Autonomous Excavation, Construction, and Outfitting

Capability Needs and Technology Gaps

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Outline

- Envisioned Future
- Capability Needs & Technology Gaps
- Demonstration Planning

Autonomous Lunar Excavation, Construction, & Outfitting

targeting landing pads, structures, habitable buildings utilizing in-situ resources

Excavation for ISRU-based Resource Production

- Site surveying, resource prospecting
- Ice mining & regolith extraction for 100s to 1000s metric tons of commodities per year

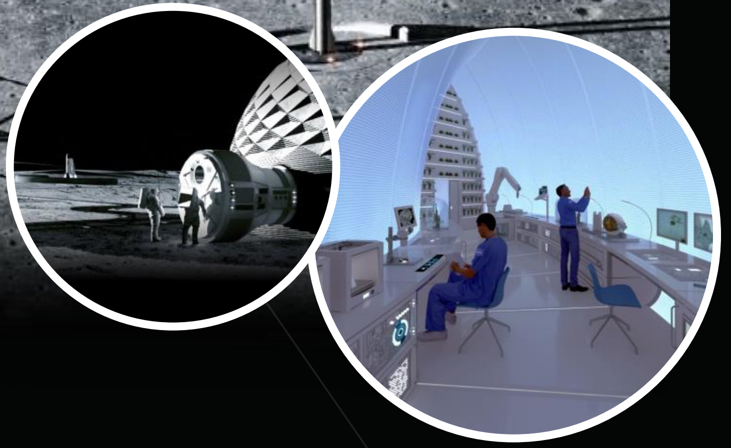
Excavation for Construction

- Site preparation for construction: obstacle clearing, leveling & trenching
- Construction materials production utilizing in-situ resources
  - 100s to 1000s metric tons of regolith-based feedstock for construction projects
  - 10s to 100s metric tons of metals and binders

Construction and Outfitting

- Landing pad construction demo scaling to human lander capable landing pads
- Unpressurized structure evolving to single and then multi-level pressurized habitats
- Outfitting for data, power & ECLSS systems
- 100-m-diameter landing pads, 10s km of roads, 1000s m^3 habitable pressurized volume

Sustainable Off-Earth Living & Working



- Commercial autonomous excavation and construction of landing pads, roads and habitable structures
- Fully outfitted buildings to support a permanent lunar settlement and vibrant space economy
- Extensible to future Mars settlement

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

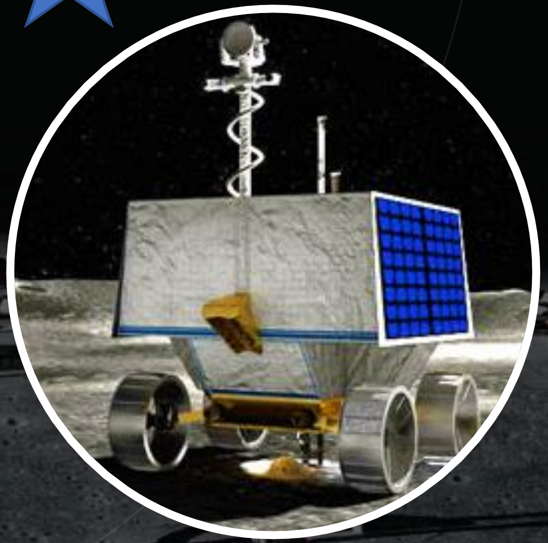
Excavation for ISRU-Based Resource Production

