

# **Lunar and Planetary Excavation Systems: Lessons Learned at the Colorado School of Mines**

The logo of the Colorado School of Mines is a shield-shaped emblem. It features a pickaxe and a hammer crossed in the center. The words "SCHOOL OF MINES" are written along the top curve of the shield, and "COLORADO" is written along the bottom curve. The year "1874" is prominently displayed in the lower center of the shield.

Tue. 6/8/2010  
Joint Meeting of  
Space Resources Roundtable  
&  
Planetary and Terrestrial  
Mining Sciences Symposium

Paul van Susante  
Chris Dreyer

# CSM activities

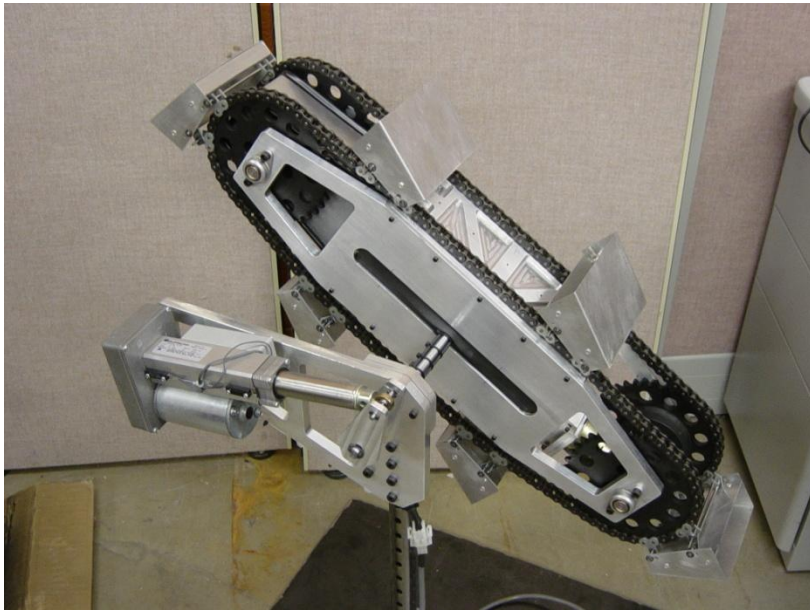
- Bucketwheel
  - Bucket ladder I,II,III, IV, V
  - Backhoe
  - Material transport
  - Beneficiation
  - Processing
  - Measurement & Testing
- 
- System Engineering and Decision making tools
  - Economic Analysis, Chemical Processes
  - Lunar Base & Lunar Telescope Construction

# Bucketwheel



50 kg/hr, auger, directly into processing unit, discard proceeds

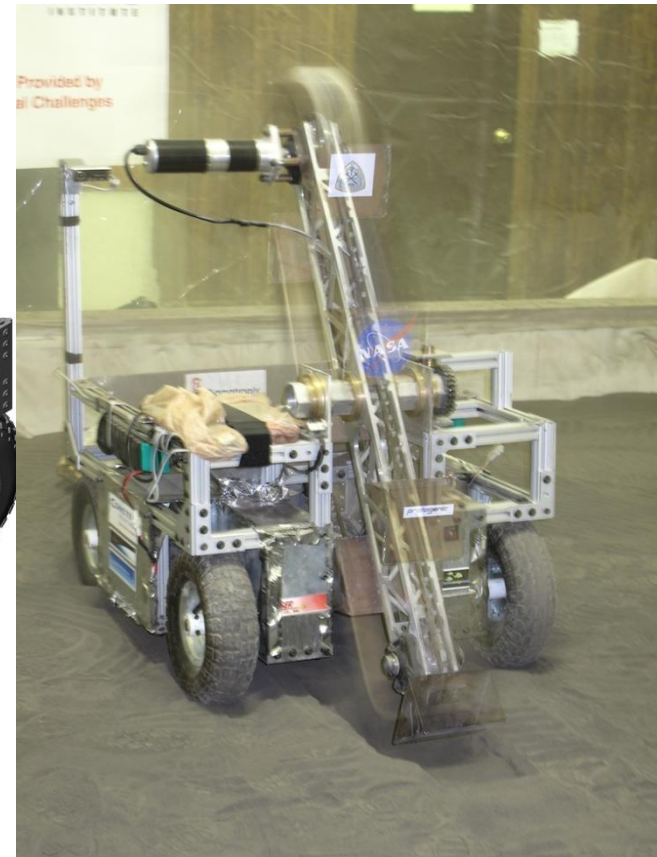
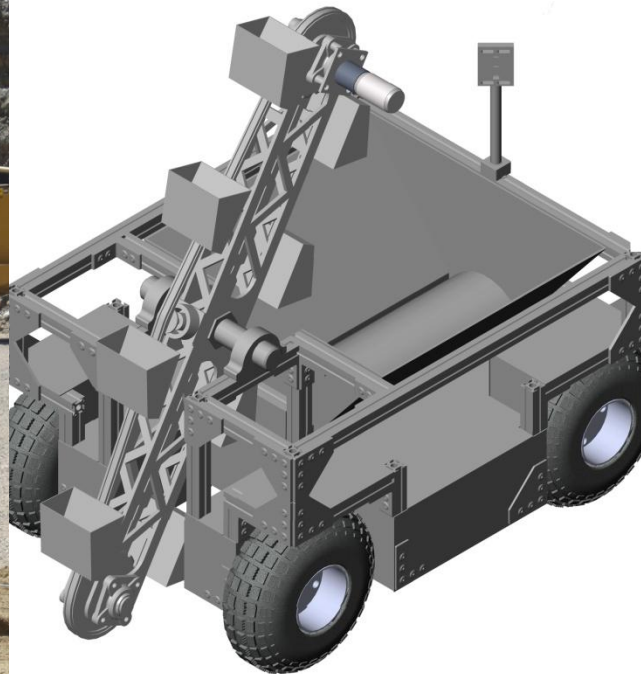
# Bucketladder I, II



