National Aeronautics and Space Administration

# Evolution of Extra-Terrestrial Mining Robot Concepts

## SRR/PTMSS
## Golden, Colorado
## June 4-7, 2012


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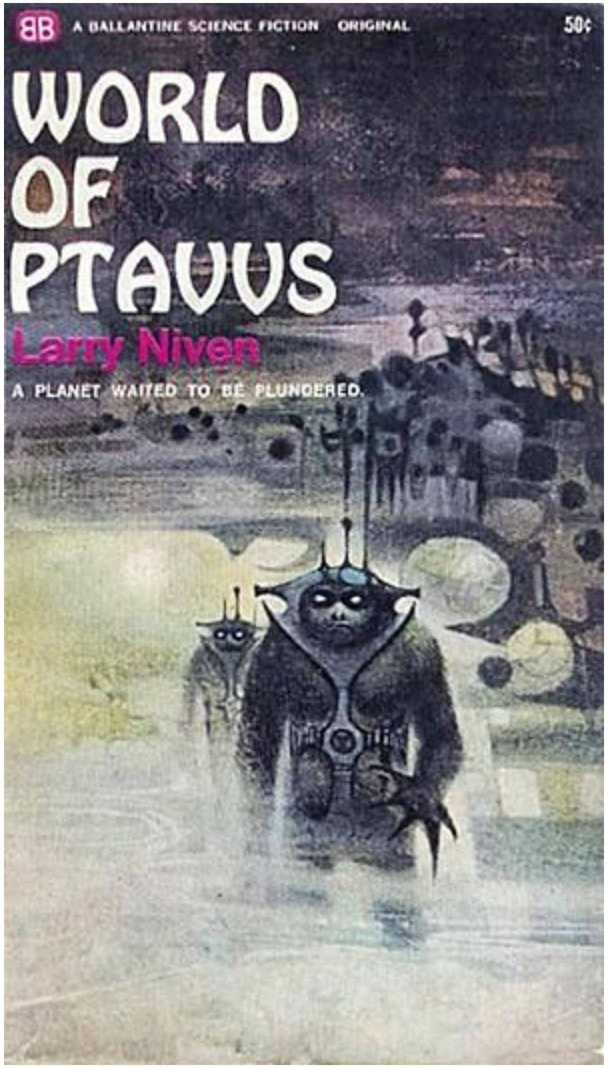
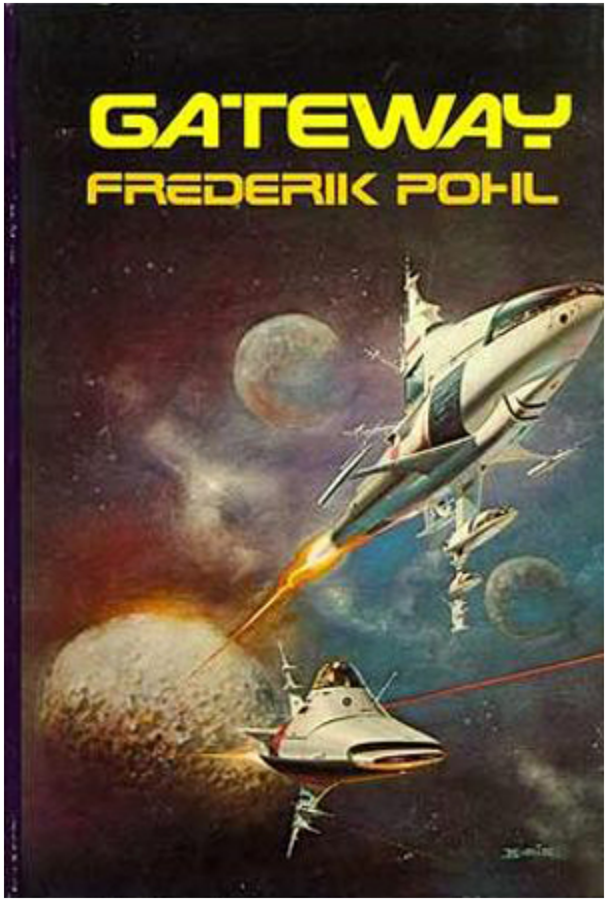
# Space Mining is Part of Our Popular Culture



# Asteroid Mining in Science Fiction

- One of the earliest works to explore this idea is the 1898 American space opera, the Thomas Edison-endorsed "Edison's Conquest of Mars." Written by astronomer-fiction author Garrett P. Serviss, the book, which also stars Edison as the hero, follows a fleet of spaceships that run into huge-headed Martians mining asteroids for gold. The book was a watershed title for the sci-fi genre, introducing tropes like asteroid mining, as well as alien abductions, disintegrator laser beams and more.

- Hugo-winning sci-fi writer Larry Niven used ore-rich asteroids to populate the universe in his famed collection of novels, "Known Space."

- Isaac Asimov's 1944 short story "Catch That Rabbit," part of his "Robot" series, uses an asteroid mining station as the setting. (Drama ensues when Dave the robot malfunctions and ceases his mining duties.) Asimov's peer, Robert Heinlein, also depicted asteroids as vessels for precious commodities.

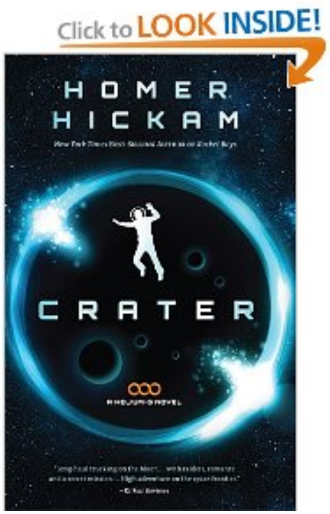
- In his 1952 novel "The Rolling Stones," Heinlein gave the asteroid belt the Gold Rush treatment. Galactic prospectors ventured from far and wide to find the space rocks, which brimmed with radioactive ores that promised fabulous wealth.

- Stripping near-Earth objects has also been used as a plot device in TV and film, like in the 2004 "Battlestar Galactica" episode "The Hand of God." The characters discover Cylons mining an asteroid that's ripe with tylium, a fuel source.

