EXPLORE SPACE TECH
TECHNOLOGY DRIVES EXPLORATION

Excavation, Construction, and Outfitting (ECO) Envisioned Future Priorities

Updated

Jan. 4, 2023

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Autonomous Lunar Excavation, Construction, & Outfitting

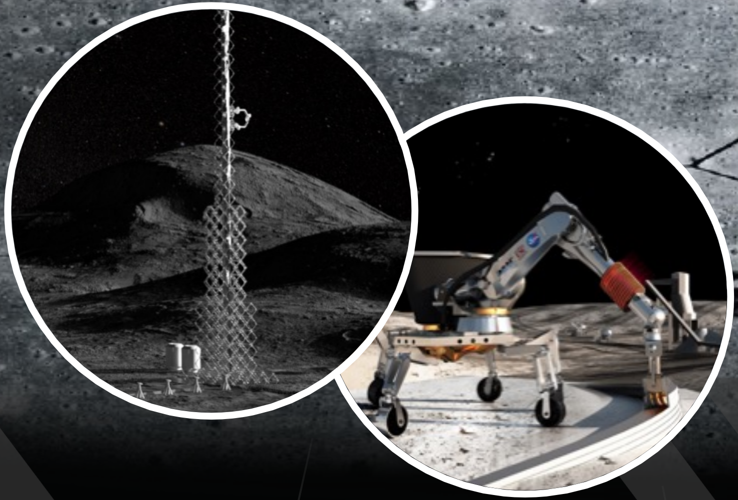
targeting towers, roads, landing pads, and habitable buildings utilizing in-situ resources

Excavation for ISRU-based Resource Production

- Ice mining & regolith extraction 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

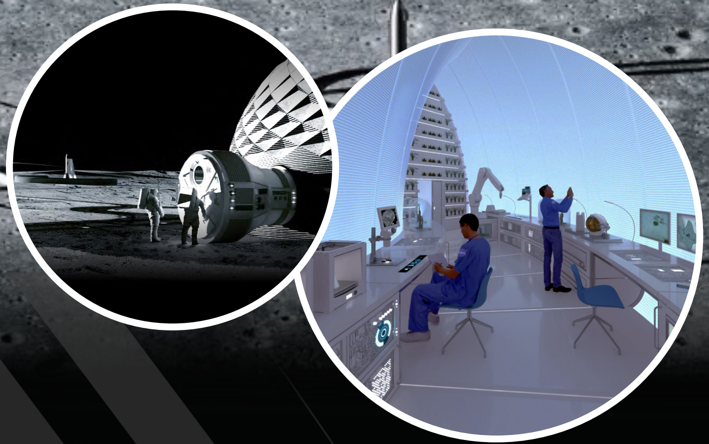
Regolith Manipulation & Site Preparation

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



Construction and Outfitting

- 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
- Outfitting for data, power & ECLSS systems
- 100-m-diameter landing pads, 100s km of roads, 1000s m^3 habitable pressurized volume



Commercial ECO Capabilities for Sustainable Infrastructure & Economy

- Commercial capabilities to construct tall towers, landing facilities, roads, and habitable structures
- Fully outfitted facilities and buildings to support a permanent lunar settlement and vibrant space economy
- Capabilities extensible to future ESDMD, SMD and Mars missions

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

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 - Provide landing sites, blast containment shields, landing aids.

TX 03 Advanced Power – Receive power; Provide excavation and construction services necessary for power infrastructure

TX 07.1 In-Situ Resource Utilization – Provide regolith for commodities and feedstock production; receive resource information and manufacturing/construction feedstock.

TX 07.2.5 & TX 12.1 Advanced Materials and Dust Mitigation – providing and using technologies for surviving extreme environments

TX 10 Autonomous Systems – Receive Autonomous Systems & Robotics technologies for complex Excavation, Construction, & Outfitting operations (see backup slide on Autonomy)

TX07.2 Assembly, TX12.3 Mechanical Systems - Shared capability areas with Servicing & Assembly (OSAM)

TX 12.4 Manufacturing – Receive manufactured parts for Lunar surface Construction and Outfitting from Adv. Manufacturing

ECO Mapping to M2M Blueprint Objectives

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.