SBIR I with sysRAND

500 kg/hr, transport, dump into collection bin,

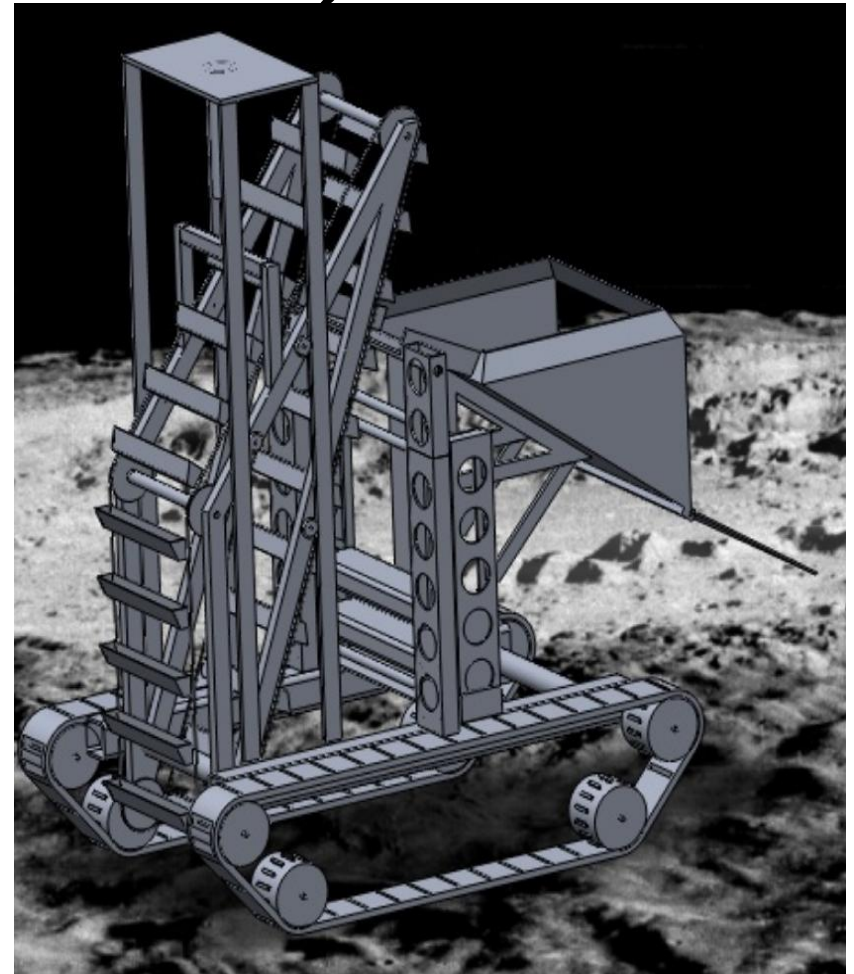
# Bucketladder IIIa, b



Integrated with rover, 1500 kg/hr, transport, dump into collection bin, dump in processing unit using ramp

# Bucketladder IV, V

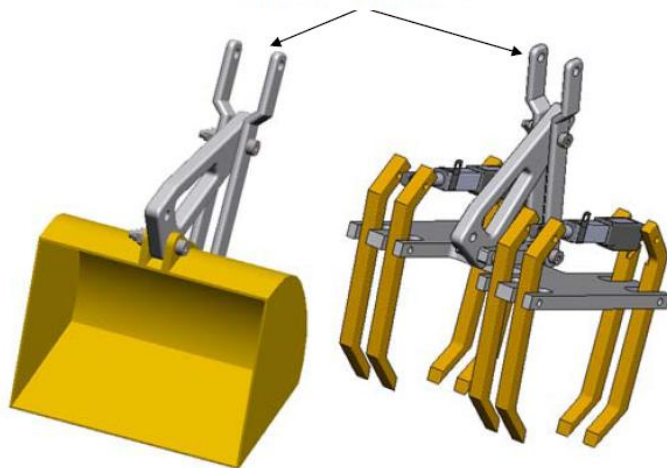
- Lunabotics Competition



Integrated with rover, 1500 kg/hr, transport, dump into collection bin, dump in processing unit by lifting collection bin