- In Yoshiyuki Tomino's anime and novel franchise "Gundam," asteroid mining is mentioned often: For example, the 1985 anime "Mobile Suit Zeta Gundam"features Axis, an asteroid mining colony located in the asteroid belt, that becomes a stronghold for the Republic of Zeon.

- British sci-fi sitcom "Red Dwarf" saw the eponymous mining cargo ship transport ore (presumably extracted from asteroids), only for the journey to go awry.

# He$^3$ Moon Mining in Science Fiction





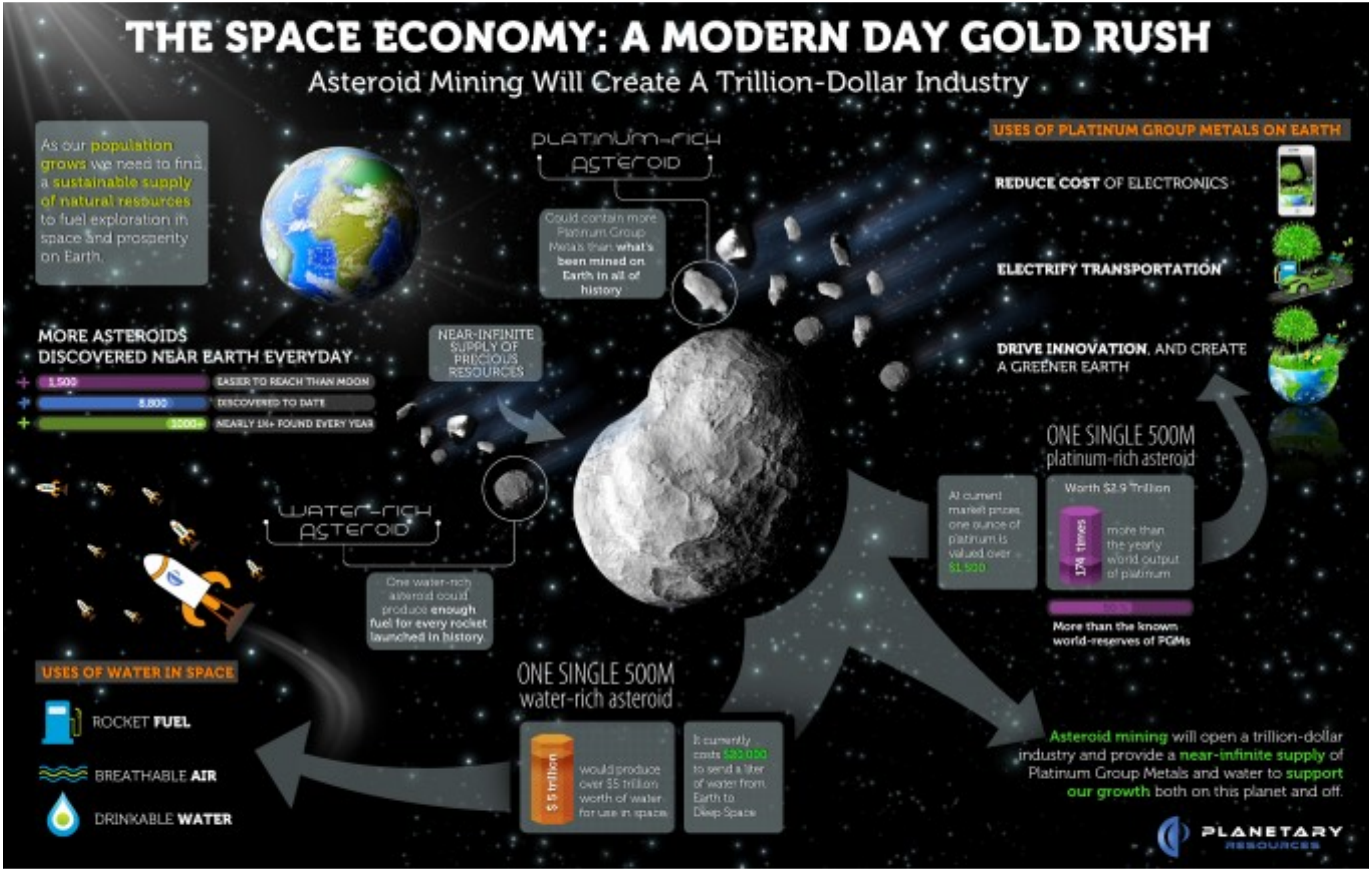
*"Crater shows what it would be like to live on the Moon: to work there, to struggle and to triumph. A fine piece of work."*

*-Ben Bova, author of Leviathans of Jupiter*

Helium-3 was harvested in the 2009 science fiction movie *Moon*, by the story's protagonist Sam Bell, the occupant of a mining station on the far side of the Moon.

Helium-3 was harvested in the 2012 science fiction movie *Iron Sky* by Nazis who had fled to the far side of the Moon at the end of World War II.

