A Review of Extra-Terrestrial Regolith Excavation

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Introduction

- Regolith is present on many extra-terrestrial bodies, and the crushed rock material it is made of contains many of the resources that are enabling for In-Situ Resource Utilization (ISRU)
- None of these valuable ISRU activities can proceed without first acquiring the regolith granular material with some type of excavation device and method
- Regolith Excavation in reduced gravity environments is a Critical Technology and is enabling for ISRU
- Only small scale excavation for scientific sampling has been achieved on the Moon, Mars and Asteroids (kg's)
- Lunar construction will need thousands of tons of regolith excavation with payload mass and energy constraints
- How will this happen?

Regolith Resource Uses

- Science investigations
- Geology investigations
- Propellant Oxidizer (O2) Extraction from silicates
- Water Extraction (H2O) for industrial consumables
- H2/O2 propellant
- Water (ice or liquid) radiation shielding
- Human life support consumables
- Plant growth consumables
- Fuel cell consumables
- Other volatiles extraction (He3, H2, CH4, CO, etc.)
- Metals extraction for manufacturing
- Mineral glass fibers for manufacturing
- Regolith bulk aggregate (Berms, Contours, sandbags)
- Radiation bulk shielding for human health: Solar Particle Events (SPE) & Galactic Cosmic Rays (GCR)
- Nuclear power plant bulk regolith radiation shielding
- Construction materials feedstocks (Concrete, bricks, pavers, etc.)
- Industrial processes (solvents, reactant, etc.)
- Solar photo voltaic arrays manufacturing for electrical power
- Thermal wadi's for heat energy storage

