



#### Robotic Construction on the Moon

International Space University Space Studies Program (SSP) 21 July 23, 2021

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#### 2

### Outline

- Introduction NASA Lunar Artemis Program
- In Situ Resources for Construction Materials
- Project Site Characterization
- Robot Operations
- Robot Characteristics
- Lunar Challenges
- Examples of Robotic Construction





#### **ARTEMIS** PHASE ONE: Lunar South Pole by 2024

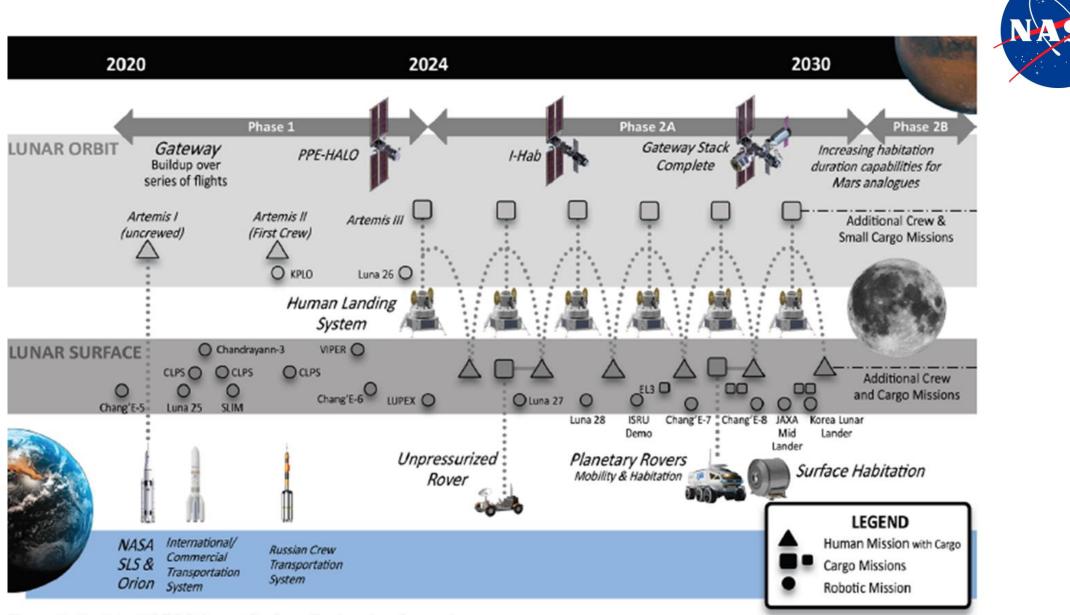


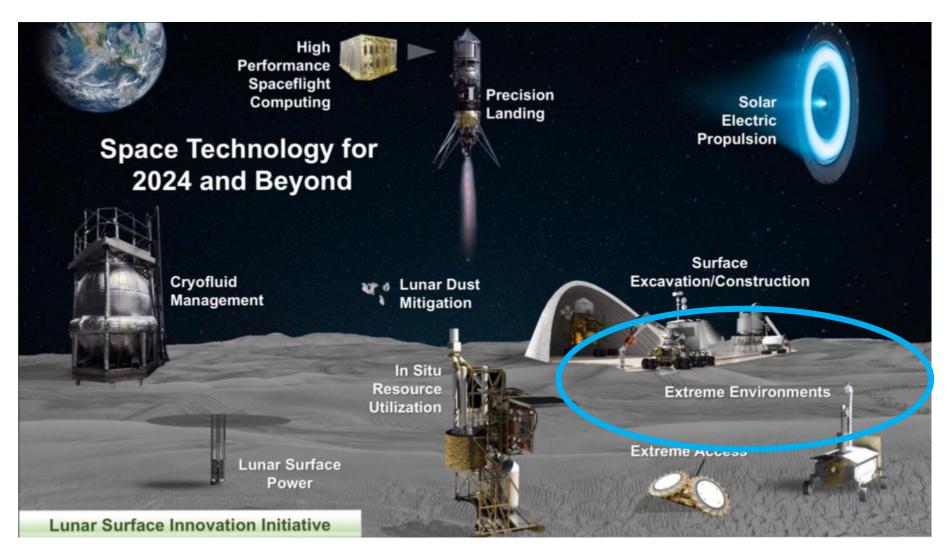
Figure 1. Updated ISECG Lunar Surface Exploration Scenario.