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



Volatiles Investigating Polar Exploration Rover (VIPER) ~2024 mission

RASSOR Excavator

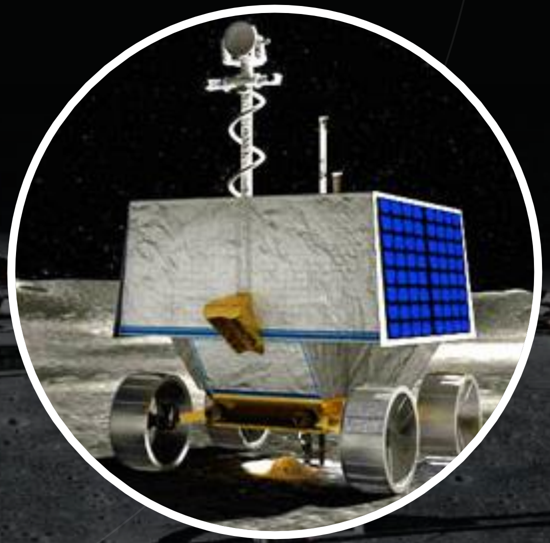
MTBF = Mean Time Before Failure

MTTR = Mean Time to Repair

Excavation for ISRU-Based Resource Production

Gap Areas

- Excavation of granular and hard/icy regolith
- Dust mitigation for actuators, sensors, seals, joints, mechanisms
- Wear-resistant materials and wear characterization
- Regolith flow/interaction with implements
- Long-life lubricants, motors, avionics
- Sensors for geotech & topology characterization, SHM
- Low mass robotic platform
- Power and wireless recharging
- Dust tolerant thermal control system
- Autonomy for high throughput operations
- Autonomous repair



Volatiles Investigating Polar Exploration Rover (VIPER) ~2024 mission

RASSOR Excavator

Excavation for Construction and Site Preparation

Capability Description - Similar to Excavation for ISRU plus…

- Site survey – geotechnical and topography
- Site clearing, level, grade, and compact
- Rock removal and gathering
- Load, Haul, Dump
- Bulk regolith manipulation – berms, piles, and overburden
- Trenching

Outcomes

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

CHARIOT with LANCE Blade

Excavation for Construction and Site Preparation

Gap Areas

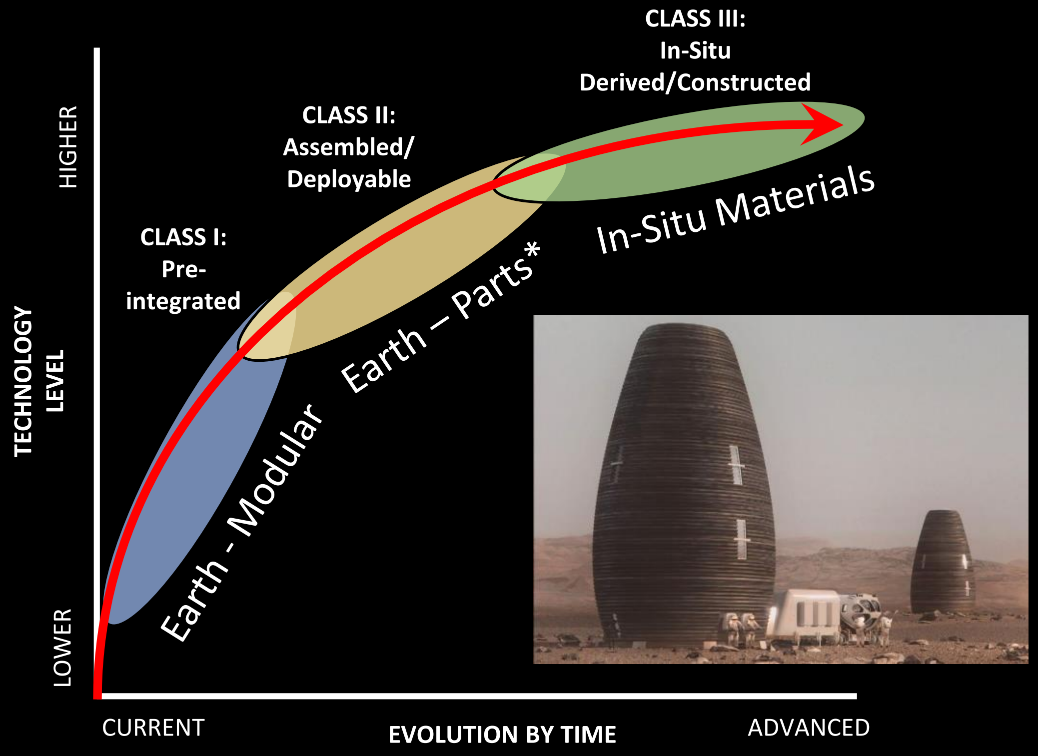
- Low mass robotic platforms for excavation and site prep
- Implements for rock handling, grading, leveling, compaction, berm building, trenching
- Dust mitigation for actuators, sensors, seals, joints, mechanisms
- Wear-resistant materials and wear characterization
- Regolith flow/interaction with implements
- Long-life lubricants, motors, avionics
- Sensors for Geotech & topology characterization, site prep V&V, SHM
- Power and wireless recharging
- Dust tolerant thermal control system
- Autonomous operations and repair