# Backhoe Design

Bucket Actuator Mount Point



Bucket Actuator

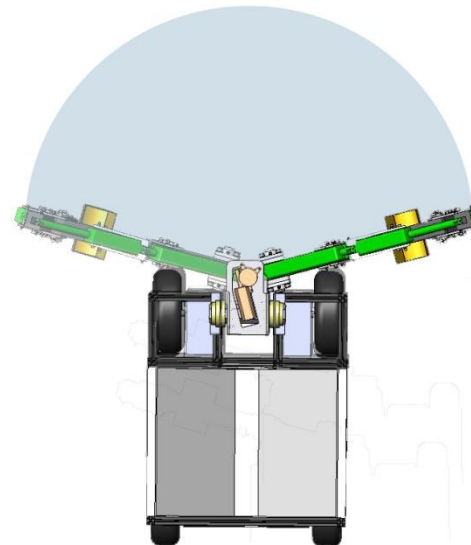
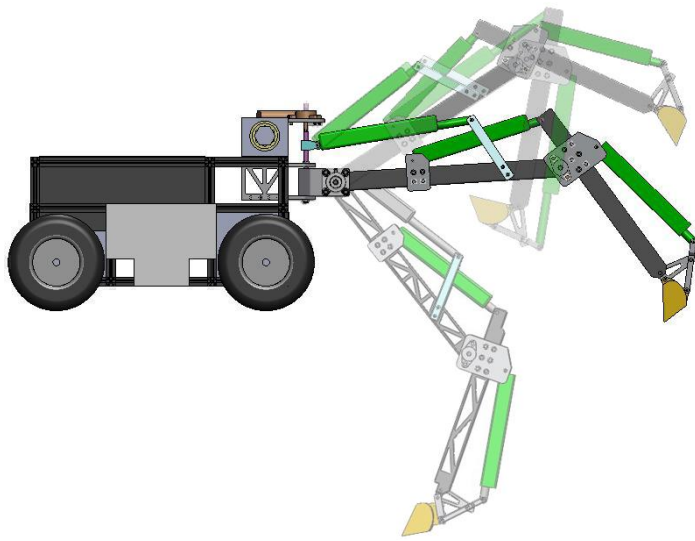
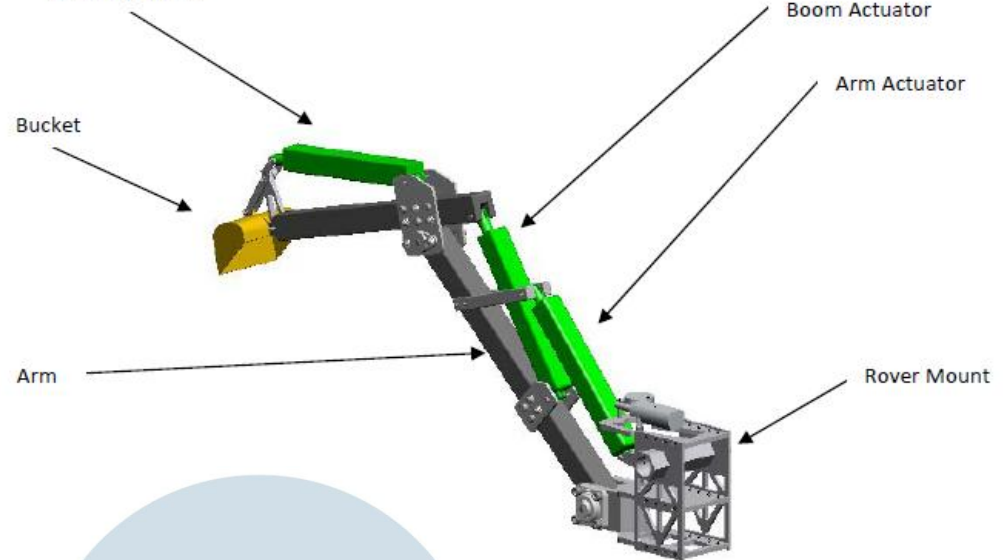
Bucket