# Recent New Space Mining Private Ventures



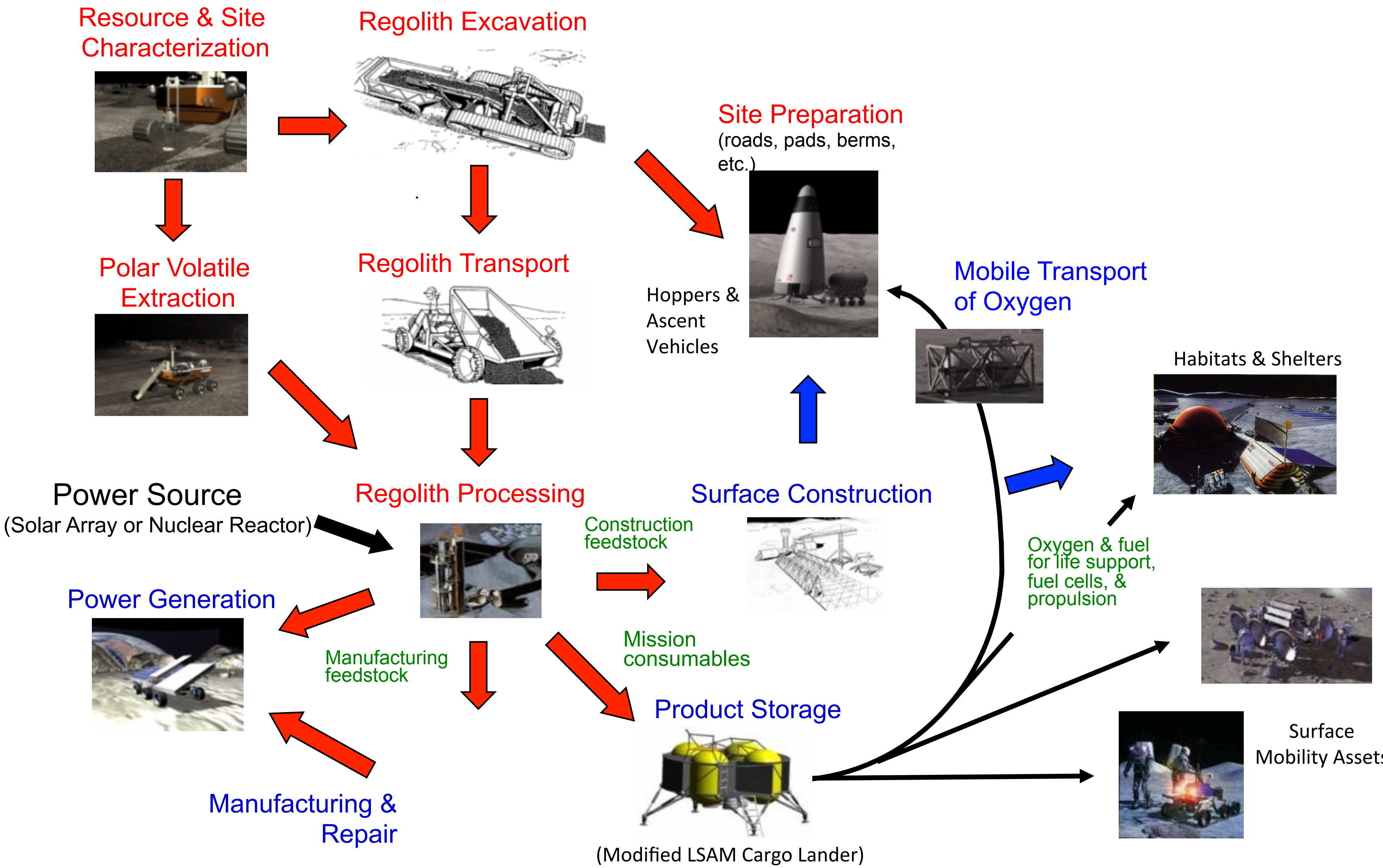
# In-Situ Resource Utilization (ISRU)

**When considering all aspects of ISRU, there are 5 main areas that are relevant to human lunar and Mars exploration (Sanders et al, 2010):**

1. **Resource characterization and mapping for planning and science**
2. **In-situ production of mission critical consumables and propellants for crew, power, and transportation**
3. **Civil engineering and construction for hardware and crew protection and infrastructure growth**
4. **In-situ energy production and storage**
5. **In-situ manufacturing, repair, and reuse**

**Areas 1, 2,3 and 5 require Regolith Operations and/or Regolith Mining**

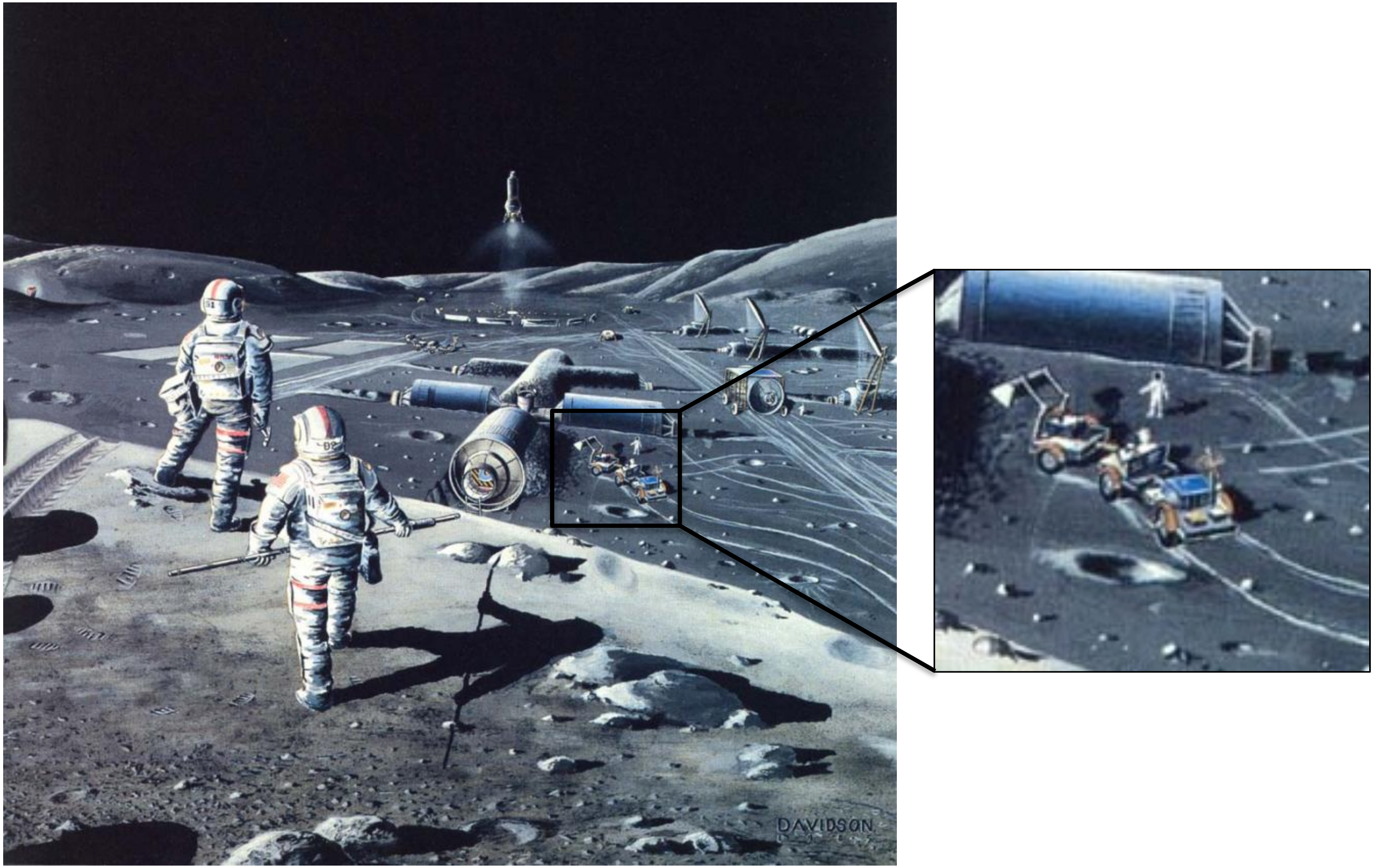
# In-Situ Resource Utilization (ISRU)



