A Review of Extra-Terrestrial Regolith Excavation Concepts and Prototypes

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Introduction: Space Policy Directive 1

- Current NASA policy aims to use space resources on the Moon to ensure a sustainable future

- The resources on the Moon are, to a large degree, contained in the energy from the Sun, minerals and volatiles in the lunar regolith

- In order to acquire the regolith, robotic excavation technologies will be necessary and these robotic excavators will be very different from terrestrial excavators

- Very different and harsh environment on the Moon and there are severe mass and volume limitations that are imposed by the space transportation launch vehicles

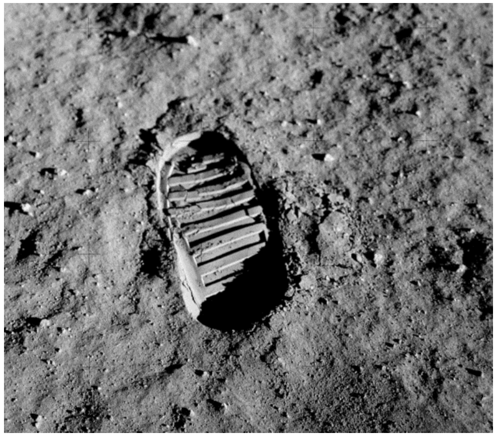
Directive Calls for Human Expansion Across Solar System

Representatives of Congress and the National Space Council joined President Donald J. Trump, Apollo astronaut Jack Schmitt and current NASA astronaut Peggy Whitson Monday, Dec. 11, 2017, for the president's signing of Space Policy Directive 1, a change in national space policy that provides for a U.S.-led, integrated program with private sector partners for a human return to the Moon, followed by missions to Mars and beyond. ***Credits: NASA/Aubrey Gemignani***

https://www.nasa.gov/press-release/new-space-policy-directive-calls-for-human-expansion-across-solar-system