Arm

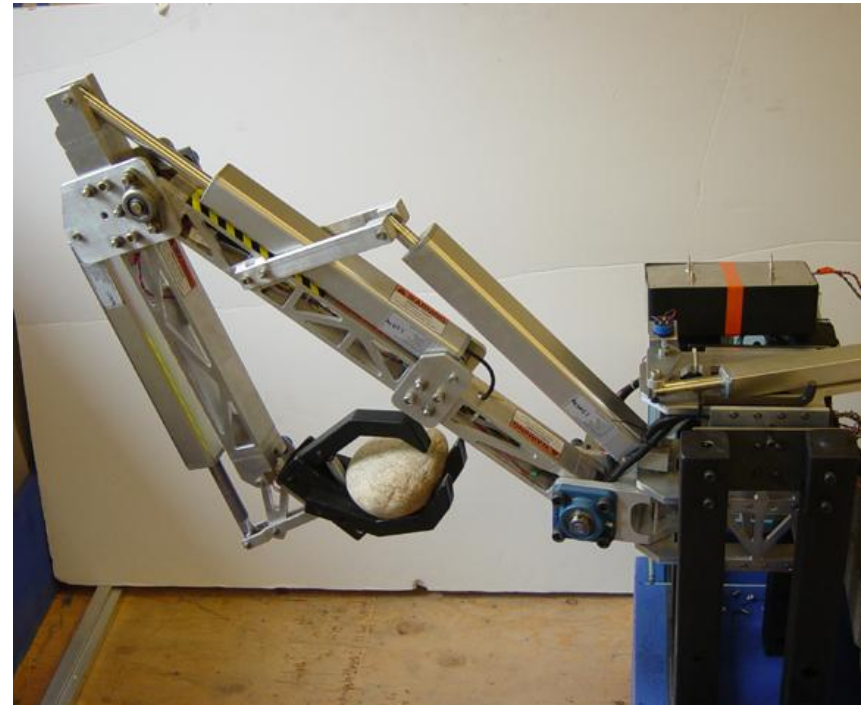
Boom Actuator

Arm Actuator

Rover Mount



# Backhoe Prototype



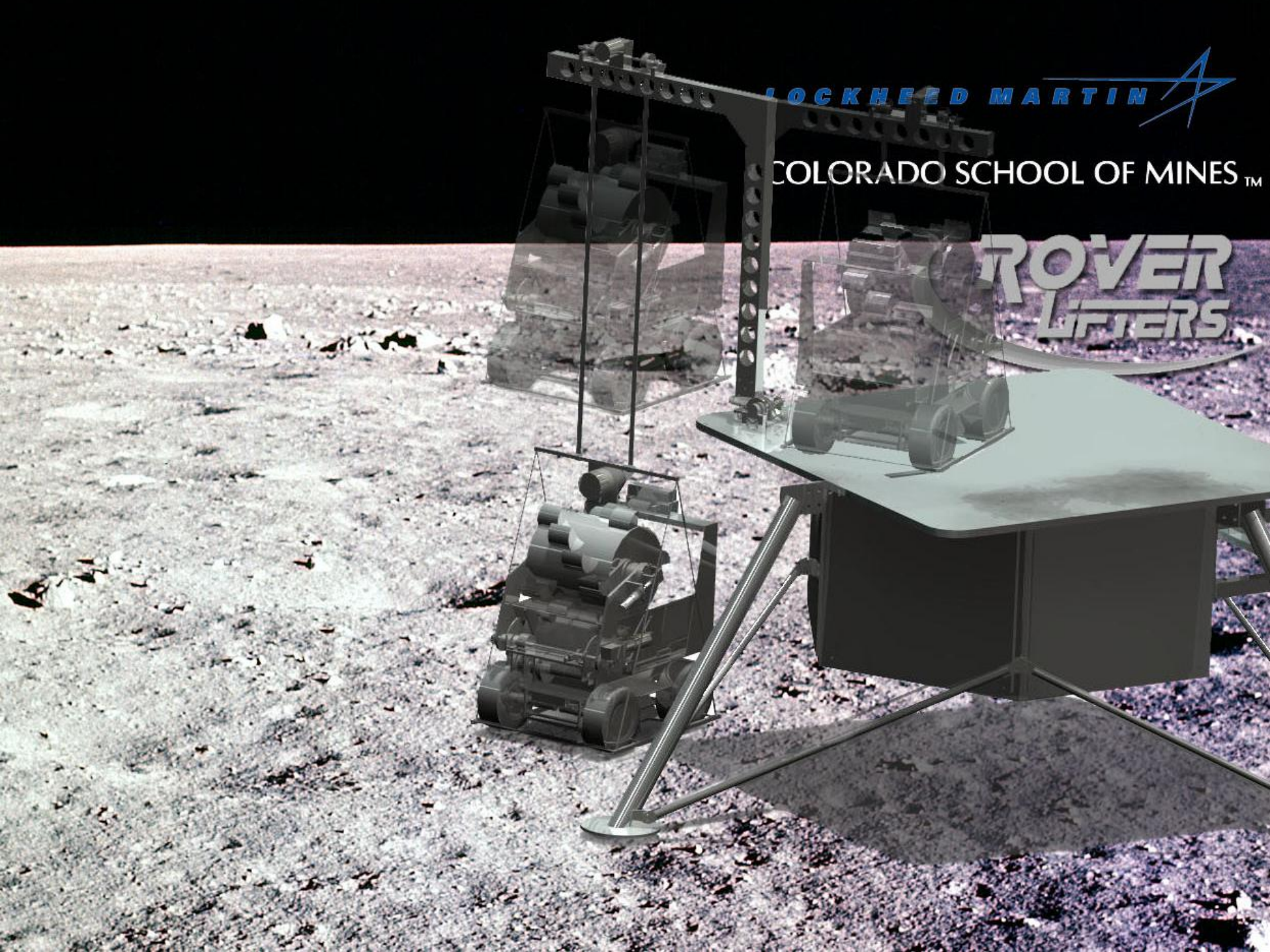
Integrated with rover true 'quick connect', 100 kg/hr, 1m depth, 10 kg rock