#### ARTEMIS PHASE TWO: Mars Forward Capabilities, Sustainable Lunar Presence

#### Lunar Surface Innovation Initiative (LSII)

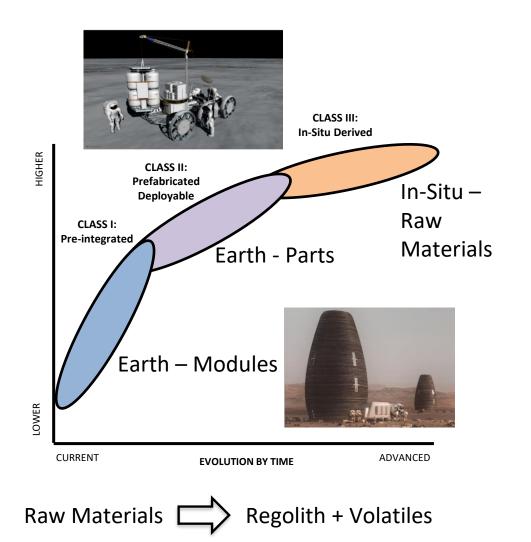




http://lsic.jhuapl.edu/

#### **Surface Construction Classifications:**

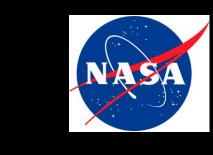


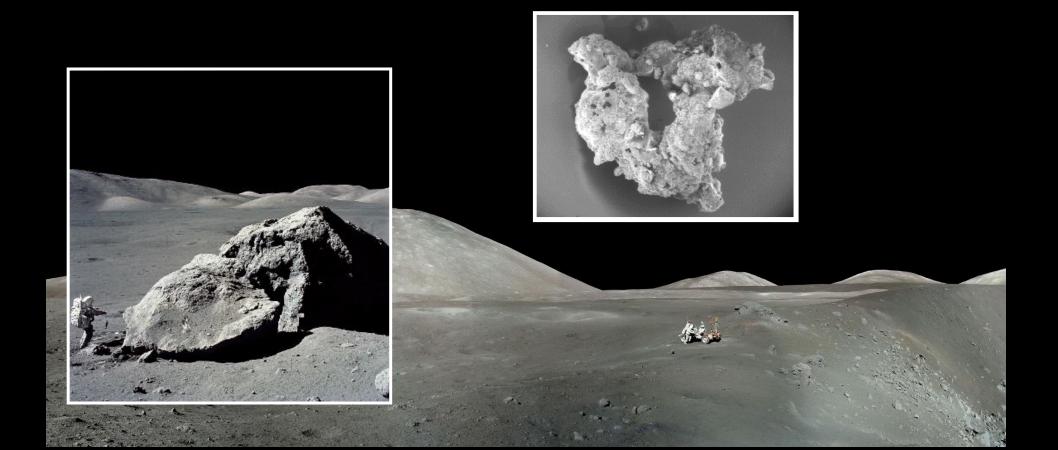


Habitat Classification	Key Characteristics		
CLASS I	Earth Manufactured		
Pre-integrated	Earth Assembled & Fully Outfitted		
	Pre-Integrated & Tested prior to Launch		
	Space Delivered with Immediate Habitation Capability		
Modular	Launch Shroud Constrained		
	Limited to Launch Vehicle Payload Size Capability		
	Limited to Launch Vehicle Payload Mass Capability		
<u>CLASS II</u>	Earth Manufactured		
Prefabricated	<ul> <li>Requires Space Deployment, Assembly &amp; Outfitting</li> </ul>		
Deployable. Space	Requires Robotic and Human Labor During Assembly		
or Surface	<ul> <li>Partial Integration Capable for Subsystems</li> </ul>		
Deployed &	Requires some or all Internal Outfitting emplacement		
Assembled	Critical Subsystems are Earth Based and Tested prior to		
Assembled	Launch		
	<ul> <li>Requires Assembly &amp; Checkout prior to Human</li> </ul>		
Parts	Occupancy		
	Larger Volumes Capable		
	<ul> <li>Not Restricted to Launch Vehicle Shroud Size</li> </ul>		
	Restricted to Launch Mass. Deliver on multiple vehicles		
<u>CLASS III</u>	Manufactured In-Situ Derived with Space Resources		
In-Situ Derived and	(Lunar or Mars)		
Constructed	In-Space Constructed		
	Requires Robotic Manufacturing Capability &		
	Infrastructure		
Raw	Requires Robotic and Human Labor During Construction     Requires Integration of Submittees		
	Requires Integration of Subsystems		
Materials	Requires all Internal Outfitting emplacement     Critical Subsystems are Earth Based and Tested prior to		
	<ul> <li>Critical Subsystems are Earth Based and Tested prior to Launch</li> </ul>		
	<ul> <li>Requires Assembly to become Operability</li> <li>Larger Volumes Capable</li> </ul>		
	Not Restricted to Launch Vehicle Size		
	Not Restricted to Launch Mass		

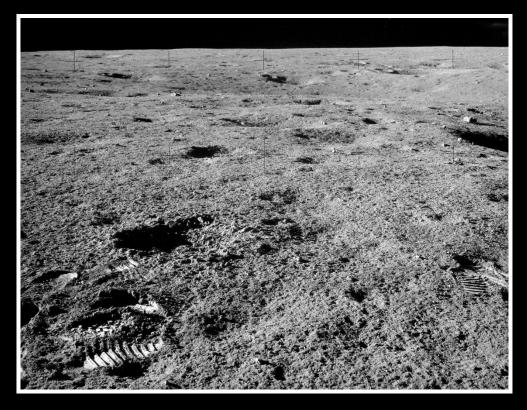
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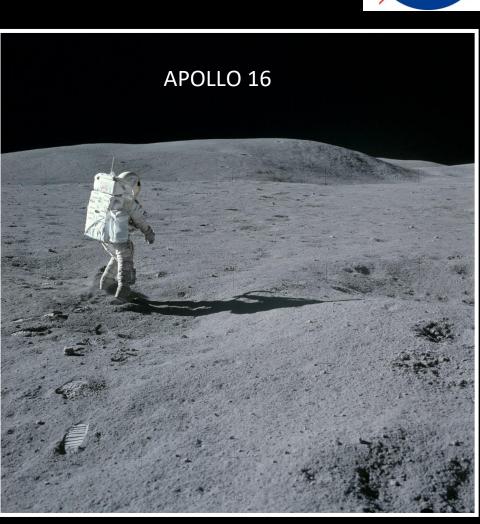
**Regolith**: Surficial layer covering the entire lunar surface ranging in thickness from meters to tens of meters formed by impact process – physical desegregation of larger fragments into smaller ones over time.