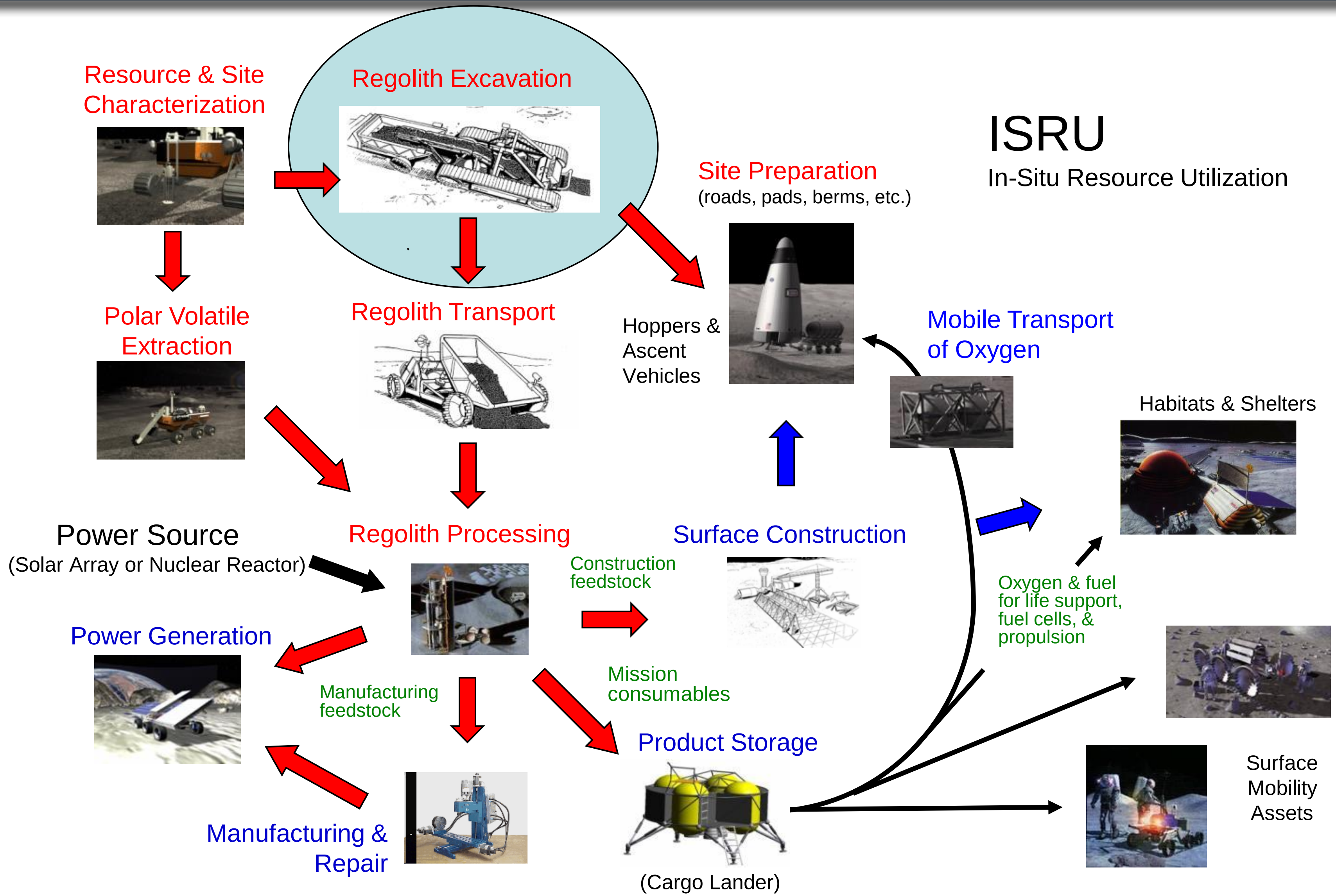
Some Uses of Regolith on the Moon

- Science investigations
- Geology investigations
- Propellant Oxidizer (O2) Extraction from silicates
- Water Extraction
  - H2/O2 propellant
  - Water (ice or liquid) radiation shielding
  - Human consumable
  - Plant Growth
  - 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, sand bags)
- Radiation Bulk Shielding for Human Health
  - SPE & GCR
  - Nuclear power plant shielding
- Construction materials (Concrete, bricks, pavers, etc.)
- Industrial processes (solvent, reactant, et.c.)
- Solar photo voltaic arrays manufacturing for electrical power
- Thermal Wadi’s for heat energy storage



NASA Images

Lunar Resources Work Flow



G. Sanders, NASA ISRU

Terrestrial Robotic Mining

- 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

Top Robotic Technical 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

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

Top Space Mining Technical Challenges

- Lunar excavation is 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 sub surface rock obstacles
- Unknown water ice / regolith composition and deep digging
- Operating in the dark cold traps of perennially shadowed craters
- Unknown soil mechanics in polar regions
- Extreme access and mobility
- Slopes >35 degrees
- Extended night time 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

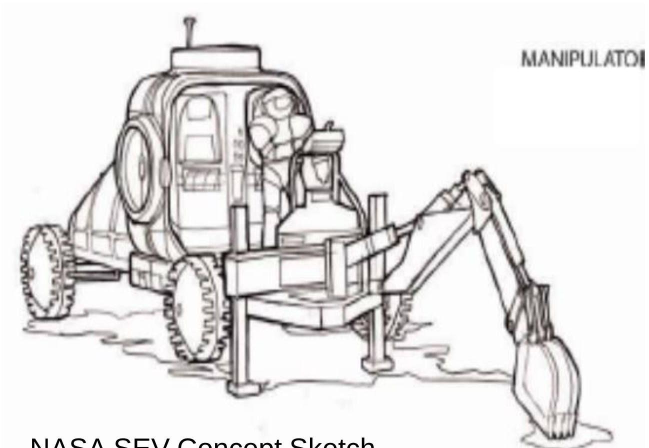
Credit: Caterpillar, inc

Credit: Lockheed Martin, inc.