LOCKHEED MARTIN

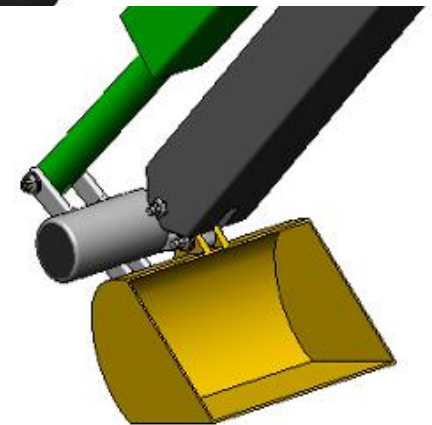
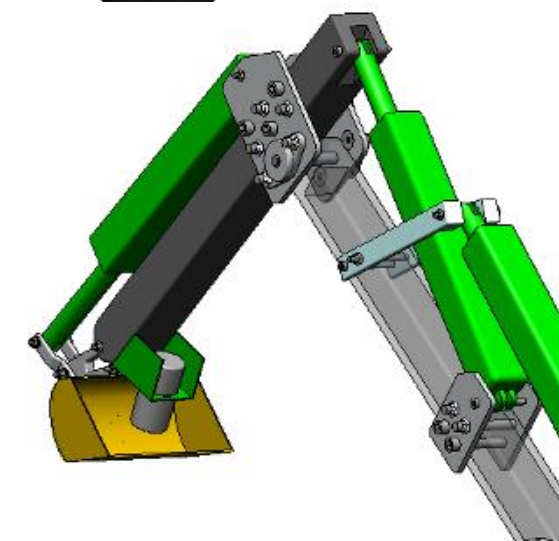
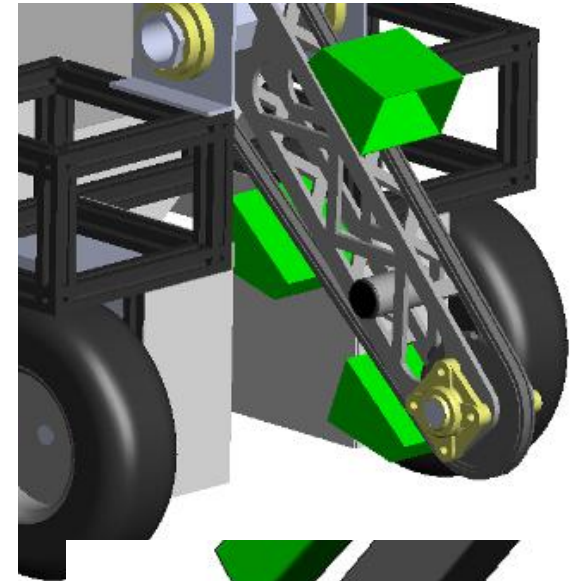
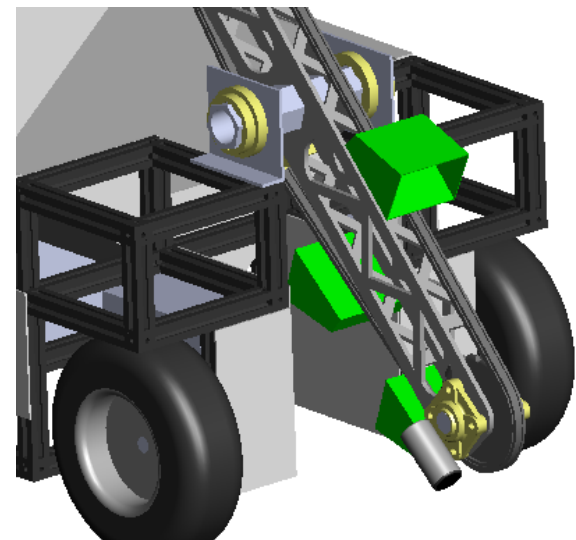


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# ROVER LIFTERS



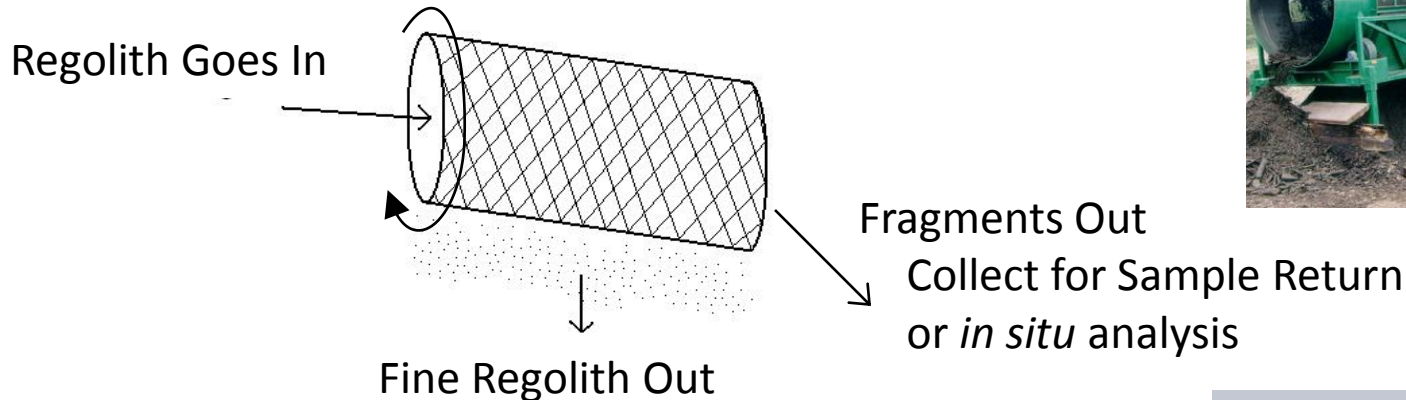
# Integration of Science with excavation



