D Printed Habitat Centennial Challenge



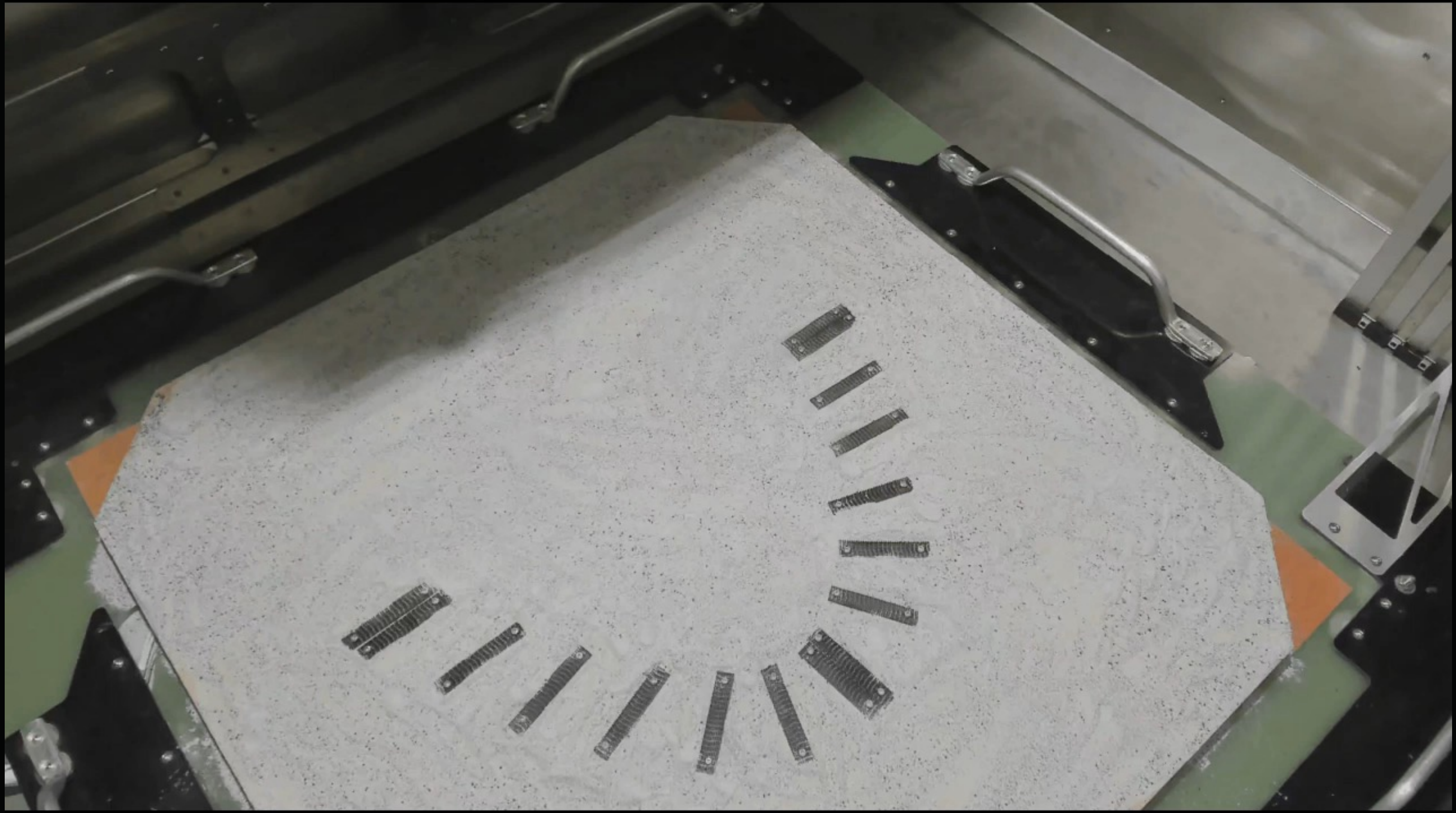
Goal: to mature this technology by exercising it in simulated lunar conditions and building a sub-scale unpressurized protective shelter