#### Rock Granular Material = In-Situ Construction Material





NASA



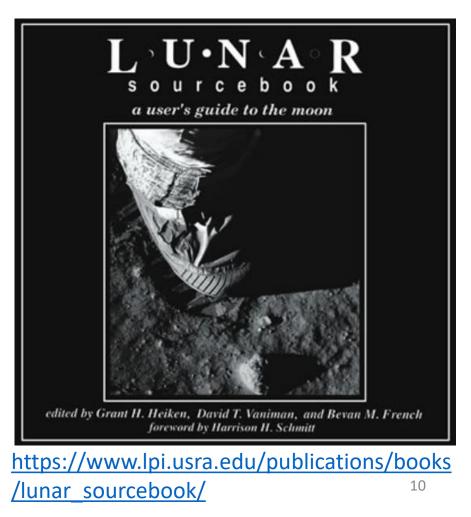
#### **Lunar Regolith Geotechnical Properties**



SLS-SPEC-159 REVISION G EFFECTIVE DATE: DECEMBER 11, 2019

#### CROSS-PROGRAM DESIGN SPECIFICATION FOR NATURAL ENVIRONMENTS (DSNE)

https://www.lpi.usra.edu/lunar/strategies/ NASA SLS-SPEC-159G DSNE 2019-12-11.pdf





#### Lunar Regolith Geotechnical Properties for Civil Engineering Analysis

Property	Value	Units	Notes	DSNE Section	Sources
Bulk Density (\varrho)	1.58 ± 0.05: 0-30 cm 1.74 ± 0.05: 30-60 cm	g cm <sup>-3</sup>	Intercrater areas	3.4.2.3.1	Carrier et al. 1991
Relative Density $(D_R)$	74±3.0-30 cm		Intercrater areas	3.4.2.3.2	Carrier et al. 1991
Specific Gravity (G)	3.1	-	Based on limited number of bulk samples	3.4.2.3.3	Carrier et al. 1991
Porosity (n)	49 ± 2: 0-30 cm 44 ± 2: 30-60 cm	%	Calculated	3.4.2.3.4	Carrier et al. 1991
Void Ratio (e)	0.96 ± 0.07: 0-30 cm 0.78 ± 0.07: 30-60 cm	-	-	3.4.2.3.4	Carrier et al. 1991
Permeability ( <i>Q</i> )	1-7 x 10 <sup>12</sup>	m <sup>2</sup>	Firing of Surveyor vernier engines on surface	3.4.2.3.5.1	Choate et al. 1968
Diffusivity	7.7 He, 2.3 Ar, 1.8 Kr	cm <sup>2</sup> s <sup>-</sup>	Measured on simulant function of gas species	3.4.2.3.5.2	Martin et al., 1973
Friction Angle $(\varphi)$	30-50	۰	-	3.4.2.4.6	Carrier et al. 1991
Cohesion (c)	c) 0.1 - 1		-	3.4.2.4.7	Carrier et al. 1991
Compression index $(C_c)$	0.3: loose 0.05: dense 0.01 - 0.11: range	-	Lab measurement on 1.2 to 200 g samples	3.4.2.4.2	Langseth et al. 1973
Recompression index $(C_r)$	0.003: avg 0 - 0.013: range	-	Lab measurement on 1.2 to 200 g samples	3.4.2.4.2.1	Carrier et al. 1991
Coefficient of lateral stress $(K_0)$ $0.45$ : normally consolidated $3-5$ : below a few mete $0.7$ : recompacted		-	Lab measurement on 1.2 to 200 g samples	3.4.2.4.3	Carrier et al. 1991
Modulus of subgrade reactions (k)	8: avg 1-100: range	kPa cm <sup>-1</sup>	Based on in situ observations of boot prints	3.4.2.4.5	Carrier et al. 1991

Table 3.4.2.3-1 Summary of bulk regolith properties taken as representative of typical lunar characteristics based on prior landed missions and sample properties.

NASA SLS-SPEC-159 DSNE Page 231

#### **Lunar Regolith Resource Potential**

Ilmenite - 15%FeO•TiO<sub>2</sub> (98.5%) Pyroxene - 50%CaO•SiO<sub>2</sub> (36.7%) MgO•SiO<sub>2</sub> (29.2%) FeO•SiO<sub>2</sub> (17.6%) Al<sub>2</sub>O<sub>3</sub>•SiO<sub>2</sub> (9.6%) TiO<sub>2</sub>•SiO<sub>2</sub> (9.6%) Olivine - 15%2MgO•SiO<sub>2</sub> (56.6%) 2FeO•SiO<sub>2</sub> (42.7%) Anorthite - 20%CaO•Al<sub>2</sub>O<sub>3</sub>•SiO<sub>2</sub> (97.7%)

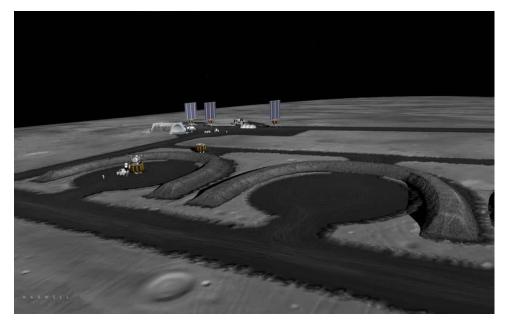


Water (?, >1000 ppm)

Solar Wind Hydrogen (50 - 100 ppm) Carbon (100 - 150 ppm) Nitrogen (50 - 100 ppm) Helium (3 - 50 ppm) <sup>3</sup>He (4 - 20 ppb)