# 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

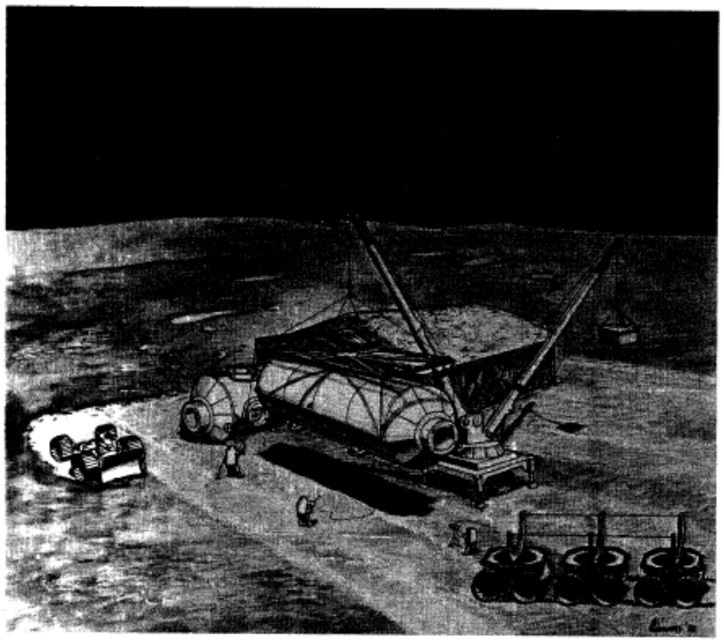
# Early Visionary Studies 1900- 1980's



# Eagle Engineering Reports -1988

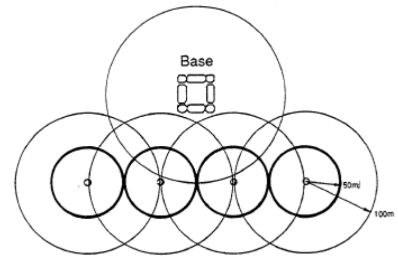
LBSS

## *Lunar Surface Construction & Assembly Equipment Study*

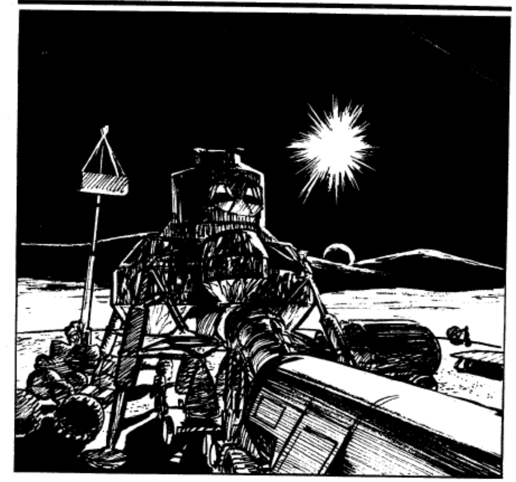


EEI Report Number 88-194
NASA Contract Number NAS 9-17878
1 September, 1988

EAGLE




## *Lunar Base Launch and Landing Facility Conceptual Design*

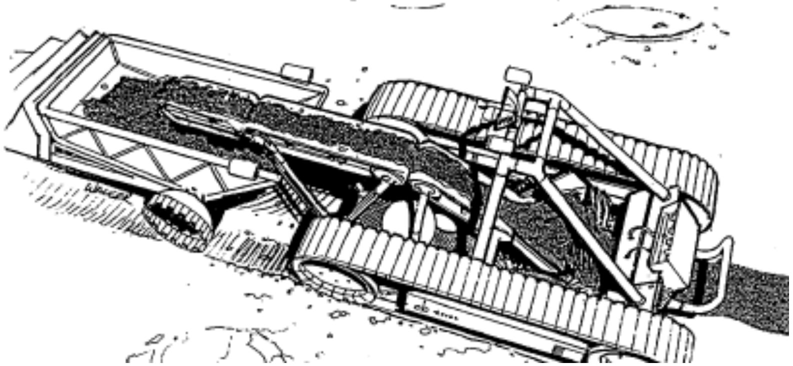


NASA Contract Number NAS9-17878
EEI Report 88-178

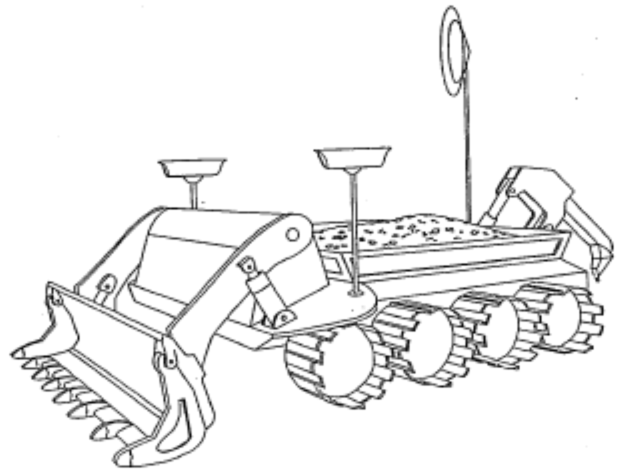
EAGLE

# Space Exploration Initiative: 1989-1991
# Planet Surface Systems Office – NASA JSC

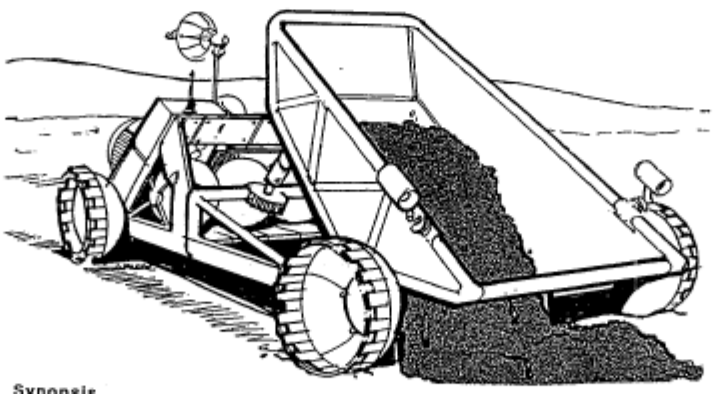
Mining Excavator/Loader, Lunar



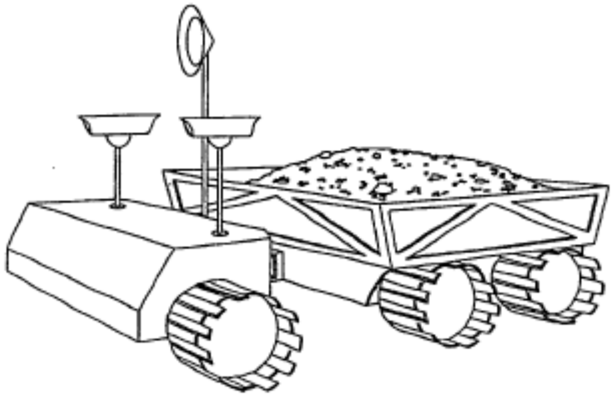
Ripper/Excavator/Loader



Regolith Hauler, Lunar



Articulated Hauler

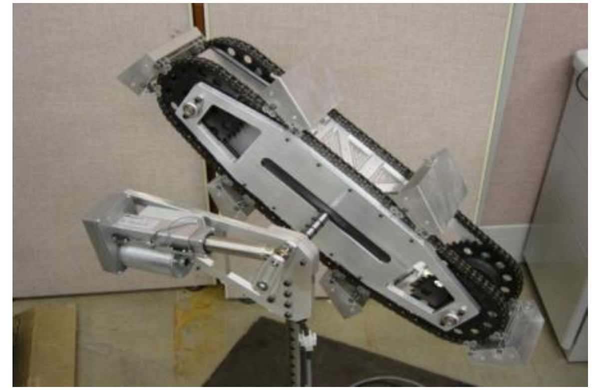


# Lunar Underground -1990's

Looking for data!