M2M Obj.	Description	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	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	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

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
- Recharging – 100s times (assuming no on-board PV charging)
- 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
Recharge Cycles (assuming no on-board PV charging)	None	10s X	100s X
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 Before Failure

MTTR = Mean Time to Repair

Excavation for ISRU

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-gen 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

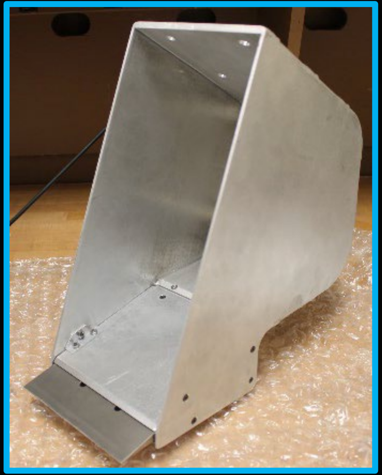
- ➢ Multi-functional low mass rugged robotic platforms for regolith excavation and delivery
- ➢ Modularity and interfaces for reconfigurability and repairability
- ➢ Autonomy for high throughput and cooperative operations
- ➢ Lunar survivability, reliability, and repair
  - ➢ Survive multiple lunar nights 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 (10mT) to initial commercial scale (1000mT/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



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
- Level, grade, and compact
- Rock removal and gathering
- Trenching and burying

Outcomes

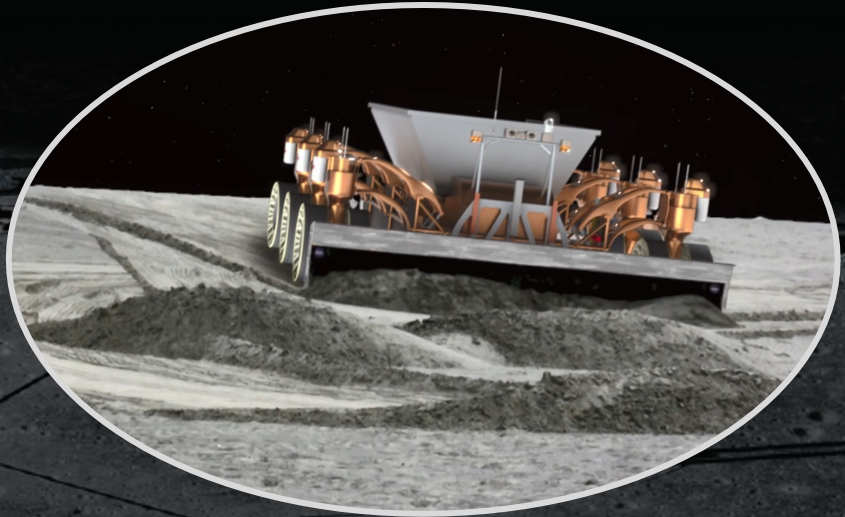
- Site preparation for construction - 1000s of m^2 of prepared surface
- Provide bulk regolith berms and overburden for shielding
- gravel surfaces for dust mitigation

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

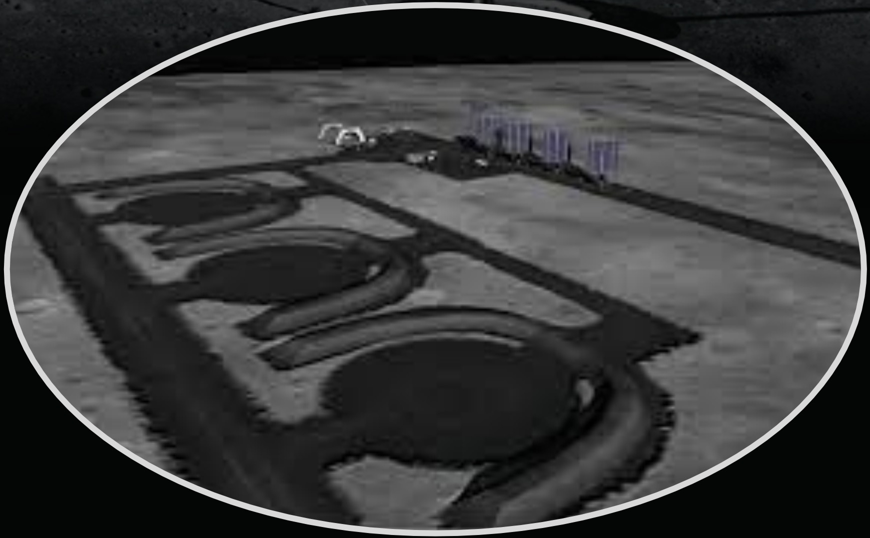
Similar KPPs as Excavation for ISRU, plus the following:

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	50 m radius
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



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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 ~4mT of loose regolith and small rocks
- Four STTR Ph1 Study to develop site prep system requirements, TRL 3/4 systems, ConOps, and analytical tools for site design

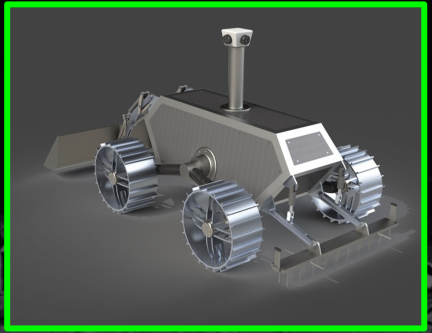
Site Preparation Implements – Proof of Concept (TRL 2-5)

- 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; **100'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



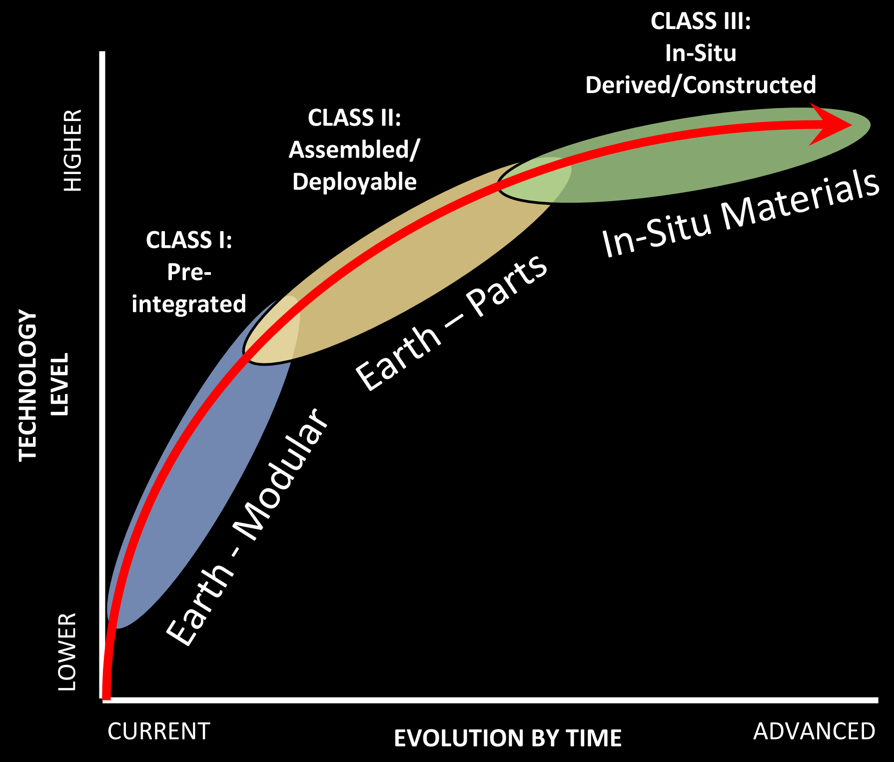
STTR Ph1 Site Prep System Study – Astroport Space Technologies, Inc.

NASA Chariot with LANCE dozer blade

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?**



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

Classification	Key Characteristics
<u>**CLASS I**</u> **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
<u>**CLASS II**</u> **Surface Deployed & 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
<u>**CLASS III**</u> **In-Situ Derived and Constructed** 	• Manufactured In-situ, Derived from Local Resources (Lunar or Mars) • In-space 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.

Surface Construction

Capability Description, Outcomes, and State of the Art

Capability Description:

- *Class II*: 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
- *Class III*: In-situ additive 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