# Beneficiation using an Excavation System: Regolith Sifter

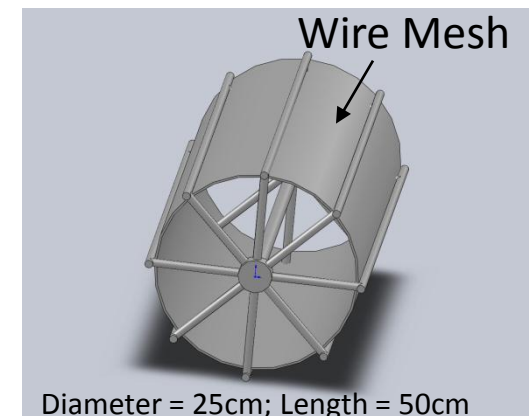
A-12 Rake Sample 4-10 mm

- ISRU: Separate large fragments from fines
- Civil Engineering: Sort out fines, coarse, etc... by purpose – road bed, landing pad, high traffic areas, etc...
- Science: Apollo Rake samples were excellent source of variety: pristine crustal rocks, impact melt rocks, and basalts.<sup>1</sup>



At CSM we are building a trommel (rotary screen) that will be able to process fragments from fines at 600 kg/hr rate of input regolith (approx excavation rate of CSM excavation rover) assuming fragments are ~5% by weight.

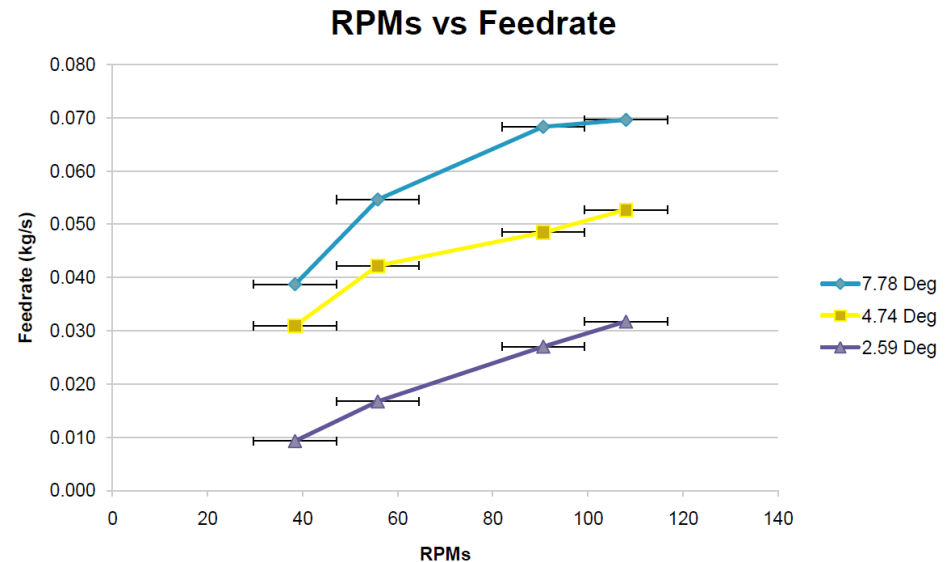
Initial sorting by size followed by sorting by rapid analytical analysis (IR imaging) – sample triage.



<sup>1</sup>: G. Lofgren, "Experience from Apollo and Challenges to Geology", presentation, OSEWG, Workshop on Robots Supporting Human Science and Exploration, Houston TX, August 2009.

## Trommel Regolith Sifter Test Results

- Engineering Physics Senior Design Project 2009/2010 (David Hall)
- Regolith Simulant
  - Fines: Low-cost, high volume from landscaping gravel with grinding by Zybek Advanced Products (73  $\mu\text{m}$  mean diameter)
  - Fragments: Jaw crusher for  $>1\text{mm}$
- Lessons Learned
  - Need a feed system for high feed rates, i.e. an excavation rover.... see excavation rover lessons learned - Only completed low feedrate testing
  - Testing suggests that when using regolith simulant, performance is not well predicted by theory used in refuse sorting – attachment RPM is greater than predicted