# Colorado School of Mines 2001 - 2011


Mike Duke Project



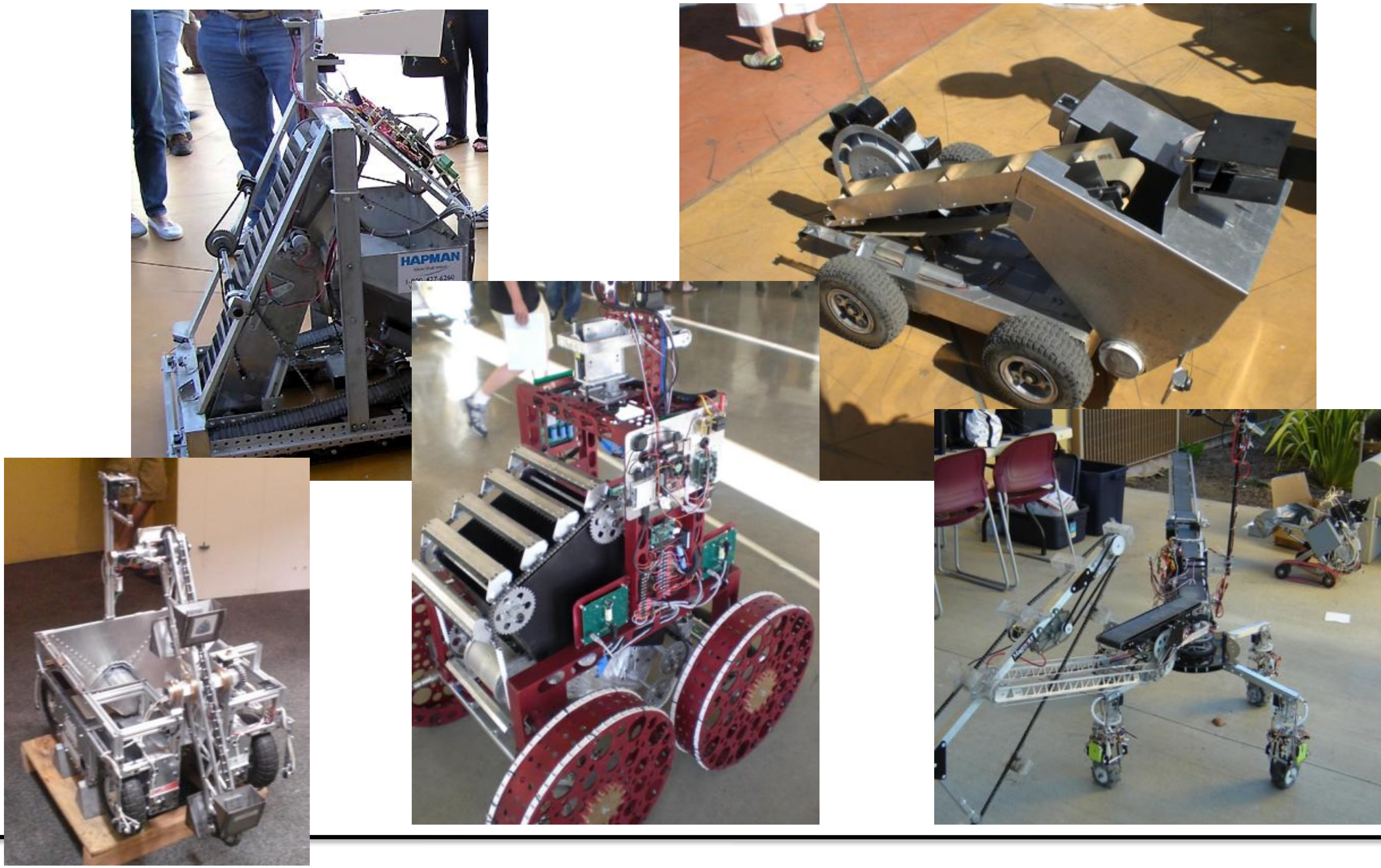
Paul van Susante Projects


SysRand NASA SBIR

# Lockheed Martin Bucket Drum - 2008


**Lockheed Martin Corp. Bucket Drum Excavator (BDE) prototype.**

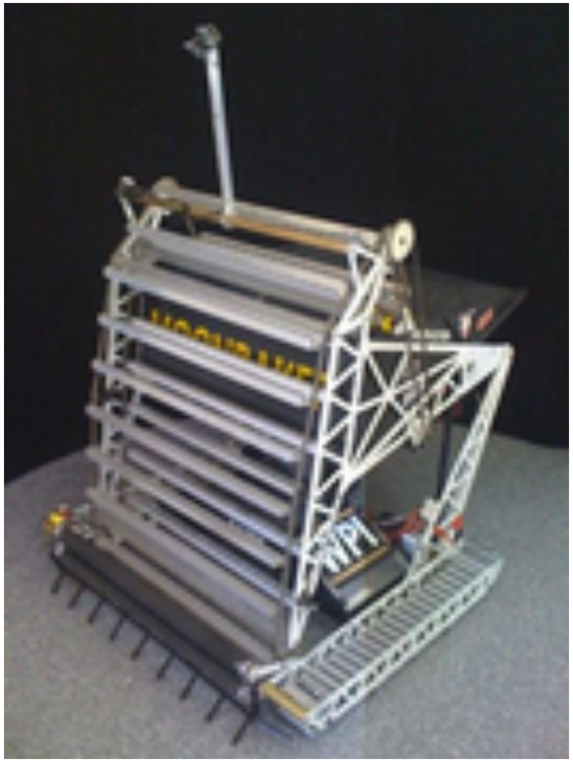
# NASA Centennial Challenge
# Regolith Excavation Competition 