- Oxygen is the most abundant element on the Moon
- Solar wind deposited volatile elements are available at low concentrations
- Metals and silicon are abundant
- Water may be available at poles
- Lunar mineral resources are understood at a global level with Apollo samples for calibration



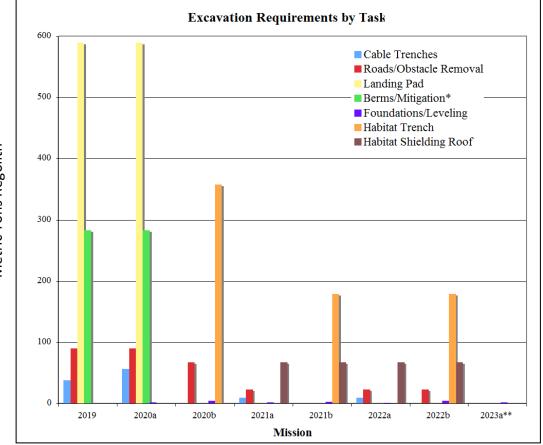


SUMMARY	
Task	%
Trenching	4
Clearing and Compacting	48
Building Berms	18
Habitat Shielding	31
	100
Ice Mining	17
Regolith Mining	83
Construction	84
Mining	16

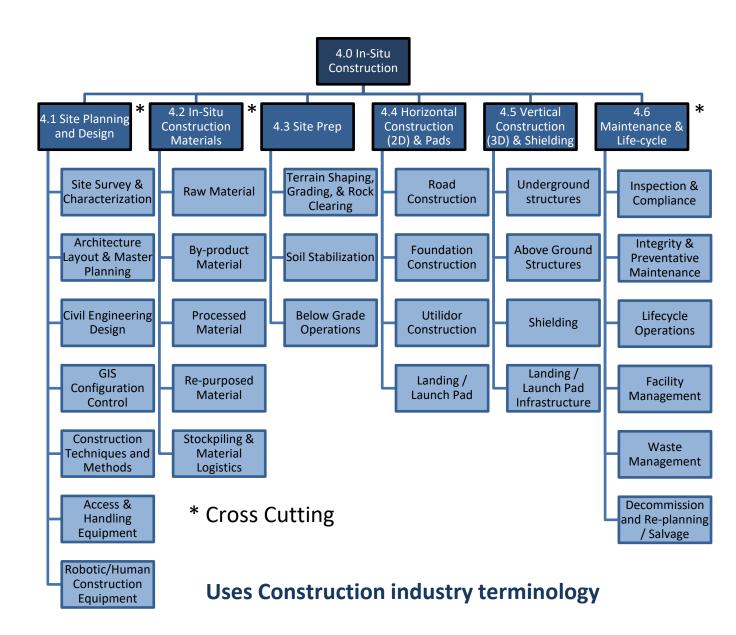
Metric Tons Regolith

#### Criteria for Lunar Outpost Excavation

R. P. Mueller and R. H. King Space Resources Roundtable –SRR IX October 26, 2007 Golden, Colorado









### Lunar Surface Infrastructure

Launch/Landing Pads

**Beacon/Navigation Aids** 

**Lighting Systems** 

**Communications Antenna Towers** 

**Blast Protection Berms** 

Perimeter Pad Access & Utility Roads

Spacecraft Refueling Infrastructure

**Power Systems** 

Radiation, Thermal & Micro Meteorite Shielding

**Electrical Cable/ Utilities Trenches** 

Foundations / Leveling

**Trenches for Habitat & Element Burial** 

**Regolith Shielding on Roof over Trenches** 

**Equipment Shelters** 

**Maintenance Hangars** 

**Dust free zones** 

Thermal Wadi's for night time survival

**Regolith Mining for O2 Production** 

H2O Ice/Regolith Mining from Shadowed Craters



# What is a Robot?



1920s: from Czech, from *robota* 'forced labor'. The term was coined in K. Čapek's play *R.U.R.* 'Rossum's Universal Robots' (1920); a machine that does work.





# Project Site Characterization

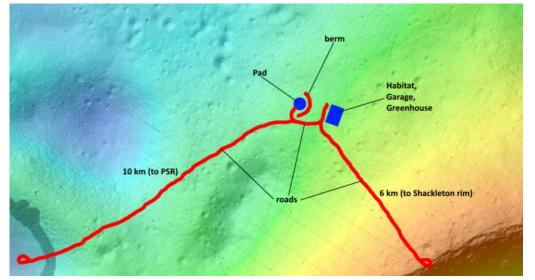


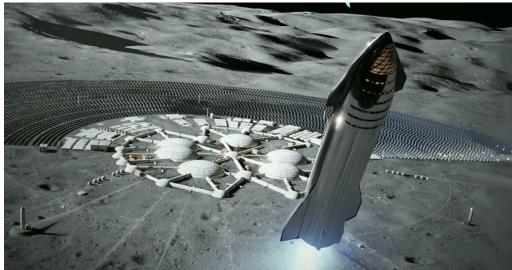
- Construction planning phased construction
  - Manifesting strategy for Earth to Moon logistics
- Topographical, terrain, geologic and geotechnical survey
- Identify site development resources