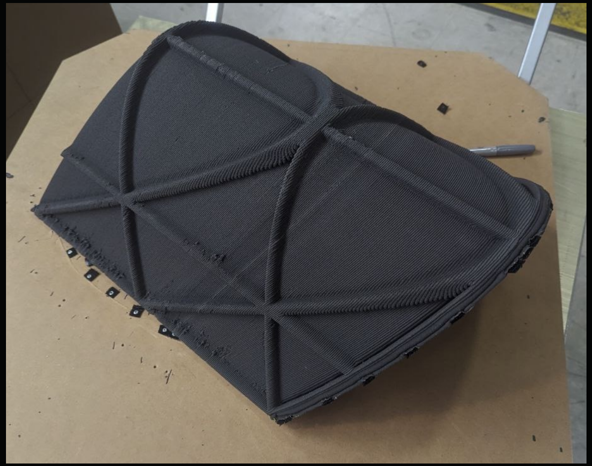
Full Scale Construction Concept of Operations



Accomplishments – In-situ Construction

Second generation protective shelter design is printed at ~10^{-5} torr on LHS-1 simulant using a 80:20 LHS-1: PLA formulation





First generation shelter design

Second generation shelter design

Outfitting

Capability Description, Outcomes, and State of the Art

Capability Description

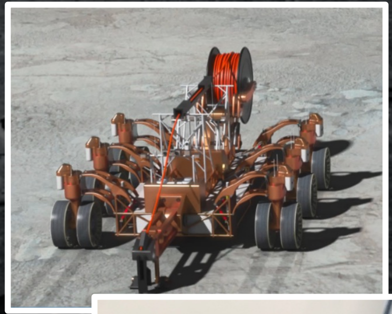
- The process by which a structure is transformed into a useable system by in-situ installation of subsystems.
  - Subsystem installation
  - In-situ testing/validation and inspection techniques with associated metrology
  - Subsystem repair and enhancement

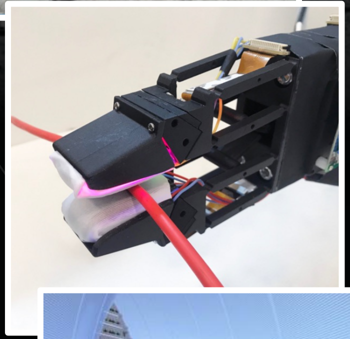
Outcomes (affects most systems that are not landed in operational self-contained state)

- Power, Lighting, Data & Communications distributed through system
- Fluids & Gasses (ISRU products) managed and stored.
- ECLSS
- Hatches and Penetrations in pressurized structures
- Interior Furnishing

SoA: Preintegrated structures, with manual in-situ upgrades and repairs.

Capability or KPP	SoA	Threshold	Goal
Conductor/Cable and Piping/Tubing line management (LM)	ISS Preintegrated on ground, EVA upgrades and repairs	LM during construction using Earth-sourced harness (50% autonomous). Manual repair; Post-construction manual LM for facility enhancement.	LM during construction using ISRU derived harness (100% autonomous). Selected auto. repair and enhancement/expansion.
Penetration management (PM) including through pressure vessels (Habitats, tanks, shelters, blast shield etc.)	ISS Preintegrated on ground, NO post launch penetrations added.	PM during construction using Earth-sourced materials (50% autonomous). Manual repair; Post-construction manual PM for facility enhancement.	PM during construction using ISRU derived material (100% autonomous). Selected auto. repair and enhancement
Attachment of secondary systems to structures.	ISS Preintegrated some IVA and EVA rerouting.	Attachment to arbitrary surfaces and structures.	Reversible attachment to arbitrary surfaces and structures on 3D printed structures.
Inspection systems to verify installation and functionality.		Pressure test piping, geometry charac. for assembly verification, load test of foundations, continuity/signal strength for communications/wiring.	Continuous process monitoring, equivalency testing, structural health monitoring for 3D printed habitat by 2035.