2007-2009



# NASA Centennial Challenge
# Regolith Excavation Competition Winner 2009

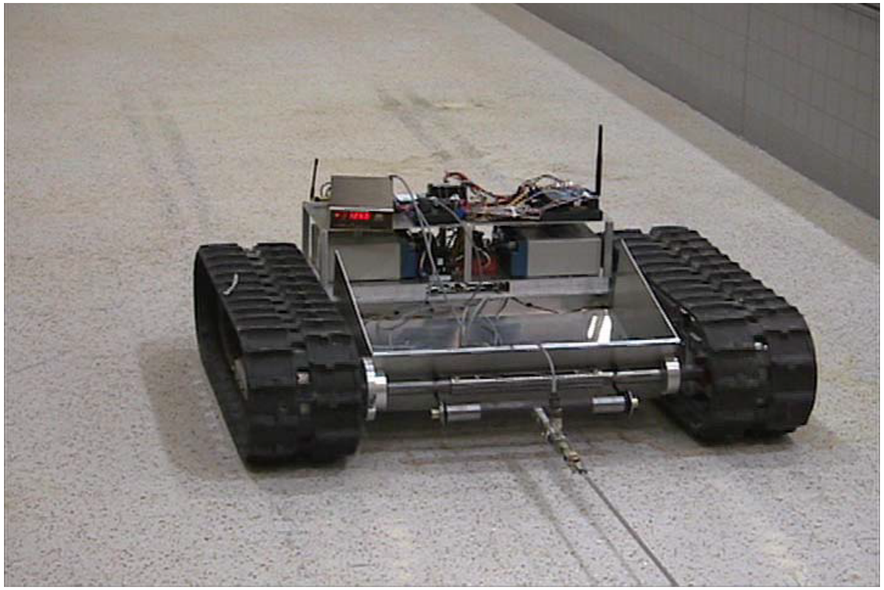


**Paul's Robotics Centennial Challenges Winner,
Worcester Polytechnic Institute (WPI), Worcester, Massachusetts**




# $500,000 Prize !

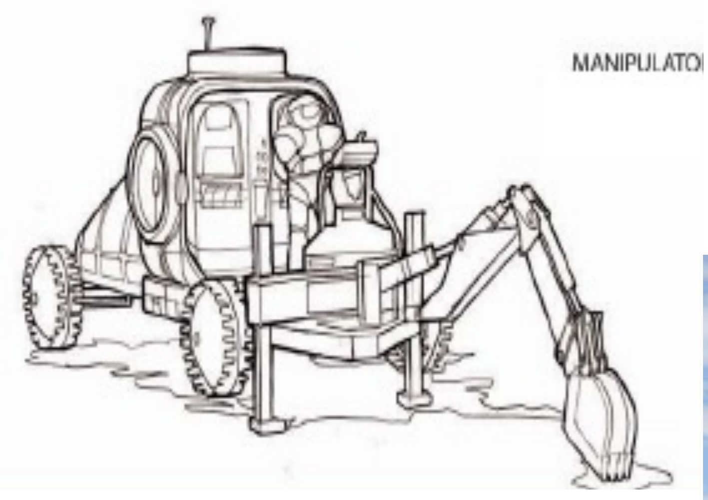
# NASA Cratos – 2007
# Glenn Research Center