CHARIOT with LANCE Blade

Surface Construction Classifications

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

- **How can we build?**



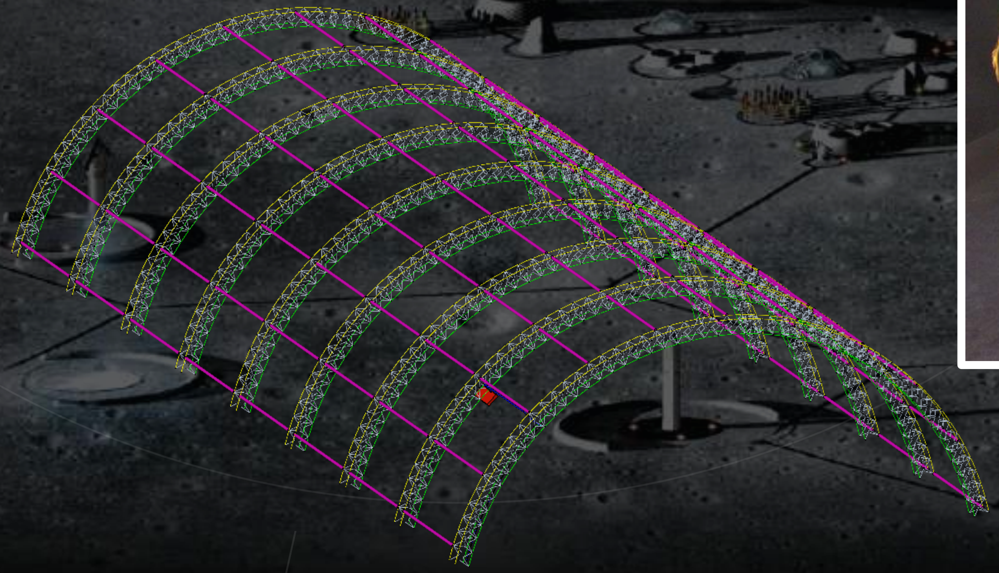
Classification	Key Characteristics
CLASS I **Pre-integrated** 	• Earth Manufactured • Pre-Integrated & Tested Prior to Launch • Space Delivered with Immediate Habitation Capability • Volume Constrained by Launch Vehicle Shroud Size • Mass Constrained by Launch Vehicle Mass Capability
CLASS II **Surface Deployed & Assembled** 	• Earth-sourced or Isru-derived • Requires Surface Deployment, Assembly & Outfitting • May Include Partial Integration of Subsystems • Critical Subsystems are Earth Based and Tested Prior to Launch • Requires Assembly & Checkout Prior to Human Occupancy • Larger Volumes 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
CLASS III **In-Situ Derived and Constructed** 	• Manufactured In-situ, Derived from Local Resources (Lunar or Mars) • In-space Constructed • Requires Robotic Construction Capability & Infrastructure • Requires Robotic and Human Labor During Construction • Requires Integration of Subsystems • Critical Subsystems are Earth Based and Tested Prior to Launch • Larger Volumes Capable and No Longer Constrained by Launch Vehicle (Constrained by Limitations of Construction Equipment) • Construction Equipment Constrained to Launch Vehicle Mass and Volume.

*Note: Class II can include ISRU derived components

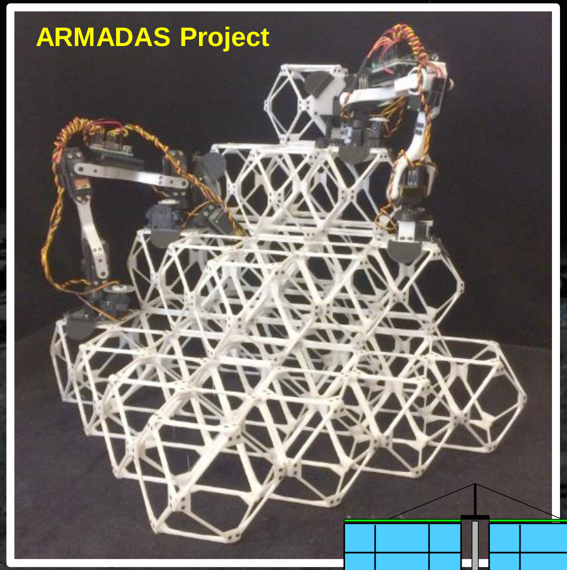
Surface Construction – Class II (Mixture of Earth Brought and ISRU Derived)