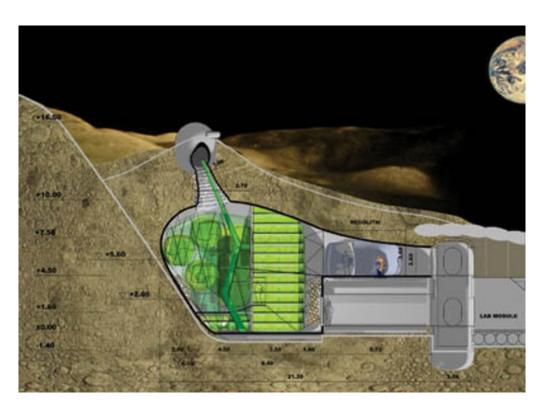


## WHAT will you build?









ESA Lunar Habitat for extended scientific research

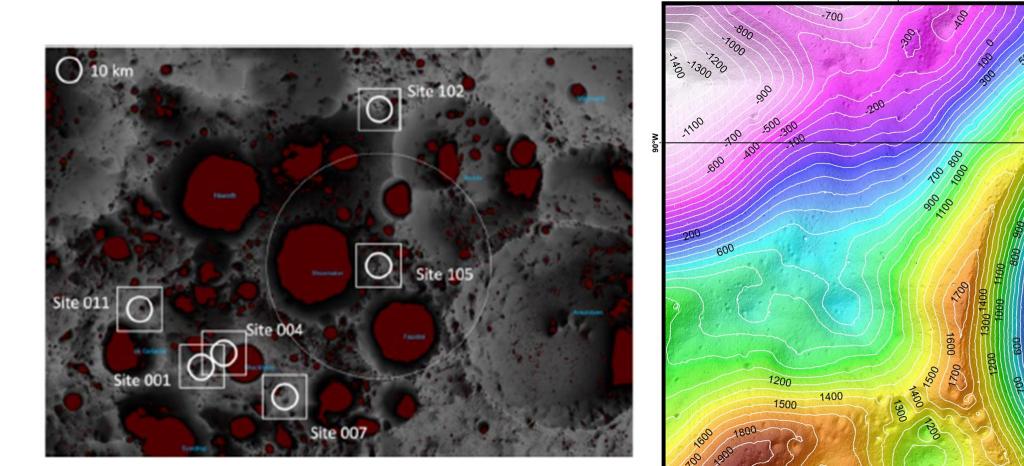
NASA/ICON/Search+

### WHERE will you build? SOUTH POLAR REGION



0°E

45°W



NASA Artemis III Science Definition Report

19

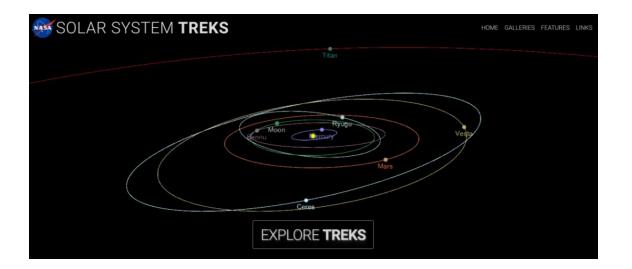
1100-1000

0024

2 km

180°E

# Topographic Survey

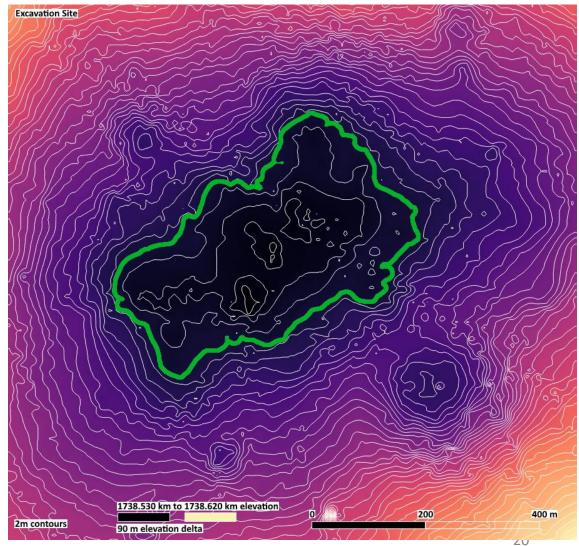


https://breaktheicechallenge.com/resources-media/

#### 2 METER CONTOURS

#### https://trek.nasa.gov/





### Lunar Terrain Types





#### SMOOTH

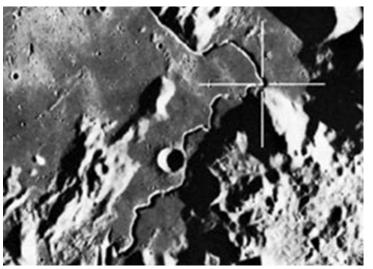
#### BLOCKY





#### OBSTRUCTED

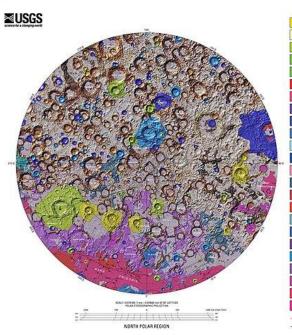
#### OUTCROP



Apollo 17 SP-330

## Geologic Survey

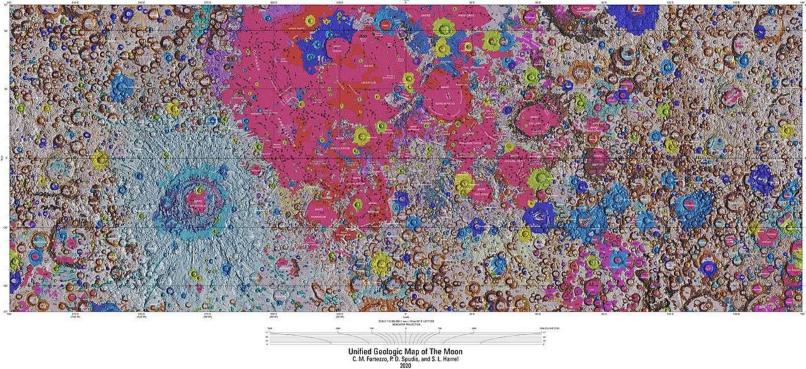
https://astrogeology.usgs.gov/search/map/Moon/ Geology/Unified Geologic Map of the Moon GI S v2