# Lunar Attachment Node for Construction & Excavation (LANCE) on Chariot – NASA JSC/KSC 2009

# Lunar Attachment Node for Construction & Excavation (LANCE) on Chariot – NASA 2009

# Space Exploration Vehicle (SEV) 2010-2012



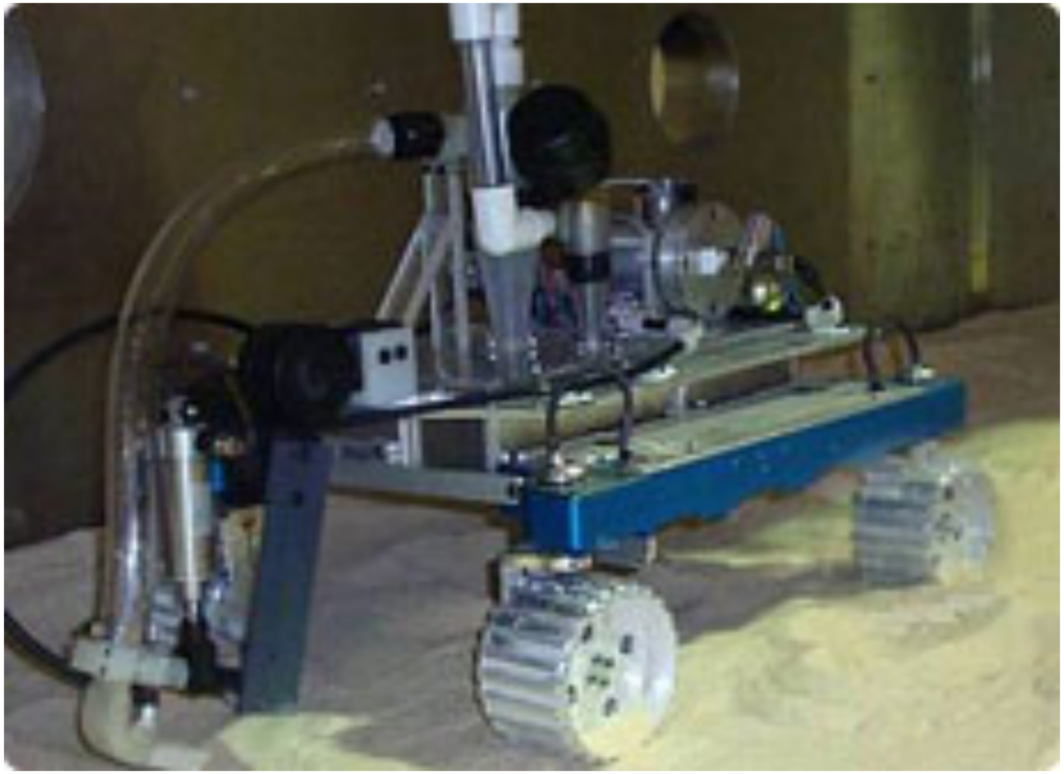

# ATHLETE Excavation, NASA : 2009 - 2011

# Automated Mining for Earth & Space
# NASA/Caterpillar - 2009


**Caterpillar 287C semi-autonomous Multi Terrain Loader**

# NASA Centaur 2 Regolith Excavator
# JSC/GRC/KSC – 2010-2011

# Pneumatic Excavation and Regolith Transport
# Honeybee Robotics and NASA KSC: 2009-2011

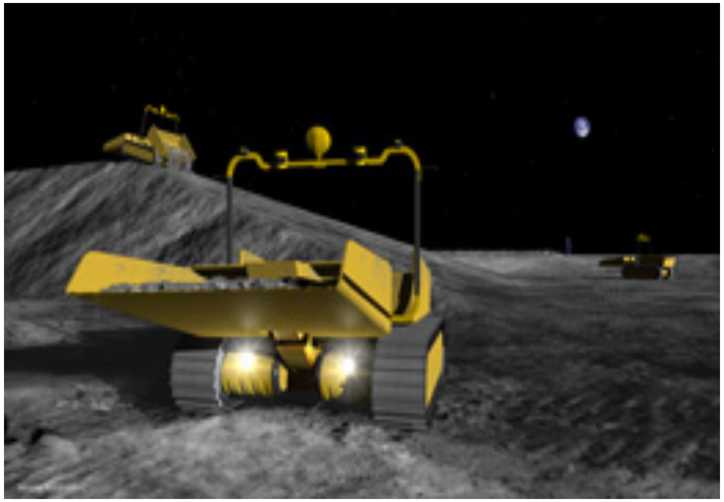


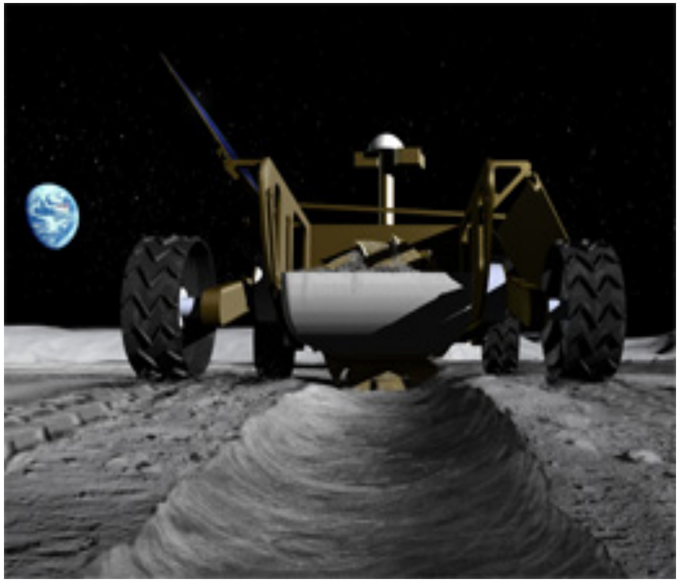
# Canadian Space Agency, 2010 Mauna Kea ISRU Tests (NORCAT & Juno NEPTEC Rover)

Load, Haul, Dump Excavator

Small Bulldozer

# Astrobotic Technology inc. Lunar Mining Concepts
# NASA SBIR 2010-2012





# Robotic Precursor Small Robotic Mining Systems (< 50 Kg) 2011-2012

**NASA Kennedy Space Center Excavator.**
**Regolith Advanced Surface Systems Operations Robot (RASSOR)**

# Regolith Excavation Mechanisms

## All excavators from three Centennial Excavation Challenge Competitions (2007, 2008 and 2009) and Lunabotics Mining Competitions (2010, 2011 & 2012)