History of Extra-terrestrial Regolith Excavators

- 1900 - 1980's: Early Visionary Studies (Von Braun, et.c.)
- 1988: Eagle Engineering Reports
- 1989-91 NASA Space Exploration Initiative
- 2001-2011 Colorado School of Mines (Mike Duke initiative)
- 2008 Lockheed Martin Bucket Drum- Mauna Kea NASA Field Tests
- 2007 NASA GRC Cratos
- 2007-2009 NASA Centennial Challenge
- 2009 -2010 NASA KSC LANCE Dozer blade & JSC Chariot
- 2009-2011 JPL ATHLETE with bucket implement
- 2009 -2010 Caterpillar Multi Terrain Loader Tele-Operations at JSC
- 2009-2010 SysRand Moonraker
- 2009-2015 Honeybee Pneumatic PlanetVac Micro Excavator
- 2010-2012 NASA JSC Space Exploration Vehicle (SEV) & LANCE
- 2010-2012 CSA NORCAT / Juno Load, Haul Dump
- 2010-2019 NASA Lunabotics Robotic Mining Competition
- 2010-2012 Honeybee Planetary Volatile EXtractor (PVEX)
- 2010-2012 Astrobotic Polaris
- 2010-2019 NASA KSC Swamp Works RASSOR
- 2013-2019 NASA JSC/GRC/KSC Centaur+ APEX + Badger bucket

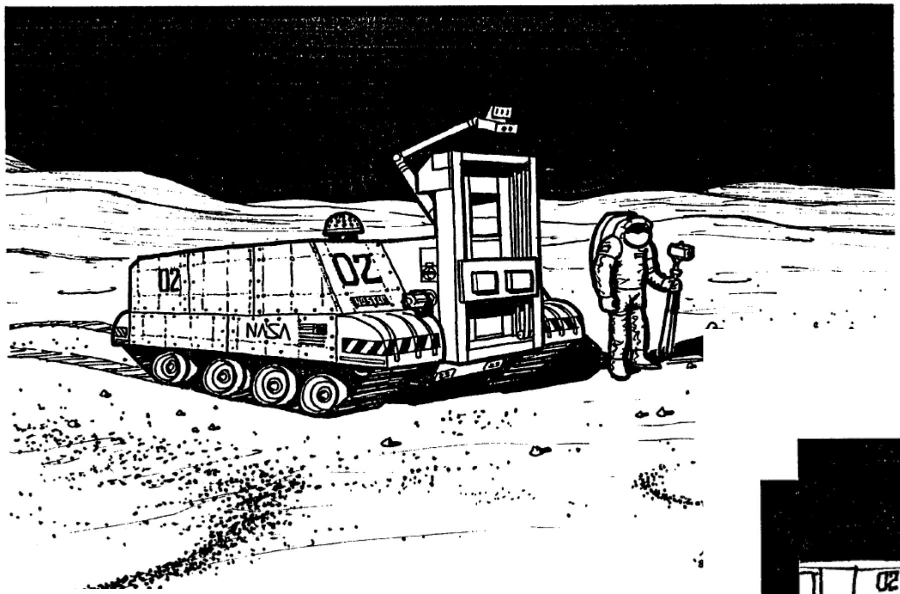
Mike Duke/ Colorado School of Mines Bucket Wheel Excavator