Outfitting

Capability State of the Art, Current Activities, and Technology Gaps

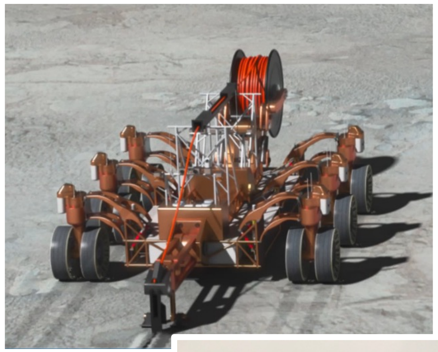
Outfitting SoA & Current Activities

Design and Prototype Outfitting Elements – (TRL 2-4)

- XHab Challenge – explore approaches to habitat outfitting; Trade and prototype components and interior goods for habitats; some testing of human and robotic outfitting tasks (TRL 2/3)
- Several NASA-led activities related to printing of components that could be used in the outfitting process (TRL 3/4)
    - Printing parts using polymer binders with regolith filler
    - On-demand additive manufacturing using metals, polymers, electronics
    - Large-scale printing of flooring and walls.

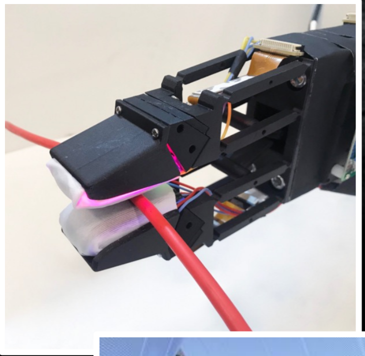
Technology Gaps

- Robotic outfitting technologies for installation of lighting, harnesses, beacons, sensors, fluid transfer systems, HVAC, etc.
- Design of pressure vessel connections/seals with penetrations
- Inspection methods & repairs
- Autonomy for complex outfitting and inspection tasks
- Common interface definition
- Architectural and ConOps studies
- Outfitting requirements and standards
- Utility corridor design

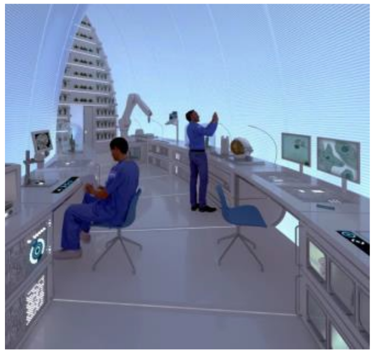


Trenching and cable laying

Cable handling



Outfitted facility



ECO – Priority Activities

Adequate investment
Some investment
Little/no investment

1. **Complete the IPEx project and conduct the first lunar surface excavation demo**
   - Complete development and ground testing of IPEx excavation system to TRL6 in FY27
   - Pursue lunar surface test of IPEx concept to demonstrate the autonomous ***excavation and delivery*** of 10t regolith (e.g. LIFT-1)
2. **Initiate NASA and industry-led projects to develop pilot-scale robotic ISRU and site prep systems to support ECO ground and lunar demonstrations, working towards initial commercial capability**
   - Initiate the development of ***regolith delivery systems*** to support ***ISRU commodity production and construction***
   - Continue and expand the development and scale-up of robotic systems and implements for ***site prep and regolith manipulation***
   - Initiate the development of cross-cutting capabilities for ***robotic ECO platforms***
     - *Modularity and interfaces for reconfigurability and repairability*
     - *Autonomy and robotics for high-throughput and cooperative operations*
     - *Survive multiple lunar nights and shadowed regions*
3. **Initiate NASA and industry-led projects to develop technologies for the assembly and outfitting of large-scale truss-based structures on the lunar surface**
   - Initiate new-start project to ***develop and demonstrate the autonomous assembly and outfitting*** of lunar surface structures
     - *Tall truss-based Power and Comm tower*
     - *Radiation shielding for fission surface power system*
     - *Shelter for surface assets*
   - 2024 SBIR topic for the assembly and outfitting of tall truss-based towers with extensibility to other structures
   - **Big growth area…desire more industry and academia involvement**