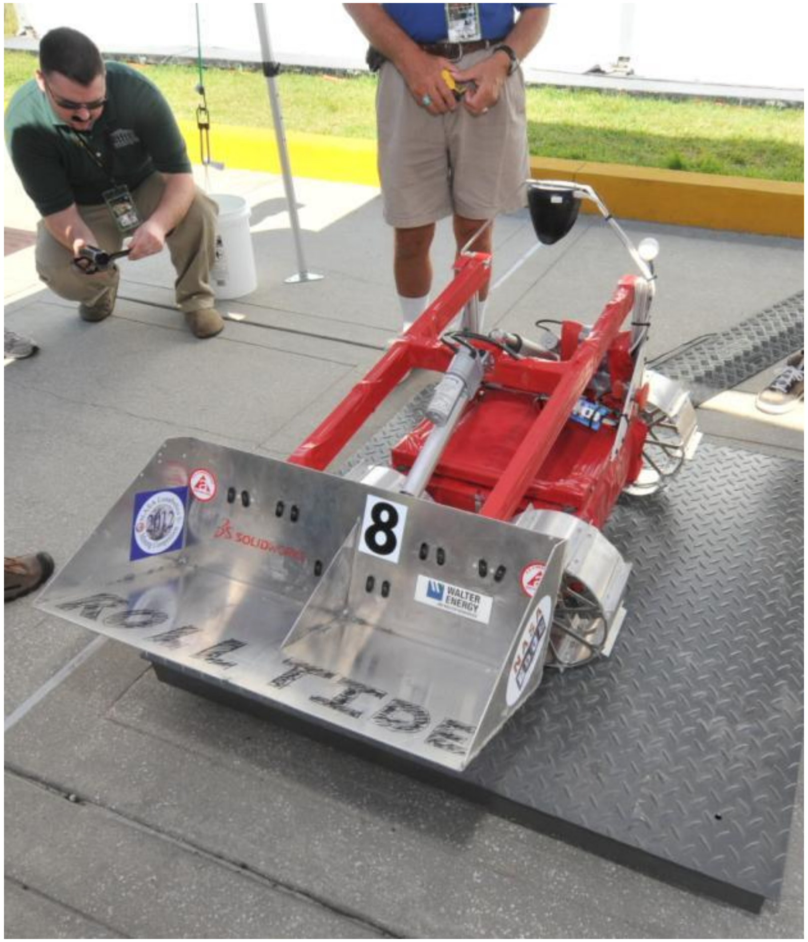
| Regolith Excavation Mechanism | # of machines employing excavation mechanism | Lunabotics 2012 |
|---|---|---|
| Bucket ladder (two chains) | 29 | 10 |
| Bucket belt | 10 | 6 |
| Front End Loader | 10 | 14 |
| Scraper | 8 | 8 |
| Auger plus conveyor belt / impeller | 4 | 3 |
| Backhoe | 4 | 0 |
| Bucket 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 |

# NASA Lunabotics Mining Competition Robot Systems 2010 - 2011

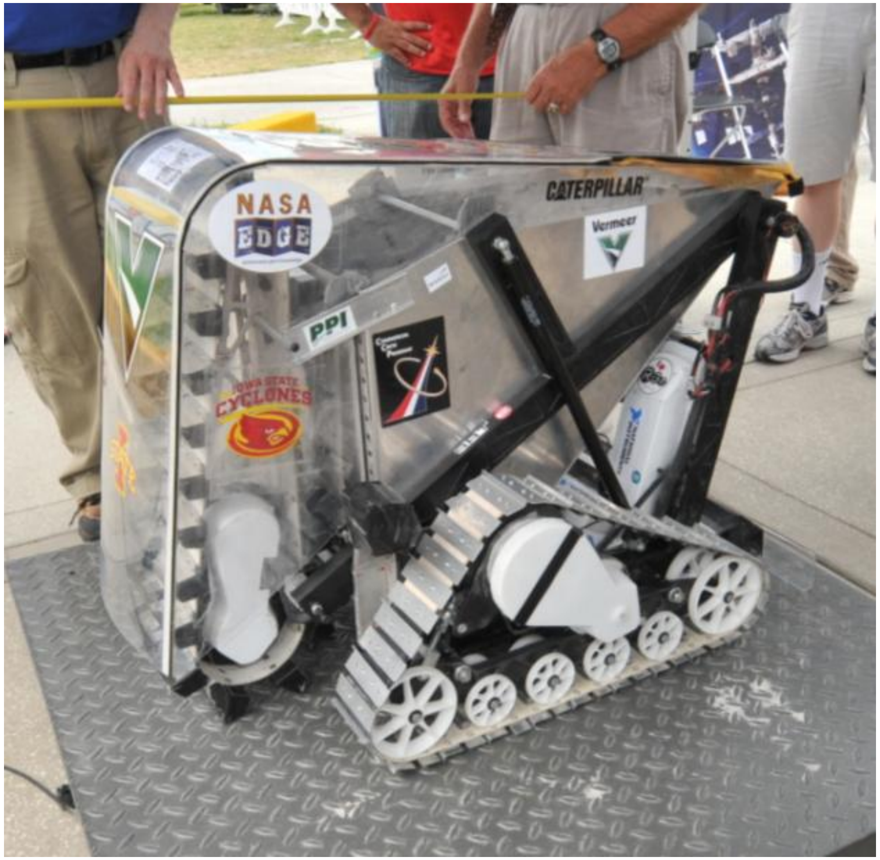

**2010 Lunabotics Mining Competition Winner: Montana State University "The Mule" Lunabot, from Bozeman, Montana**

**2011 Lunabotics On Site Mining Category Winner: Laurentian University "Production" Lunabot, from Sudbury, Canada**

# 2012 Lunabotics Mining Winners




U Alabama – Grand Prize




Iowa State U – On Site Mining Category

# 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

- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Encountering sub surface rock obstacles
- Long life and reliability
- Unknown water ice / regolith composition and deep digging
- Operating in the dark cold traps of perennially shadowed craters
- Extreme access and mobility
- Extended night time operation and power storage
- Thermal management
- Robust communications

# 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