# Experimentation





# Movies



Movie cent challenge  
demo



# Things that went wrong

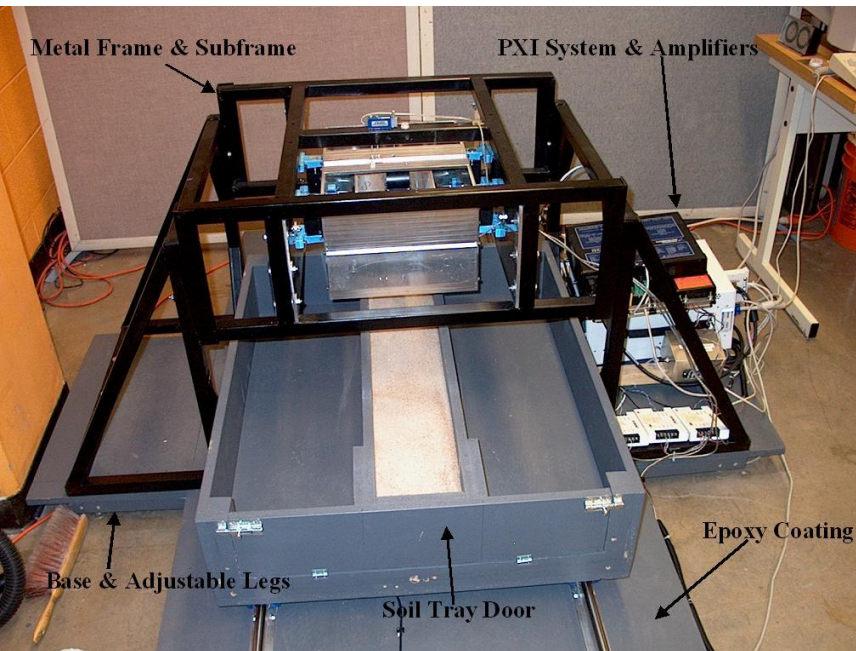
- Planning
  - Ordering
  - Machining
  - Testing time
  - Integration with class requirements
  - Competing interests / claims on time
  - Did not bring all tools needed to site
- Group dynamics
  - Personalities
  - Different working methods and attitudes
- Unforeseen circumstances
  - Dropping out of students
  - Changing programs
- Broken equipment / hardware
  - Electronics, motors, laptops, tools (drill bits)
- Communication problems
  - Things that work in the lab do not work well in the field, on site (networks)
- Lack of status of robot and communications
  - Sensors, basic communication

# Lessons Learned

Some of the experience with the CSM excavator development and lessons learned from the Centennial Challenge and Lunabotics development and :

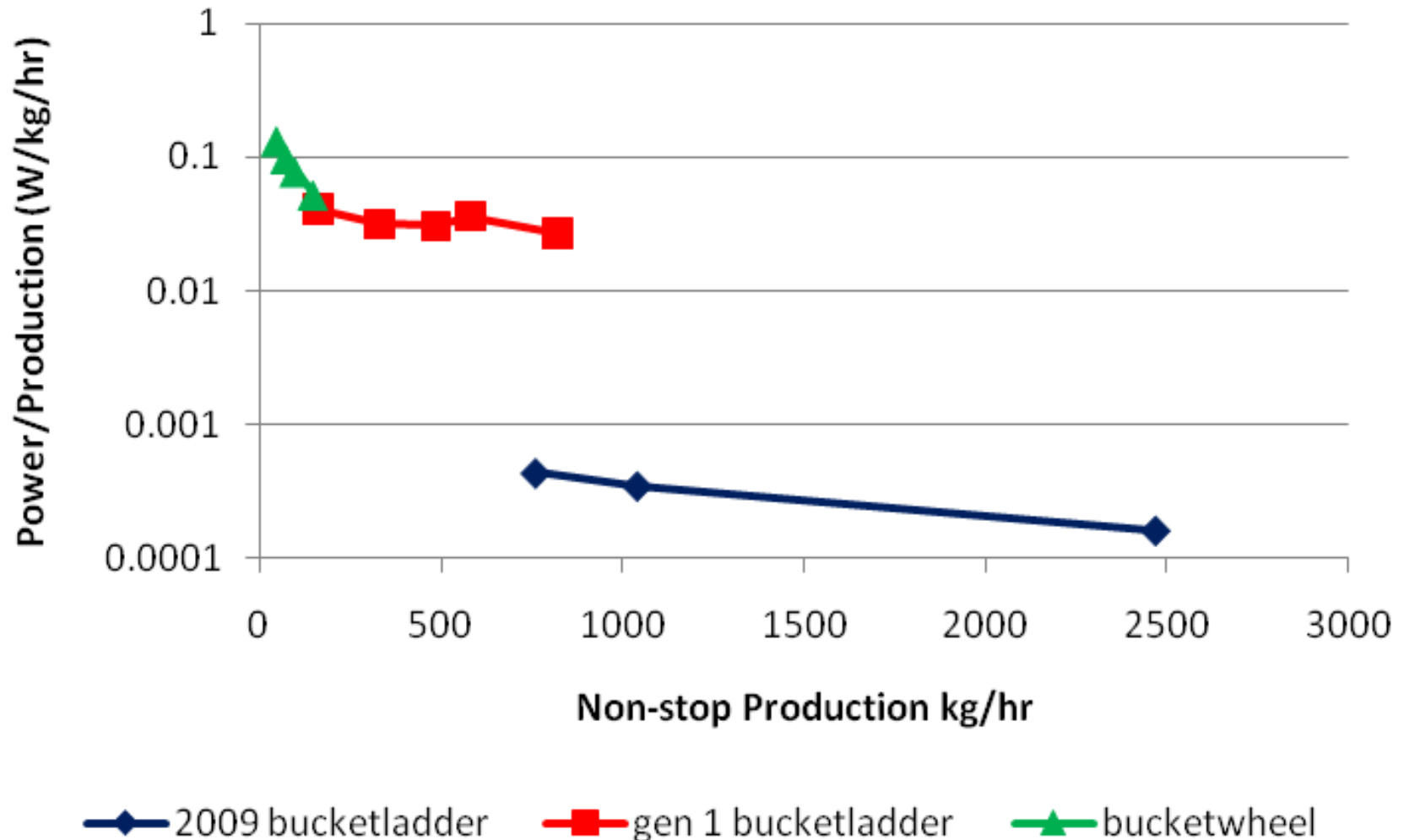
- Murphy never sleeps. If something can go wrong, it will at some point.
- Testing testing testing, of the whole system, every component and subsystem/assembly. (Leave time to fix problems found during testing)
- Working in parallel is important to meet deadlines.
- Team communication and a strong team leader is essential.
- Situational awareness of the excavator itself and its surroundings is crucial.
- Noise control in the electronics is very important in an ungrounded system.
- A system integration approach is important, the earlier the better.
- Lots of thin cuts work well for fast excavation.
- Traversing up a ramp costs a lot of power.
- Dumping regolith simulant works well with smooth steep sides.
- Wheels are vulnerable to losing traction, tracks are more reliable and versatile.
- Different workstyles can give reason for friction in interdisciplinary team.
- It is very difficult to design a high production, low power, robust, working excavator
- Local climate can make a big difference
- Great Spirit and great interest / working together / helping together
- Experience disappears with students, retained in faculty, some other in neighborhood