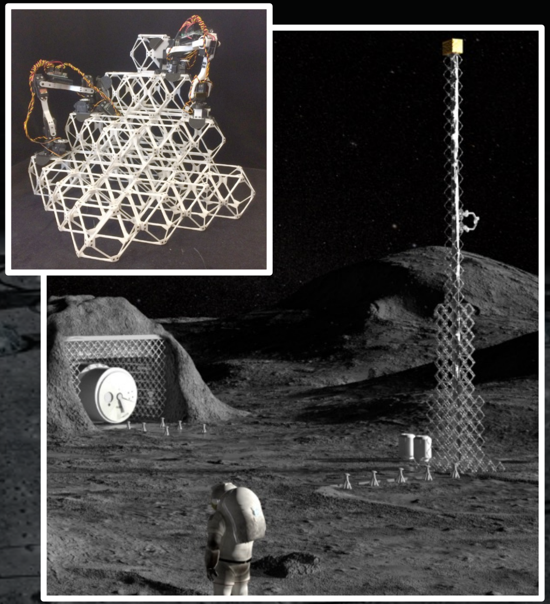
Outcomes

- Towers (50+ m tall for Power and Communication)
- 10s km of roads
- 100-m-diameter launch/landing pads (LLPs)
- Blast containment shield (BCS)– 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, BCS, 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	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 auto. 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 Before Failure

MTTR = Mean Time to Repair

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Class II Surface Construction

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

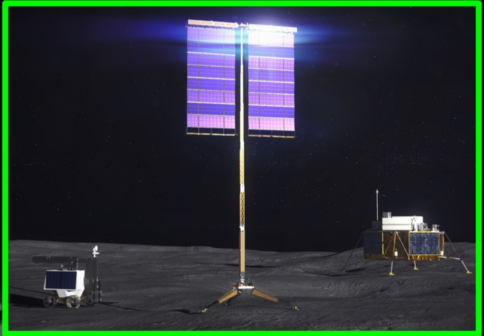
Assembled Surface Structures – Proof of Concept (TRL 2-5)

- 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 under development, not flight rated, no outfitting (TRL 4)
- Concepts for the assembly of Blast Containment Shields and Shelters (truss and panel assemblies) (TRL 2/3)

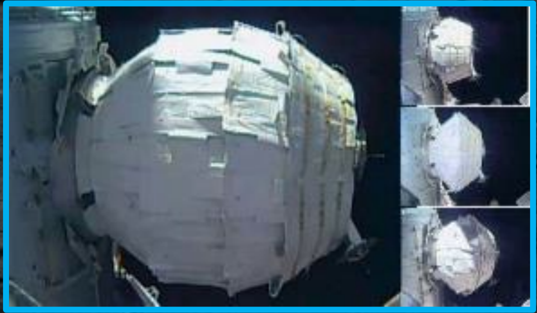
Technology Gaps

- ➢ Accelerated materials and creep testing for inflatable structures
- ➢ Integration of hard structures into inflatables (hatches, windows, bulkheads, attachment points)
- ➢ Structural health monitoring of istructures
- ➢ Advanced joining methods for assembly (e.g., in-space welding, reversable joining)
- ➢ Production of ISRU-based structural elements for Assembly
- ➢ Pressure sealing for pressurized assembled structures

Deployable Vertical Solar Array (VSAT)

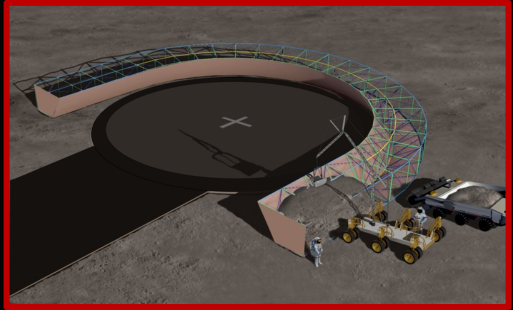


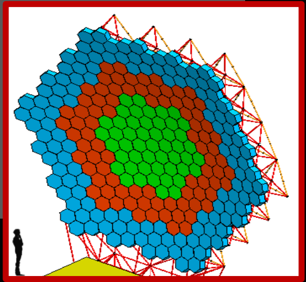
Bigelow Expandable Activity Module (BEAM)



Inflatable crew transfer tunnel concept

Assembled Blast Containment Shield (BCS) concept





Precision Assembled Space Structures (PASS)

Class III Surface Construction

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

SoA & Current Activities

In-situ Additive 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

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

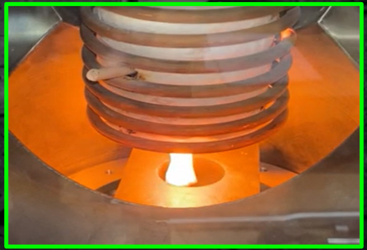
- ➢ Deposition of print material in low-pressure environment while controlling porosity
- ➢ High-temperature materials for LLPs
- ➢ LLP Paver joining
- ➢ Surface stabilization, Foundations, and Anchors
- ➢ Repair technologies
- ➢ Process inspection and control
- ➢ In-situ V&V of construction materials