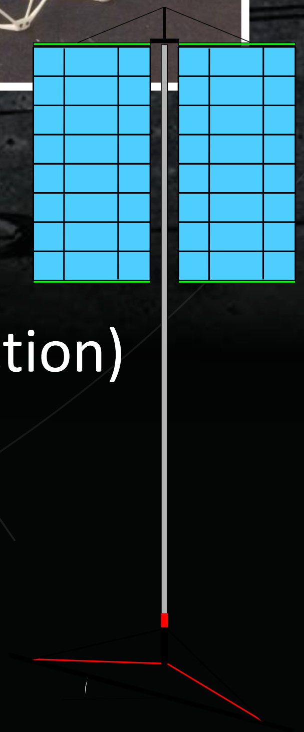
Capabilities

- Site Preparation (clearing, leveling, compacting, etc.)
- Horizontal construction
    - Launch/landing pads
    - Roads
    - Dust-free zones
- Vertical construction
    - Towers
    - Blast shields
    - Shelters & Habitats
- Supervised Autonomy (ability to operate for 30 minutes without direct interaction)
- System maintenance, repairability, SHM
- V&V – process inspection
    - Site preparation and construction verification

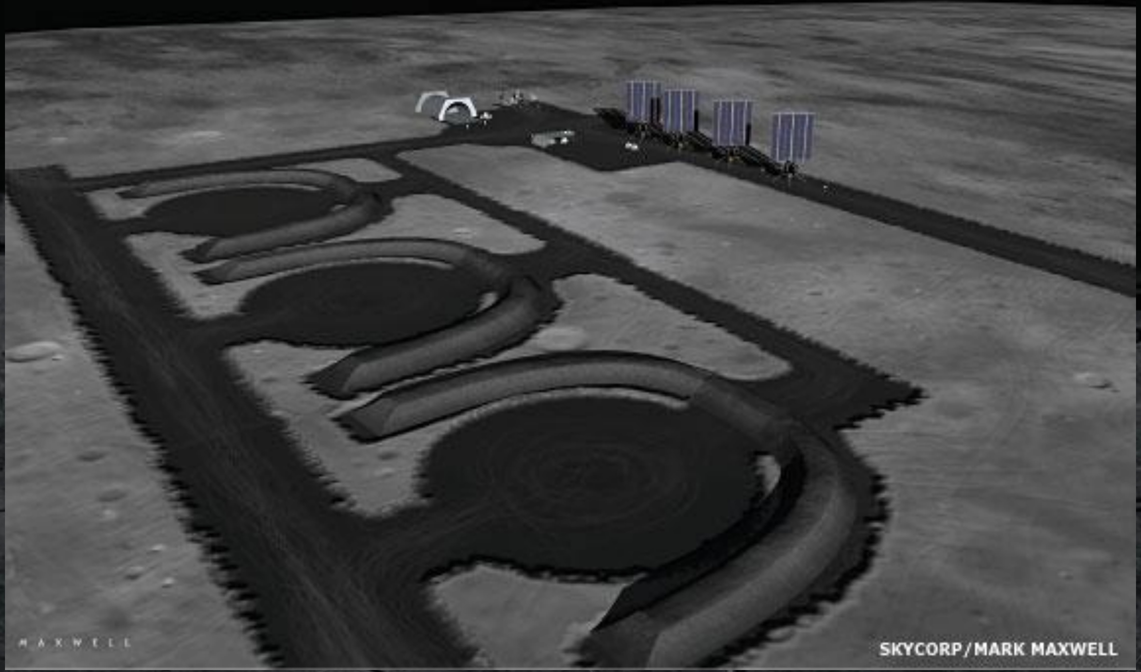


CLASS II:
Prefabricated
Deployable





Surface Construction – Class II



Gaps

- Deployment and Assembly of discrete elements (towers, blast shield, shelters…)
- Robust wiring harness route planning integration and attachment (Outfitting: lighting, beacons ...)
- Autonomous conduit & tubing installation, routing and connection (Outfitting).
- Bulk regolith manipulation and overburden planning and placement (grading, excavation, piling for blast shield, shelter …)
- **Manufacturing of ISRU-based structural elements**
- **In-situ testing and inspection techniques for certification (material and structural)**
- **Structural enhancement and repair**
- **Construction System: design for lunar survivability, reliability, and maintenance**
- Autonomous deployment of construction system
- By-product volatile and particulate protection