# Force Measurements

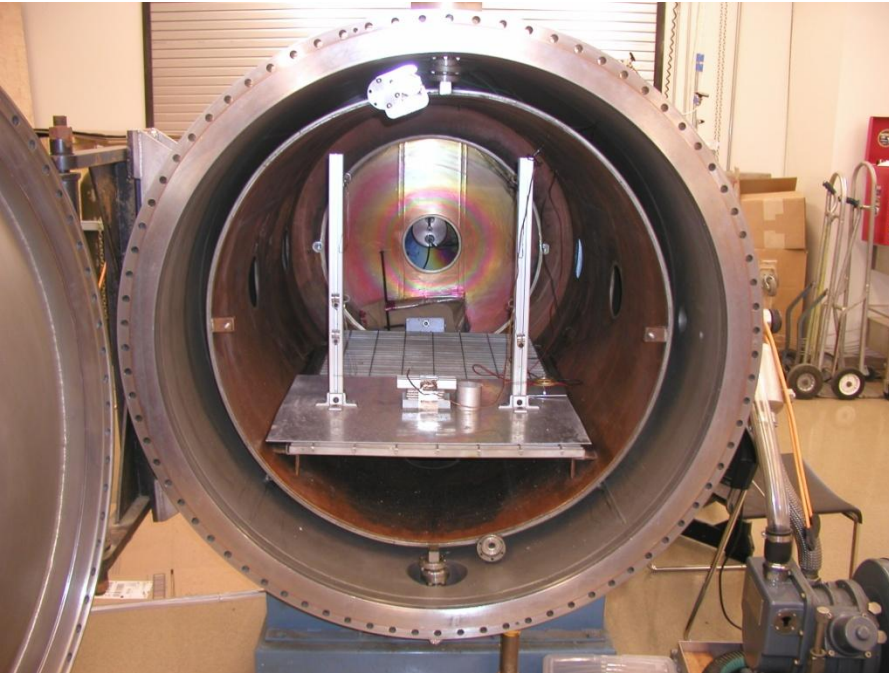


Testbed to measure x, and y forces  
Modified testbed to fly on 1/6<sup>th</sup> gravity campaign

# Excavation Power Use

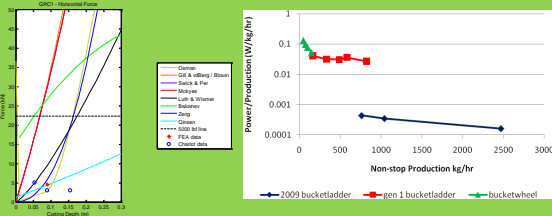


# Vacuum Chambers

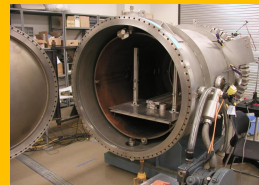


- 48" diameter (42" effective due to cryo shroud) 50" long 'dirty' vacuum chamber ( $10^{-11}$  torr) at CSM for testing using regolith, cold ( $-200^{\circ}\text{C}$ ) or hot ( $200^{\circ}\text{C}$ ) temperatures.

## Analysis, theory

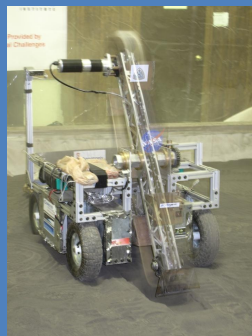


# Prototypes



## Fidelity

A photograph showing the interior of a boat cabin. In the foreground, there is a metal structure, possibly a railing or part of a machine. A window in the background looks out onto a boat race on a body of water, with several boats visible. The cabin has a white interior and a dark floor.



## Science & System Engineering Inclusion

A photograph of a sunset over the ocean. The sun is low on the horizon, creating a bright orange glow. The sky is filled with soft, orange-tinted clouds. In the foreground, the silhouettes of palm trees and two tall, thin light poles with conical tops are visible against the bright sky. The water of the ocean is calm, reflecting the light from the sun.

# QUESTIONS?

# Thanks to STUDENTS

(Free (cheap) Labor)