Process Development

Laser melting in vacuum

Microwave sintering in vacuum

Molten extrusion in vacuum



Additive Construction

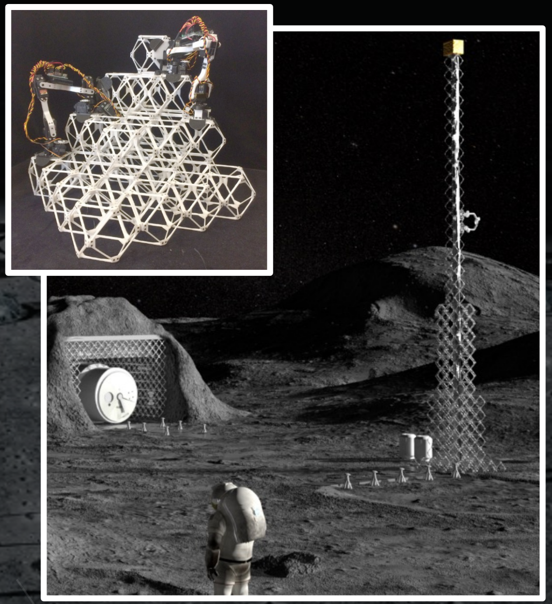
Polymer-regolith printing in a vacuum

Terrestrial printing of cementitious material

Surface Construction

- Additional Cross-cutting Gaps for Class II and Class III Construction
  - Master Planning and ConOps studies to determine construction needs and requirements
  - Geotechnical and seismic characterization to inform foundation design
  - Building requirements and standards
  - Long-life robotic construction equipment and tools
    - Cranes, manipulators, and mobility systems for asset offloading and positioning
    - Robotics and specialized tools for structural assembly and repair
    - Specialized robotics/tools for in-situ additive construction
    - Dust tolerant/abrasion resistant systems/mechanisms
  - Autonomy for complex construction and inspection tasks
  - Inspection methods (e.g., process, materials, structures)
  - Outfitting
  - End-to-end ground demonstrations for infrastructure construction leading to lunar surface demos (tall towers, roads, LLPs and BCS)

Class II: Assembly & Deployables



Class III: In-situ Construction

Outfitting

Capability Description, Outcomes, and State of the Art

Capability Description

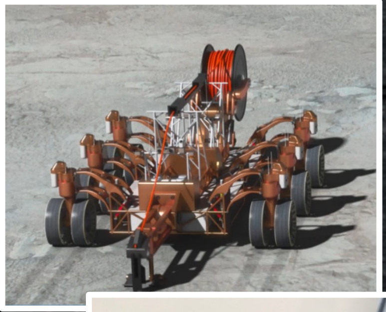
- The process by which a structure is transformed into a useable system by <u>in-situ</u> installation of subsystems.
  - Subsystem installation
  - In-situ testing/validation and inspection techniques with associated metrology
  - Structural repair and enhancement

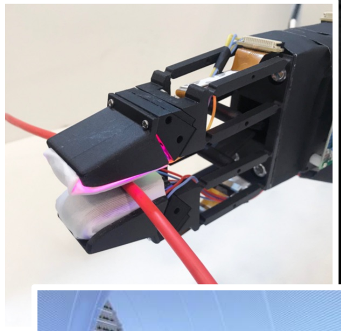
Outcomes (affects most systems that are not landed in operational self-contained state)

- Power, Lighting, Data & Communications distributed through system
- Fluids & Gasses (ISRU products) managed and stored.
- ECLSS
- Hatches and Penetrations
- 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% auto.). Manual repair; Post-construction manual LM for facility enhancement.	LM during construction using ISRU derived harness (100% auto.). 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% auto.). Manual repair; Post-construction manual PM for facility enhancement.	PM during construction using ISRU derived material (100% auto.). 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.