NASA SEV Concept Sketch

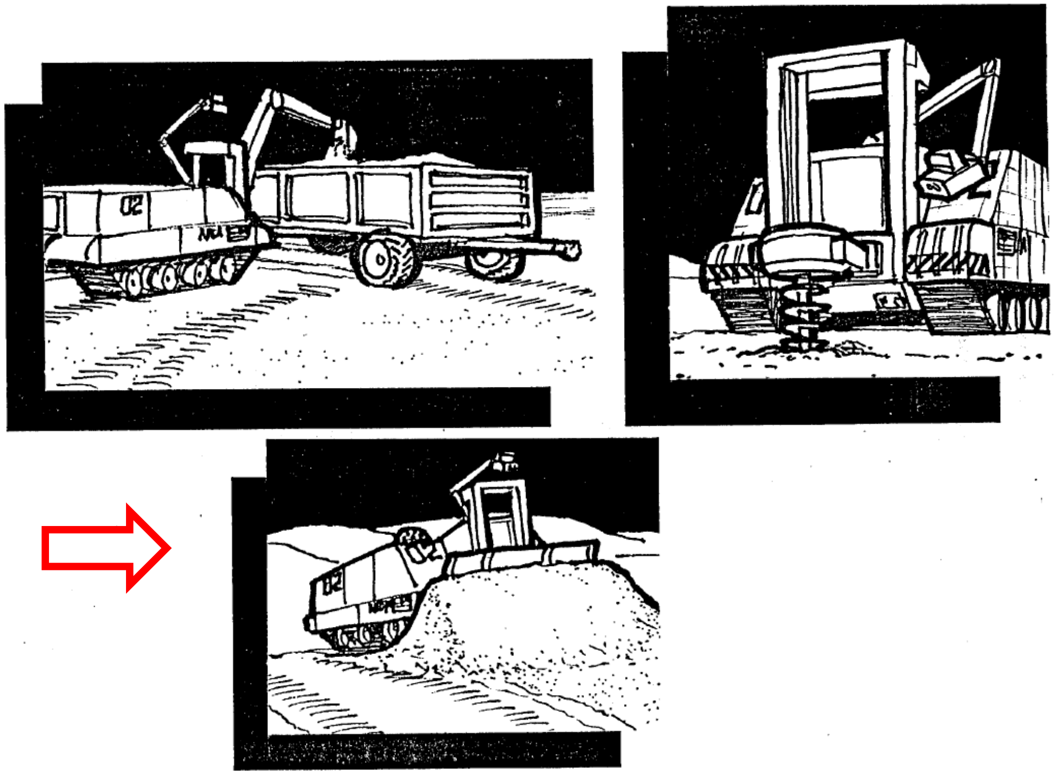
NASA / Eagle Engineering Studies 1988

Figure 5-6. Lunar Prime Mover (Shown Without Attachments)



Prime Mover

Figure 5-7. Typical Prime Mover Operations: Filling Trailer, Bulldozing, Drilling