	Brief Description of Map Units a	nd E	Explanation of Map Symbols			
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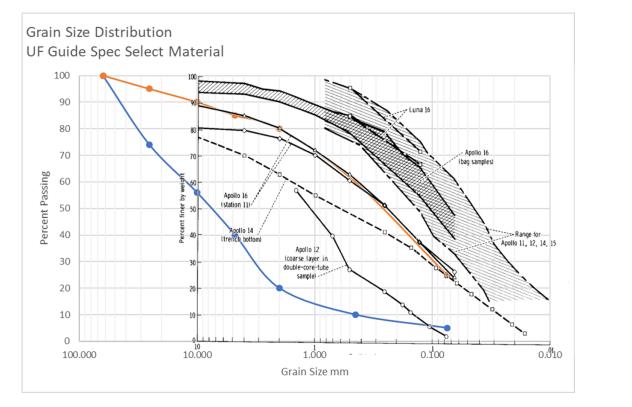


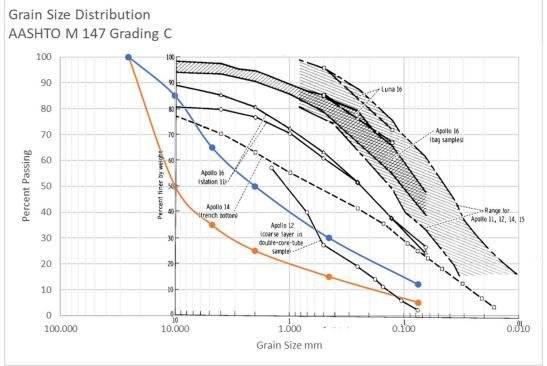
SOUTH POLAR REGION



### **Geotechnical Properties**







# Site Development Resources





- Borrow pits
- Quarries
- Spoil piles





## Robot Operations – General Purpose

- Lifting
- Excavating and Trenching
- Hauling
- Material handling (conveying)
- Grading and compacting
- Surveying



# Robot Operations – Special Purpose



- Grading and paving surfaces
- Create dust free zones
- Paver, Brick and Block laying
- Anchoring & grounding systems
- Assembly of pre-fabricated components
- Molding and Formwork installation
- 3D Printing of concrete



NASA

## Construction material

- Loose material
  - Quarry-run (as excavated)
  - Processed (crushed, sieved, sorted, blended)
- Manufactured
  - Bricks and blocks
  - Concrete
- Imported material
  - Air locks, ports, etc.
  - Mechanical and electrical equipment

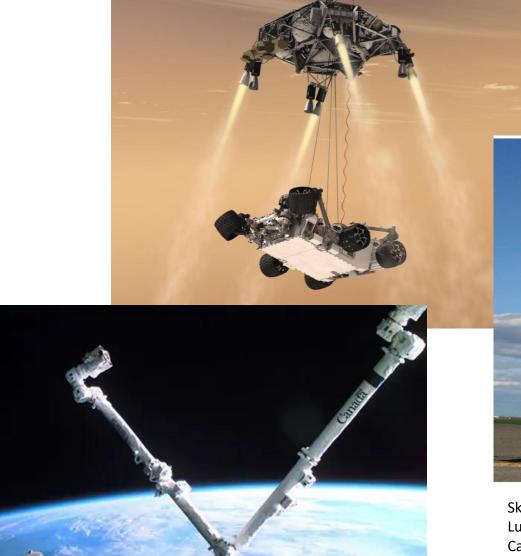




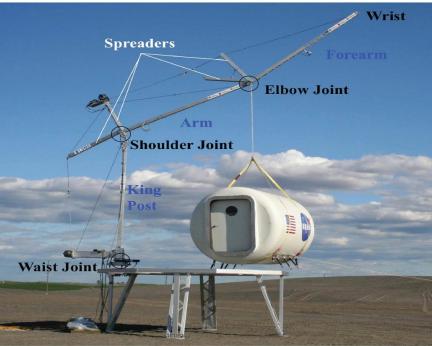
NASA

# Lifting

- Cranes
- Derricks
- Articulated Arm
- Mobile
  - Tire or track
  - Flying
- Fixed
  - Tower
  - Ringer







Sky Crane – NASA JPL Lunar Surface Manipulator System – NASA LaRC Canada Arm – Canadian Space Agency (CSA) 28