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Outfitting

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

Outfitting SoA & Current Activities

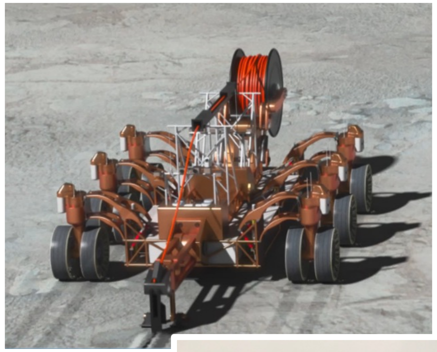
Design and Prototype Outfitting Elements– (TRL 2-4)

- 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

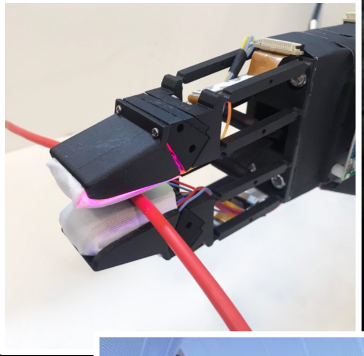
- Architectural and ConOps studies
- Outfitting requirements and standards
- Robotic outfitting technologies for installation of lighting, harnesses, beacons, sensors, fluid systems, HVAC, etc.
- Design of pressure vessel connections/seals with penetrations
- Common interface definition
- Inspection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

Apollo 14: Setting up long duration experiments.