Attachment Implements

NASA Chariot LANCE Tractor Dozer
2009-2010

NASA JSC / KSC

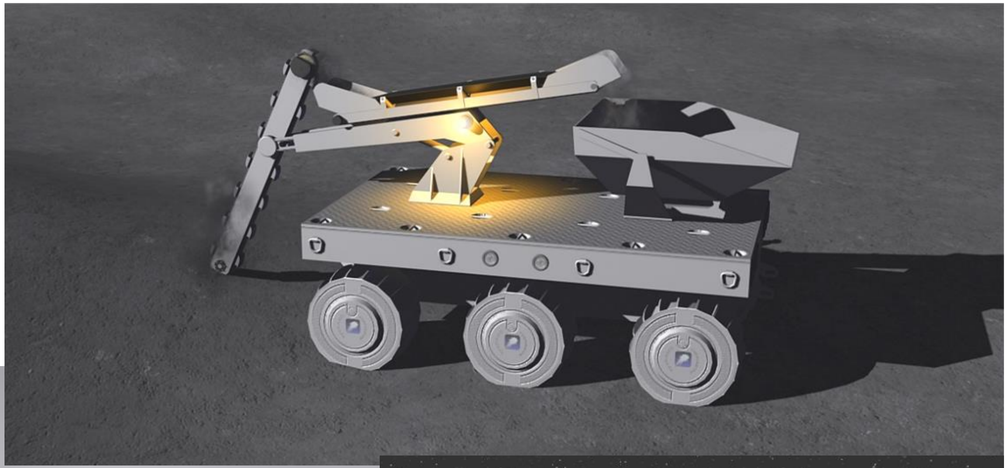
NASA Images

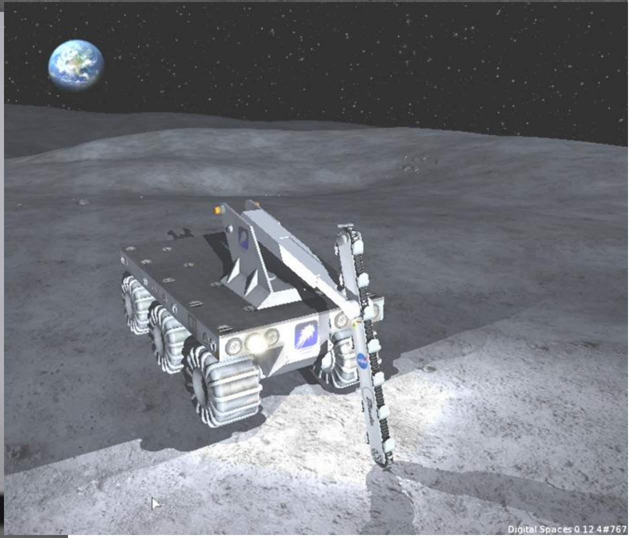
Moonraker Excavator
2009-2010

SysRand NASA SBIR

Multi-Purpose
Excavation Demonstrator

(MPED)





SysRand / NASA Images

Examples of RMC Regolith Excavator Student Prototypes 2010-2019

Lunabotics Robotic Mining Competition (RMC) Excavators:
Over 500 university prototypes built and tested in 10 years
of annual senior design project competitions

NASA Images

Example: Taxonomy of RMC Regolith Excavators for Space
(Update in work by Mueller and van Susante via SSERVI)

Regolith Excavation Mechanism	# of machines employing excavation mechanism	Lunabotics 2010/11
Bucket ladder (two chains)	29	10
Bucket belt	10	6
Front End Loader	10	14
Scraper	8	8
Auger plus conveyor belt / impeller	4	3
Backhoe	4	0
Bucket ladder (one chain)	4	1
Bucket wheel	4	2
Bucket drum	3	4
Claw / gripper scoop	2	0
Drums with metal plates or brush (street sweeper)	2	1
Bucket ladder (four chains)	1	0
Magnetic wheels with scraper	1	0
Rotating tube/scoops entrance	1	1
Vertical auger	1	0
Rotating Scoop		1

Mueller, Robert P., and Paul J. Van Susante. "A Review of Extra-Terrestrial Mining Robot Concepts." *Earth and Space 2012: Engineering, Science, Construction, and Operations in Challenging Environments*. 2012. 295-314.

Polaris Excavator
2010-2012

https://hackaday.com/2017/12/12/living-on-the-moon-the-challenges/astrobotics_polaris_test_vehicle/

Astrobotic NASA SBIR

https://archive.triblive.com/business/local-stories/strip-district-startup-astrobotic-works-on-rover-capable-of-landing-on-moon/

LHD Excavator
2010-2012

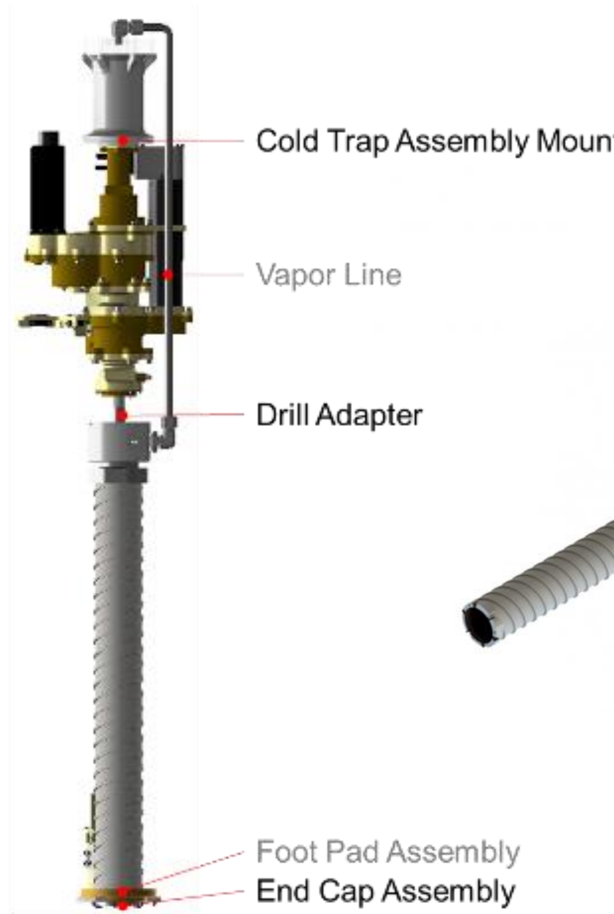
Canadian Space Agency, 2010 Mauna Kea NASA ISRU Tests (NORCAT & Juno NEPTEC Rover)