ISRU Workflow

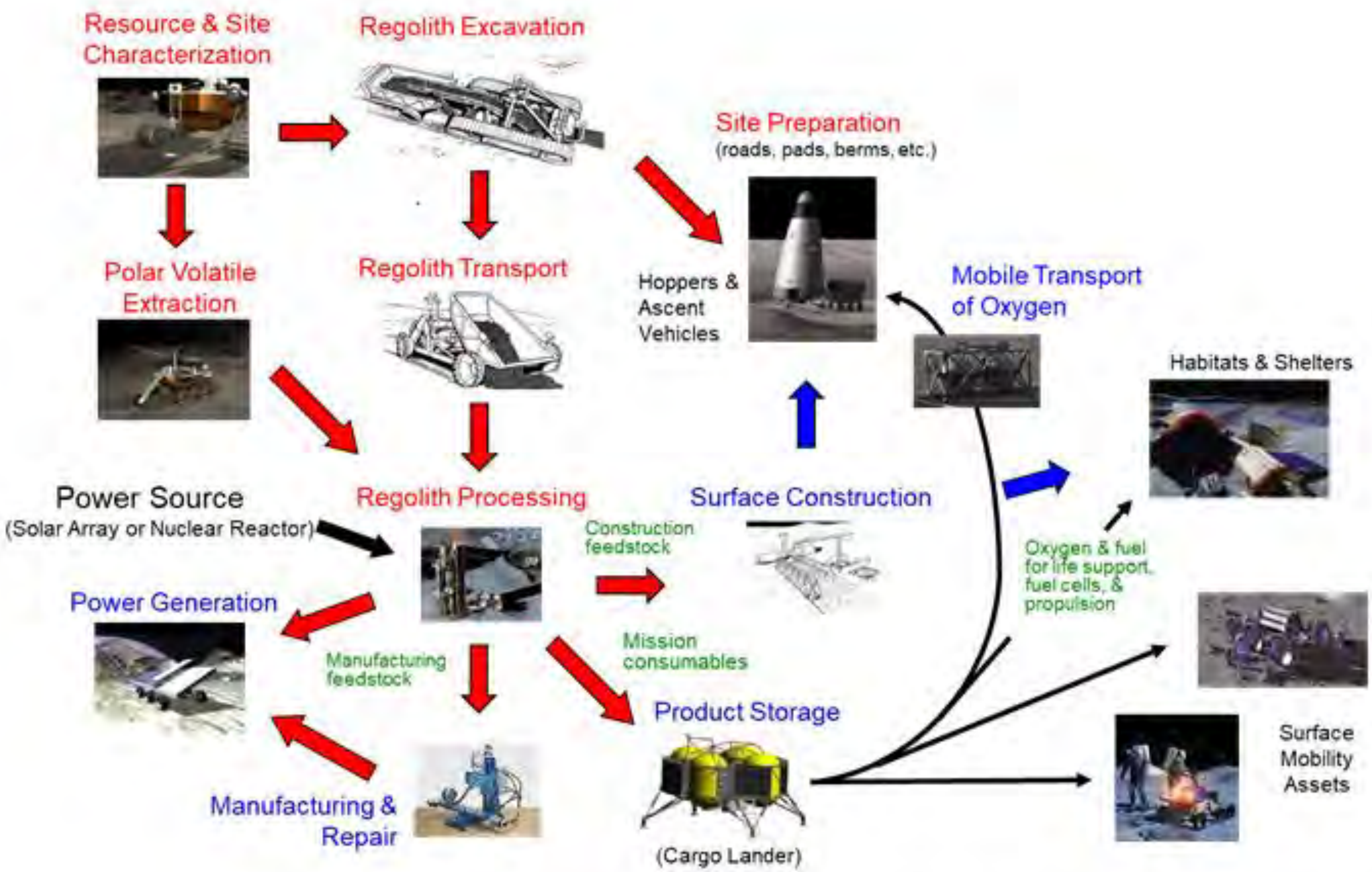

Figure 1. ISRU Workflow showing the Role of Regolith (G. Sanders, NASA)

Terrestrial Autonomy

Autonomy has been widely embraced in the Mining Industry on Earth:

- Increased safety and improved working conditions for personnel
- Improved utilization by allowing continuous operation during shift changes
- Improved productivity through real-time monitoring and control of production loading and hauling processes
- Improved draw control through accurate execution of the production plan and collection of production data
- Lower maintenance costs through smooth operation of equipment and reduced damage
- Remote tele-operation of equipment in extreme environments
- Deeper mining operations with automated equipment
- Lower operation costs through reduced operating labor
- Reduced transportation and logistics costs for personnel at remote locations
- Control of multiple machines by one tele-operator human supervisor

Differences in Space

- Lunar excavation requirements are different than terrestrial excavation
- Launch mass and volume limitations
- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Encountering unknown sub surface rock obstacles
- Unknown water ice / regolith composition and deep digging
- Operating in the dark cold traps of permanently shadowed craters
- Unknown soil mechanics in polar regions
- Extreme access and mobility
- Slopes >35 degrees
- Extended nighttime operation and power storage
- Electrical power storage with high power density
- Thermal management in temperature extremes
- Robust "line of sight" RF or laser communications
- Long life and reliability
- Long term maintenance & life cycle

NASA Prototypes

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Table 1. History of NASA lunar excavator prototypes

Dates	Excavator Prototype
1989-91	NASA Space Exploration Initiative (SEI) Eagle Engineering inc. Concept Studies
2001-2011	Colorado School of Mines (Dr. Mike Duke research initiative)
2007	NASA GRC Cratos Scraper Excavator
2007-2009	NASA Centennial Challenge for Lunar Excavation
2008	Lockheed Martin Bucket Drum - Mauna Kea, Hawai'i NASA Field Tests
2008-2012	Canadian Space Agency, Mauna Kea, Hawai'i ISRU Tests (NORCAT# / Ontario, Drive & Gear (ODG) inc./Neptec inc. Juno Rover)
2009-2010	NASA KSC LANCE* Dozer blade & JSC Chariot Mobility Platform
2009-2011	JPL ATHLETEŦ hexapod robot with bucket implement
2009-2010	Caterpillar inc. Multi Terrain Loader Tele-Operations at JSC
2009-2010	SysRand inc. Moonraker bucket chain excavation implement
2009-2015	Honeybee inc. Pneumatic PlanetVac Micro Excavator
2010-2012	NASA JSC Space Exploration Vehicle (SEV) & LANCE
2010-2022	NASA Lunabotics Robotic Mining Competition
2010-2012	Honeybee inc. Planetary Volatile EXtractor (PVEX)
2010-2012	Astrobotic inc. Polaris Bucket transverse bucket wheel excavator
2013-2019	NASA JSC/GRC/KSC Centaur+ APEX^ + Badger bucket
2010-2019	NASA KSC Swamp Works RASSORε
2019-2022	NASA KSC Swamp Works ISRU Pilot Excavator (IPEx)

Northern Centre for Advanced Technology (NORCAT) now Deltion, inc.
* Lunar Attachment Node for Construction Excavation (LANCE)
Ŧ All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE)
^ Advanced Planetary Excavator (APEX)
ε Regolith Advanced Surface Systems Operations Robot (RASSOR)

Lunabotics Competition

The annual NASA Robotic Mining Completion (RMC): Lunabotics competition is a full-on engineering exercise where students receive practical experience in the full engineering lifecycle process from concept development, design, robot fabrication, hands on competition to system closeout.