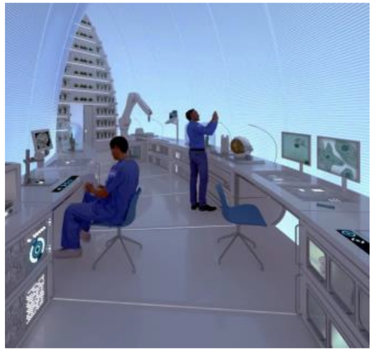


Trenching and cable laying

Cable handling



Outfitted facility

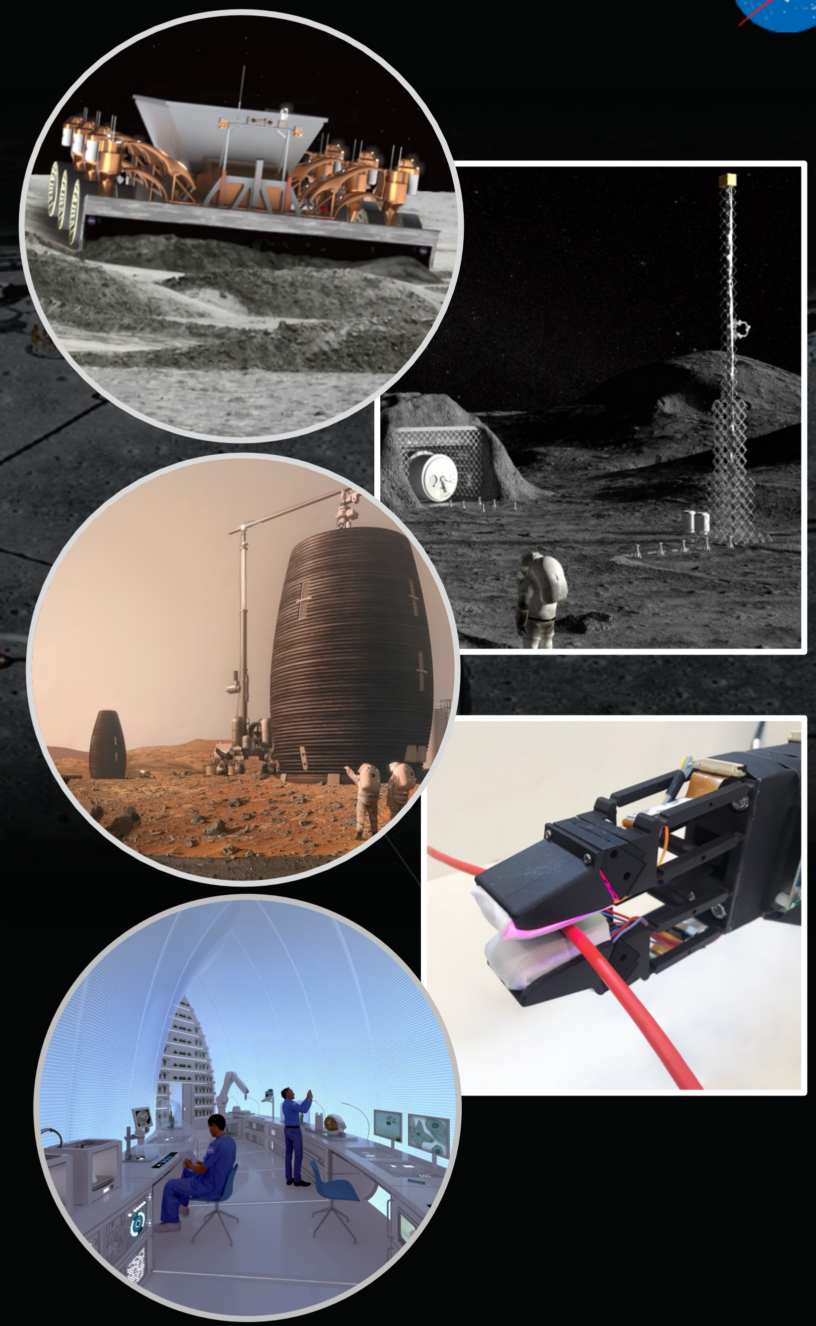


Mapping Top Priority Gaps to ECO Capability Areas & Taxonomy

StarPort Gap ID	Gap Title	Excavation for ISRU and construction feedstock	Regolith Manipulation and Site Prep	Class II Construction	Class III Construction	Outfitting	ESDMD Gap/ Architecture Elements	Taxonomy
369	Excavation of granular (surface) regolith material for ISRU consumables production & construction feedstock	X					X	7.1.2
385	Regolith and resource delivery system	X	X				X	7.1.2
386	Mechanisms and mobility components for long-duration operations with abrasive regolith in the lunar environment	X	X	X	X		X	12.3.2
389	Sensors for regolith collection and excavation force measurement	X	X				X	4.1.1, 7.1.1
390	Rugged low mass robotic excavation and site prep platforms	X	X				X	4.2.4, 7.1.2
391	Sensors and systems for geotechnical characterization	X	X				X	7.1.1, 13.5.2
392	Sensors and systems for high-resolution topological characterization		X				X	7.1.1, 13.5.2
394	Excavation - Autonomous rock clearing/collection		X				X	7.2.3, 13.5.2
395	Excavation - Autonomous grading and leveling		X				X	7.2.3, 13.5.2
396	Excavation - Autonomous surface compaction		X				X	7.2.3, 13.5.2
416	Deposition of print material in low-pressure environment while controlling porosity				X			7.2.3.4
418	Materials for Printing Landing / Launch pad structural elements (materials gap)				X			7.2.3.4
421	V&V: Process Inspection and Control			X	X			12.4.2
422	V&V: In-situ Verification and Validation of Construction Materials				X			7.1.4, 12.4.2
434	Transportation of loose regolith within an AC system for deposition				X			7.2.3
617	Assembled Truss-based Tower			X			X	7.2.3
618	Autonomy and robotics for tower assembly			X				4.3, 7.2.3
619	Assembled Joint Catalog			X				7.2.3
620	Assembled Shelter			X			X	7.2.3
621	Assembled Blast Containment Shield (BCS)			X			X	7.2.3
623	Outfitting: Design & Integrate Electrical Harness					X		7.2.3.5, 13.5.7
624	Outfitting: Connect Lights, Sensors, etc.					X		7.2.3.5, 13.5.7
629	Power/communication tower super gap		X	X		X	X	7.2.3
630	Outfit tower with photovoltaics or reflector to form power tower					X		7.2.3
631	ISRU-based structural elements for surface assembly			X		X		7.2.2, 7.2.3
635	Foundation anchors for surface assembly and construction		X	X	X			7.2.3
636	Structural elements catalog for assembly			X				7.2.3
661	Power and wireless recharging	X	X	X	X	X	X	3.3.2
662	Robotic site preparation system (parent gap to 394, 395, 396)		X	X	X		X	4.2.4, 7.2.3, 13.5.2
663	Outfitting - Power and Data Cable line management					X		7.2.3
666	ISRU-based Additive Construction of Horizontal Structures.				X		X	7.2.3
673	Regolith LLP paver joining and repair				X			7.2.2, 7.2.3
674	Road construction		X		X		X	7.2.3
1293	In-situ construction of launch/landing pads		X		X		X	7.2.3
1294	ISRU Paver/brick production for LLP structures (processing gap)				X		X	7.2.2
1335	Offload Payloads from Lander						X	4.3

Plan to Develop ECO Capabilities

- **Overall Plan**
  - Technology development roadmaps and requirements have been developed that lead to a logical buildup of ECO capabilities and scale that culminate in a series of ground and lunar demonstrations
  - Invest in technology development activities that span entire TRL space
  - Leverage terrestrial civil engineering expertise through NASA solicitations and public-private partnerships
  - Leverage APL/LSIC Working Groups to perform reviews, studies, & integration
- **Next Steps**
  - Continue existing high-priority activities, assess progress of funded activities towards closing gaps, identify and plan the next phase of investments.
  - Continue modest internal and external pilot projects addressing top priorities and initiate new projects (top priorities presented herein)
  - Identify and plan ground and lunar surface demos necessary for gap closure