# Excavating and Trenching

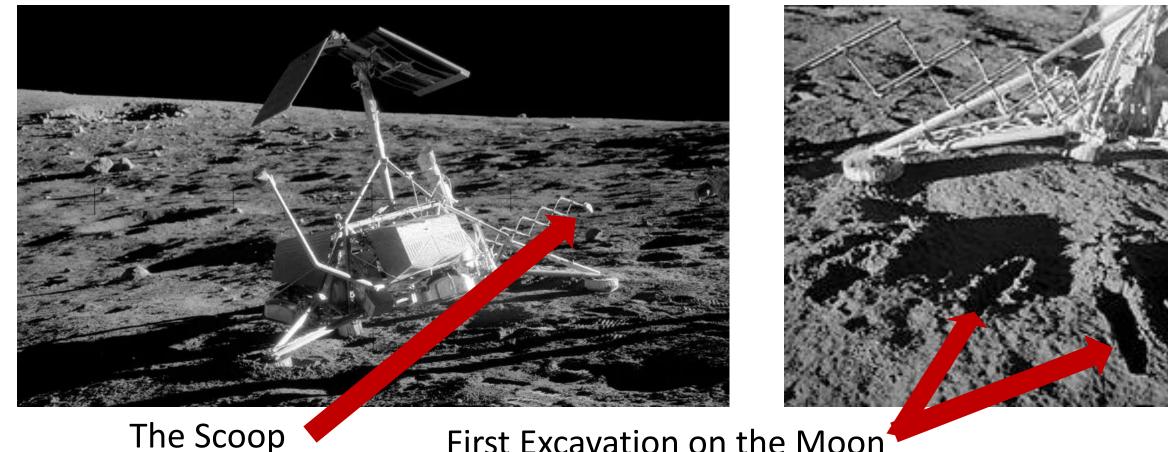


- Hoes
- Shovels
- Draglines
- Clam Shells
- Bucket Wheels
- Drill and blast
- Pneumatic



#### Surveyor 3: the first robotic excavation on the Moon (1967)

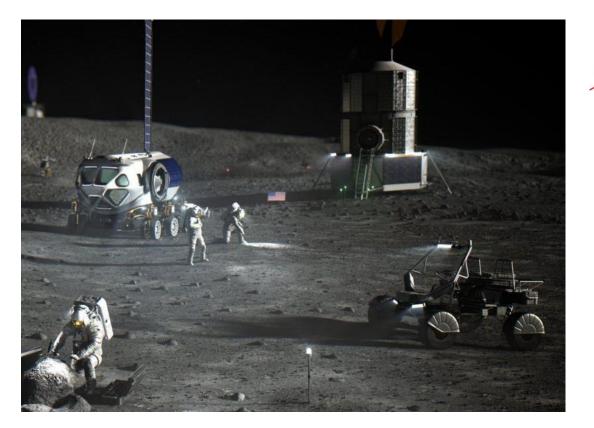


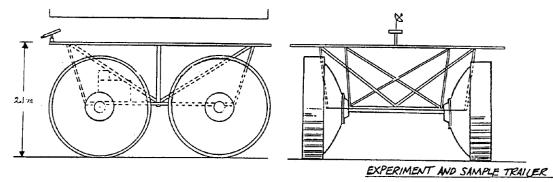


First Excavation on the Moon

# Hauling

- End dump
- Bottom dump
- Self propelled
- Trailer
- Capacity
- Mechanical properties of payload





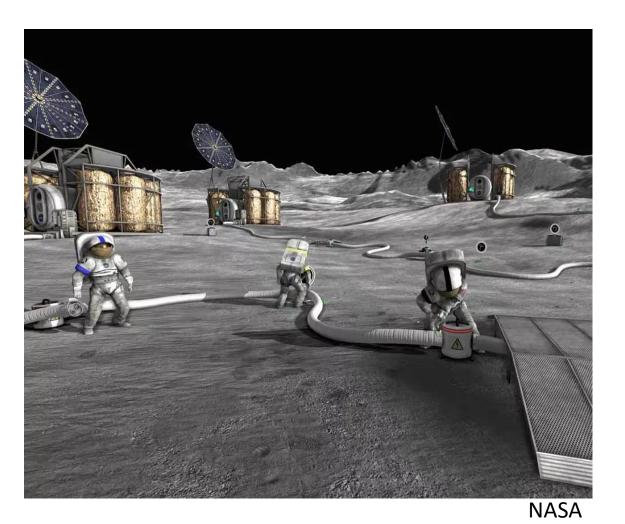
NASA Lunar Surface Construction & Assembly Equipment Study Eagle Engineering Inc, 1988