Load Haul Dump (LHD) Excavator & Dozer implements

Canadian Space Agency Images

PVEX Volatiles Extraction
2010-2019

Honeybee Robotics NASA SBIR
Planetary Volatile Extractor (PVEx)-Drill



Honeybee Robotics, inc. Images

APEX Excavator
2013-2019

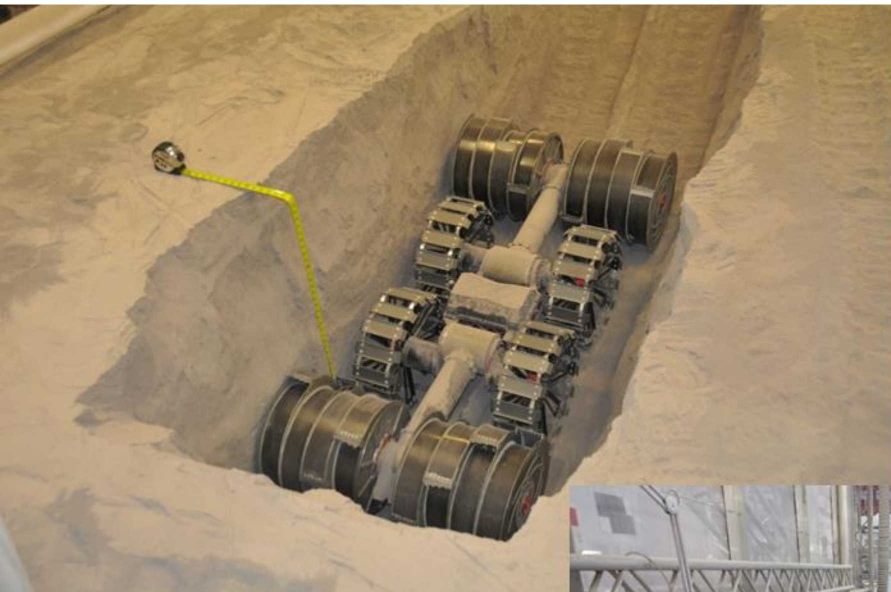
NASA GRC Excavator Arm
NASA KSC Badger Percussive Bucket
NASA JSC Centaur Mobility Platform

NASA Image

RASSOR 2.0 Excavator
2010-2019

NASA KSC Swamp Works
Regolith Advanced Surface Systems Operations Robot (RASSOR 2.0)

Capable of deep trenching > 1 m for volatiles mining and construction



NASA Images

Conclusions

- There are ***vast amounts of resources*** **in the solar system that will be useful to humans in space and possibly on Earth**
- **None of these resources can be exploited without the** ***first necessary step of extra-terrestrial mining***
- **The necessary technologies for tele-robotic and autonomous mining** ***have not matured sufficiently yet***
- **The current state of technology was assessed for terrestrial and extra-terrestrial mining and a taxonomy of robotic space mining mechanisms was presented which was based on current existing prototypes**
- **Terrestrial and extra-terrestrial mining methods and technologies are on the cusp of** ***massive changes towards automation and autonomy for economic and safety reasons***
- **It is highly likely that these industries will benefit from** ***mutual co-operation and technology transfer***