ECO EFP – Priority Activities

Adequate investment
Some investment
Little/no investment

1. **Complete the IPEx project and conduct the first lunar surface excavation demo**
   - Fully fund and complete development and ground testing of IPEx excavation system
   - Pursue lunar surface test of IPEx to demonstrate the ***excavation and delivery*** of 10mT loose regolith (potential 2026 lunar demonstration)
   - Icy regolith excavation technology developments on hold until better knowledge is obtained from VIPER on the nature of the regolith

2. **Initiate internal and industry-led projects to develop pilot-scale robotic systems to support integrated ECO ground and lunar demonstrations, working towards initial commercial capability (ISRU and site prep apps)**
   - 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*** (addressing both excavation and site prep)
     - *Low mass rugged robotic platforms*
     - *Modularity and interfaces for reconfigurability and repairability*
     - *Survive multiple lunar nights or shadowed regions*
     - *Autonomy for high throughput and cooperative operations*

3. **Initiate internal and industry-led projects to develop technologies for the assembly and outfitting of large-scale truss-based structures on the lunar surface (see Integrated Demos in Priority Activity #5)**
   - Initiate a seedling study and follow-on project to ***develop and demonstrate the assembly and outfitting*** of a tall truss-based Power and Comm tower (leverage existing PASS, ARMADAS and TLT projects, integration of Power, ECO, Comm, Robotics)
   - Initiate a seedling study and project definition for the ***assembly and outfitting of shelters and shields***
   - 2023 SBIR topic added for the assembly and outfitting of tall truss-based towers

ECO EFP – Priority Activities

4. Continue and Expand Development of ISRU-based Materials and Processes for Lunar Surface Construction
   - Continue to develop/demonstrate **multiple** viable ***ISRU-based structural materials and processes*** for the construction of structures in lunar environment (sintered regolith, binder/regolith blend, molten regolith)
   - Initiate new work on ***metals extraction***, ***molten material handling***, ***casting*** ***and printing of parts for construction and repairs and spares*** (collaboration w/ ISRU & Adv. Man.)
     - 2023 SBIR topic added for the development of ISRU-based truss elements for assembly
   - Develop detailed construction feedstock material requirements

5. Develop a series of integrated technology demonstrations (priorities in bold)
   - **Tall tower for Lunar Comm and 100-200 kWe power generation** (ECO, Power, Comm, Robotics, Auto Sys.)
     - *Tall towers needed to meet Comm requirements for Artemis*
     - *Tall power tower can provide near-continuous power for Artemis camp, tech demos, and initial commercial activities*
   - **Modular robotic system for excavation and site preparation** (ECO, Robotics, Auto Sys.)
     - Large-scale system for surface grading, compacting and bulk regolith manipulation (load, haul, dump)
     - Demonstrate autonomous reconfiguration and repair of sub-systems (e.g., wheels, battery, avionics, actuators, implements)
   - Shelter construction and outfitting (ECO, Robotics, Auto Sys., Adv. Man., Power, Comm)
   - Launch/landing facility construction and outfitting (ECO, EDL, Robotics, Auto Sys., Adv. Man., Power, Comm)
   - ISRU-based material production and manufacturing (ECO, ISRU, Adv. Man.)

ECO EFP – Priority Activities

6. Master planning exercise

- Benefit from a *“Master Plan”* exercise for site/infrastructure which will help focus technologies and capabilities and incentivize industry investment
- Leverage input from industry on the development of architecture designs and concept of operation studies
- *Deriving “requirements”* and providing a clear understanding of what a sustainable and scalable lunar infrastructure and economy could look like

7. Maintenance and Repair

- Initiate funding in the area of development of Digital Twins of E&C assets in lunar environment with the intention of better understanding of M&R. Adopt Digital Twin as the core element of predictive maintenance of lunar E&C assets.
- Leverage learnings from Industry 4 paradigm that is being adopted by many leading companies as predictive maintenance using digital twins is a big part of Industry 4.
- Leverage NASA programs by mandating that developing M&R protocols should be an integral part of their architecture or deliverable.