- **Robot Controlled Remotely or Autonomously**
- **Visual and Auditory Isolation from Operator**
- **Excavates Black Point 1 (BP-1) Lunar Basalt Regolith Simulant**
- **Weight Limit - 80 kg**
- **Dimension Limits - 1.5 m length x 0.75 m width x 0.75 m height**
- **Designed, Built and Tested by University Student Teams**
- **Uses NASA systems engineering methods**
- **Over 55 US universities attend each year at Kennedy Space Center**

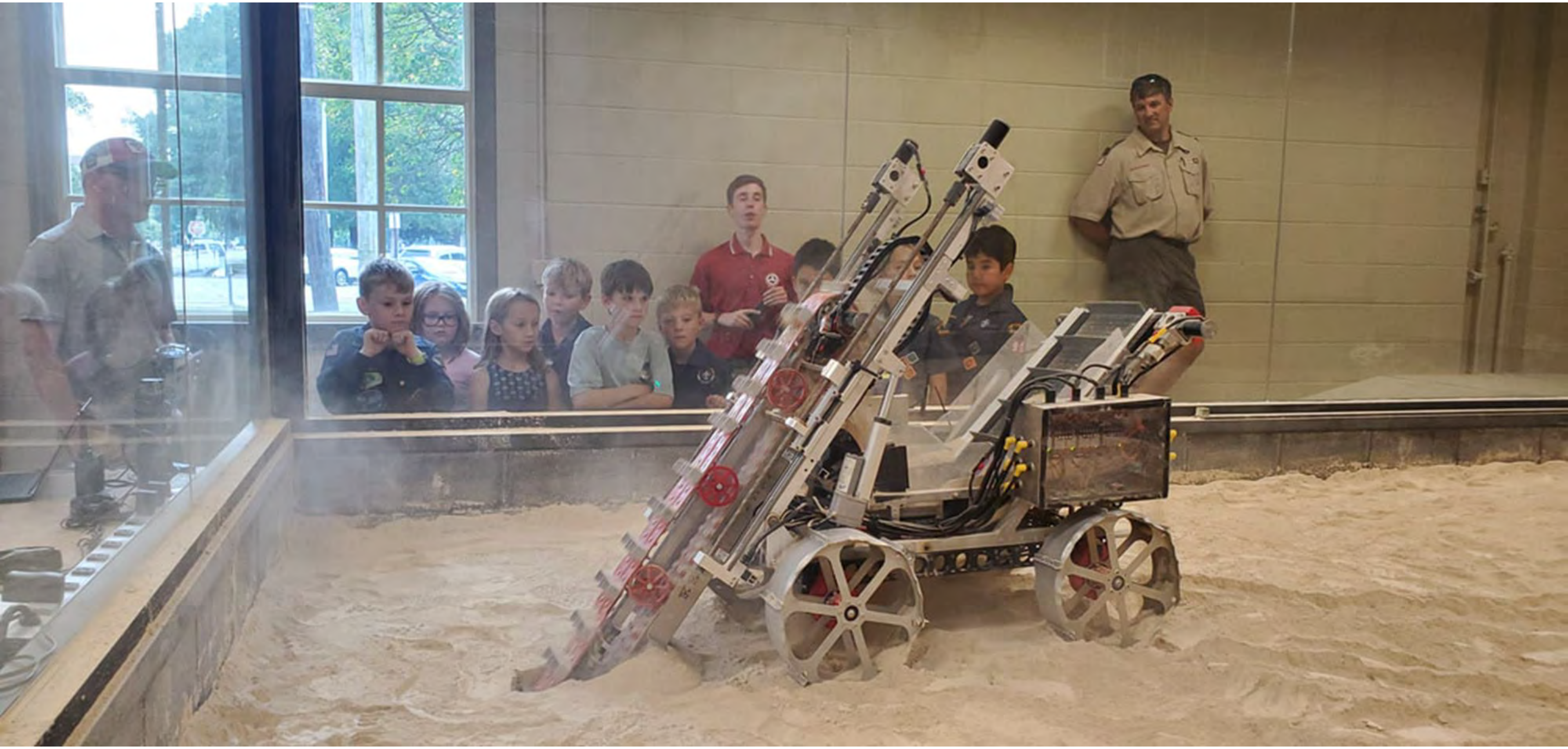
Lunabotics Competition

A Positive Experience with Personal Growth

https://www.nasa.gov/offices/education/centers/kennedy/technology/nasarmc.html

Many Lunabotics Alumni are working in the space industry today

Lunabotics Competition



U. Alabama: Outreach to the Next Generation

Popularity of Designs

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Not necessarily the best lunar excavator designs but the most popular:

Table 2. Most popular excavation and regolith transportation mechanisms

# sys	regolith excavation mechanism	# sys	regolith transportation mechanism
101	bucket ladder	103	bucketladder
37	front end loader	40	in scoop
29	bucket belt	22	conveyor belt
27	bucketwheel	21	bucketbelt
17	bucket drum	15	auger
15	snow blower (auger or brush)	11	Over shoulder dump into hopper
12	auger	8	chute for guiding regolith
8	backhoe	7	bucketdrum
8	bulldozer	7	drum
8	scraper	6	bucketwheel
7	large single scoop	6	impeller
4	dual auger	4	bucket rim
4	dual bucket wheel	4	bucketwheel discharge through bottom
4	rotating brush	4	in bucket
3	excavating wheels	4	rotate scoop to slide simulant in hopper
2	claw/gripper scoop	3	throw from impeller
2	dual bucketladder	2	bucketwheel with side discharge
2	dual counter rotating bucketdrums	2	paddle conveyor
2	large bulldozer scoop	2	raising scraper with chute
2	paddle conveyor	2	thrown from brush up ramp

Lunabotics Competition

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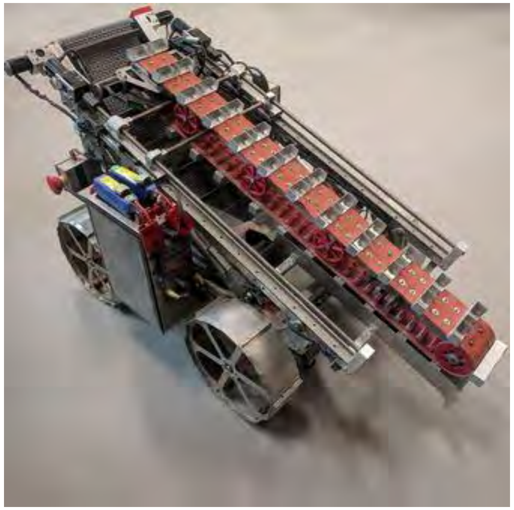
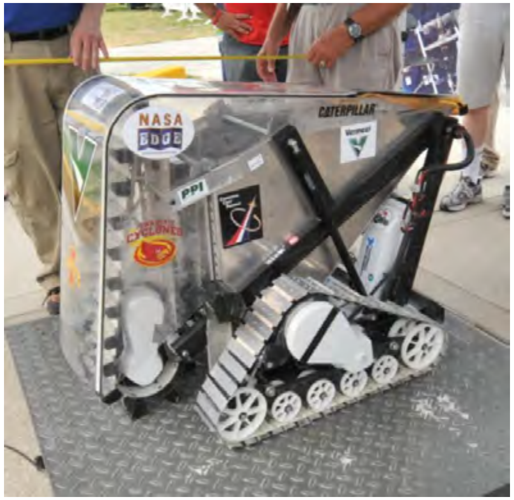
Examples of the most popular regolith excavation and transportation mechanisms: Bucket Ladders



University of Alabama



Iowa State University

Vanderbilt University

Lunabotics Competition

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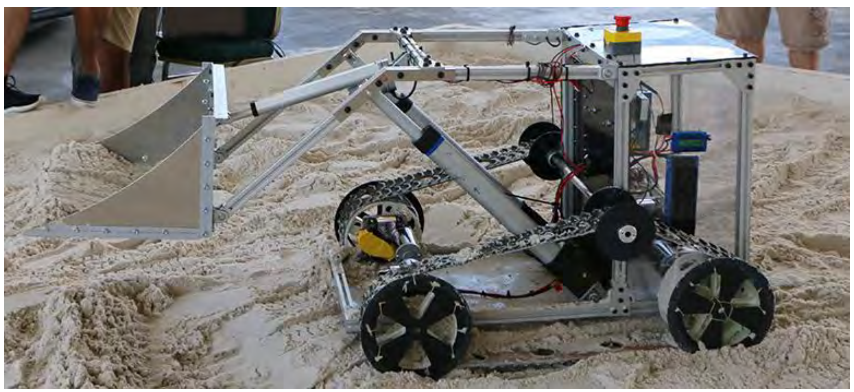
Examples of the most popular regolith excavation and transportation mechanisms: Front End Bucket Loader