# Material handling (conveying)

- Belt conveyors
- Screw conveyors
- Pneumatic
- Ballistic
- Electrostatic



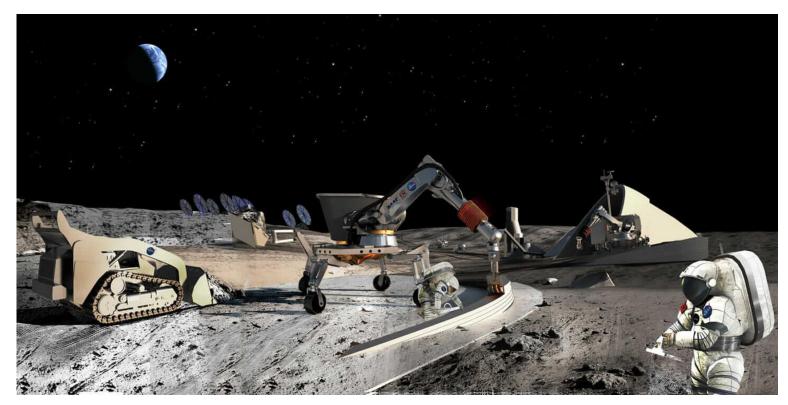




# Grading and Compacting



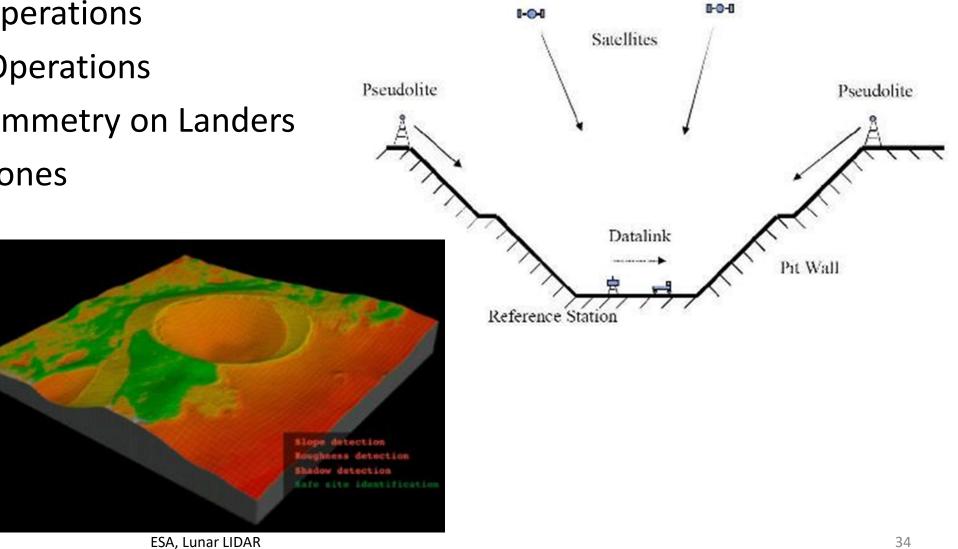
- Vibratory Rollers
- Vibratory Plates
- Blades
  - Graders
  - Dozers



NASA/ Contour Crafting Corp

# Surveying

- **Orbital Operations** •
- Surface Operations
- Photogrammetry on Landers
- **Space Drones**  $\bullet$
- LIDAR lacksquare



## **Robot Characteristics**



NASA

- Mobility
- Terramechanics
- Power Source
- Mechanical Design
- Embedded Electronics
- State Estimation
- Modeling and Control
- Navigation
- Sensors
- Perception
- Path planning
- Machine learning
- Autonomy



VIPER Mobile Prospecting Drill



ATHLETE Hexapod

#### CHARIOT with LANCE Blade

# Top Robotic challenges\*



- Object Recognition and Pose Estimation
- Fusing vision, tactile and force control for manipulation
- Achieving human-like performance for piloting vehicles
- Access to extreme terrain in zero, micro and reduced gravity
- Grappling and anchoring to asteroids and non cooperating objects
- Exceeding human-like dexterous manipulation
- Full immersion, telepresence with haptic and multi modal sensor feedback
- Understanding and expressing intent between humans and robots
- Verification of Autonomous Systems
- Supervised autonomy of force/contact tasks across time delay
- Rendezvous, proximity operations and docking in extreme conditions
- Mobile manipulation that is safe for working with and near humans \*(no specific order)

NASA Technology Area 4 Roadmap: Robotics, Tele-Robotics and Autonomous Systems (NASA, Ambrose, Wilcox et al, 2010)

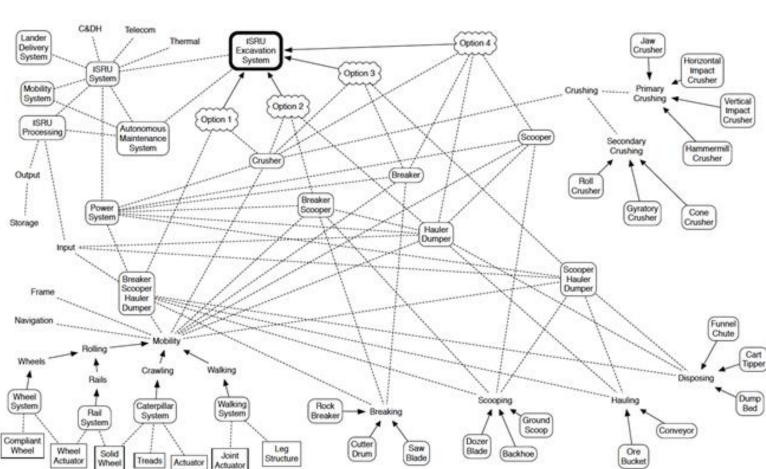
#### Power Gyratory Crusher Scooper Cone System Crusher Hauler Dumper Scooper Hauler Breaker Scooper Dumper Hauler Dumper Funnel Chute Mobility Cart Tippe Walking Crawline Disposing Dump Scooping Hauling Walking Caterpilla Rock Rail System Breaker System Ground Syster Scoop Conveyor Dozer Outle Leg Saw Blade Ore Solid Drum Backhoe Joint Structure Blade Treads Actuator Whee Actuato 37

### **Bearings**

Wheels

- Seals
- Heat rejection
- Electrical systems
- Remote operations
- Maintenance and repai
- And more....

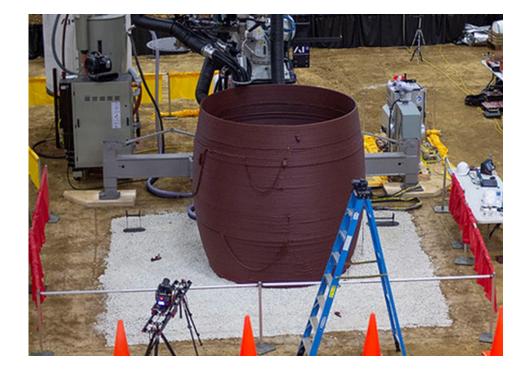
# Lunar Environment and System Challenges



## Terrestrial Example: 3D Printing of Concrete







#### Penn State University

Al Space Factory

Teams Build 3D-Printed Habitats for Moon and Mars | NASA's Centennial Challenges - YouTube



# Questions?