Surface Construction – Class III

Capabilities

- Construction material preparation
- Horizontal construction
  - Launch/landing pads
  - Roads
  - Dust-free zones
- Vertical construction
  - Blast shields
  - Shelters & Habitats
  - Towers
- Autonomy
- System maintenance, repairability, SHM
- V&V – process inspection
  - Materials
  - Construction

CLASS III:
In-Situ Derived

Surface Construction – Class III

Gaps: share many with Class II, plus the following

- Material deposition in low-pressure environment while controlling porosity
- Overhang support for printed structure
- Material processing into construction feedstock
- ISRU-based structural reinforcement
- Printer system motion dynamics, accuracy, repeatability, and calibration
- Autonomous deployment of construction system
- Sintering of regolith
- Extrusion of molten and/or cementitious materials
- Print system cleaning and maintenance
- By-product volatile and particulate protection

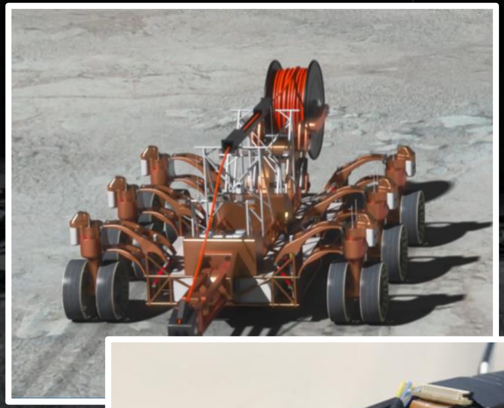
Outfitting

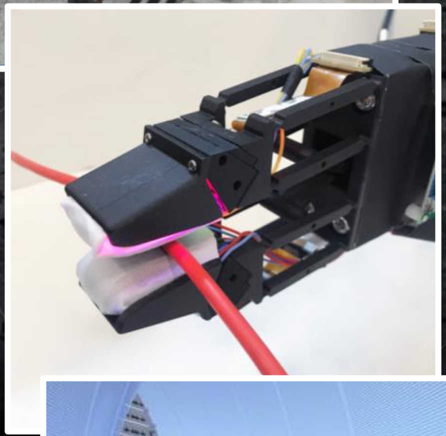
Capability Description

- 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
  - Structural repair and enhancement

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

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





Outfitting

Gaps

- Power and Data cable line management
  - Install, secure, strain-relief, splicing/connecting, CTE management, micrometeor/impact protection, radiation
- Piping/Tubing line management
  - Power and Data gaps, plus…
  - Joining, testing, repair (when wet), spill management
- Penetration Management
  - Design for discontinuities
  - Sealing and in-situ validation

Summary of Top Priority Needs

Excavation for Site Preparation and ISRU-based Commodities

- Develop and demonstrate excavation capabilities needed for site preparation and construction, and regolith extraction for ISRU-based construction materials and commodities production (ground & lunar surface demonstrations)
  - **Excavation and site preparation** including site clearing, leveling, and compacting
  - Excavation technology needed to provide 1,000s of tons of regolith feedstock for infrastructure construction and ISRU-based commodities

Large-scale Class II and Class III Construction

- Develop a combination of robotic assembly and ISRU-based construction systems capable of repeatable, reliable, autonomous construction of
  - Horizontal structures (e.g., **landing pads, roads**, dust-free zones)
  - Vertical structures (e.g., **towers**, blast containment shields, shelters, and habitats)

ISRU-based Materials and Processes for Lunar Surface Construction

- Develop/demonstrate viable ISRU-based materials and processes for the manufacturing and construction of Class II and Class III extraterrestrial structures in lunar environment (binder/regolith blend, sintered regolith, molten regolith)

Lunar Surface Technology Demonstration Planning

LSII leverages early lunar missions to accelerate development of core surface technologies