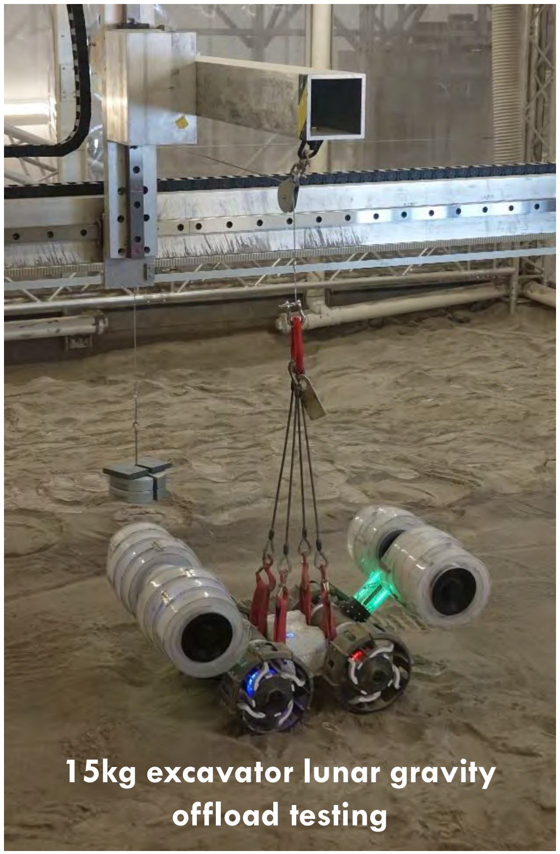


Illinois Institute of Technology

University of Utah

ISRU Pilot Excavator

Dual Bucket Drum Excavator Prototypes:



15kg excavator lunar gravity offload testing

15kg and 65kg excavator size comparison

This project will develop the ISRU Pilot Excavator: a 30 kg-class excavator for demonstration on a CLPS flight.

ISRU Pilot Excavator Overview

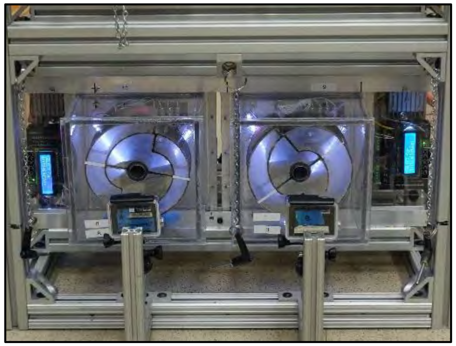
Primary Goal

Reduce risk of excavation for ISRU pilot plant demonstration

- **Partnership between KSC, JSC, JPL, and Astrobotic**
- **30kg bucket drum excavator**
- **Astrobotic CubeRover avionics and software**
- **Enter TRL 4 – Exit TRL 6**
- **11 day end-to-end ground demonstration**

Quantitative Impact

- Traverse total of **150km** in Lunar environment (3x current SOA)
- Traffic over same terrain **700x** (140x current SOA)
- Move a total of **10t (metric tons)** of regolith **100 meters** over **11 days** (200x current SOA)



Summary

- Regolith excavation and transportation form the basis of regolith mining and also have critical applications in site preparation and construction activities.
- Since 2001, many robotic excavator prototypes for extra-terrestrial uses have been attempted. However, the fidelity of the testing environments remains at a <u>low technology readiness level (TRL) of 3 or 4</u>
- The <u>reliability</u> of the proposed designs <u>has not been demonstrated</u>.
- Since these excavation robots will be operating in a much harsher and regolith interactive manner than current Mars and Moon scientific rovers, <u>new ways</u> of dealing with regolith dust, rocks, cryogenic icy regolith, extreme terrain, very cold operating temperatures, lunar nights, shadowed regions and more <u>must be developed</u>, before the NASA Artemis program, and others, can successfully use ISRU and perform in-situ construction.