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

- Site surveying, resource prospecting
- Ice mining & regolith extraction for 100s to 1000s metric tons of commodities per year
- 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
- 100s to 1000s metric tons of regolith-based feedstock for construction projects
- 10s to 100s metric tons of metals and binders

Excavation for ISRU-based Resource Production

Excavation for Construction

Construction and Outfitting

- 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

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$_2$O and volatiles - hydrogen, carbon oxides, hydrocarbons, and ammonia
- Regolith for ISRU-based construction feedstocks and binders – Metals, Silicon, Slag

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
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 m² of prepared surface
- Provide bulk regolith berms and overburden for shielding
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
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?**

<table>
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<tr>
<th>Classification</th>
<th>Key Characteristics</th>
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| **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)  

*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
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
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*

### 2020

**ISRU**
- Polar Resources Ice Mining Experiment (PRIME)
- Volatiles Investigating Polar Exploration Rover (VIPER/SMD)
- ISRU Ice-Mining Demo
- ISRU Oxygen Extraction Demo
- ISRU Processing Demo
- ISRU Pilot Plant

**Surface Power**
- Regenerative Fuel Cell Power
- Chemical Heat Integrated Power Source (CHIPS)
- Fission Surface Power Demo
- Wireless Charging for Lunar Surface Demo
- Vertical Solar Array Technology (VSAT)

**Dust Mitigation**
- Electrodynamic Dust Shield
- Lunar Dust Level Sensor & Affects on Radiators
- Lunar Dust Smart Sensor for Crewed Environments
- Lunar Dust Removal Tool
- Lunar Dust Separation

**Extreme Environments**
- Lunar Arm w/ Bulk Metallic Glass Gears
- Lunar Materials Demo
- Lunar Camera
- Lunar Thermal Toolbox
- Lunar Night Material Survivability

**Extreme Access**
- Surface Robotic Scouts
- Tipping Point Early Hopper CLPS Opportunity
- Lunar Navigation Demo
- Video Guidance System
- Day/Night Lunar Rover Obstacle Avoidance
- Autonomous Robotics
- Deployable Hopper
- Autonomous Exploration of Lunar Pits

**Excavation & Construction**
- ISRU Pilot Excavator
- Lunar Surface Construction Demo
- Lunar Surface Construction Demo (Landing Pad)

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2030

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