Lunar Surface Systems Concept Study

Innovative Low Reaction Force Approaches to Lunar Regolith Moving

27 February 2009
About Honeybee

- **Honeybee Robotics Spacecraft Mechanisms Corp.**
  - Est. 1983
  - HQ in Manhattan, Field office in Houston
  - ~50 employees
  - ISO-9001 & AS9100 Certified

- **End-to-End capabilities:**
  - **Design:**
    - System Engineering & Design Control
    - Mechanical & Electrical & Software Engineering
  - **Production:**
    - Piece-Part Fabrication & Inspection
    - Assembly & Test
  - **Post-Delivery Support:**

- **Facilities:**
  - Fabrication
  - Inspection
  - Assembly (Class 10,000 clean rooms)
  - Test (Various vacuum chambers)

- **Subsurface Access & Sampling:**
  - Drilling and Sampling (from mm to m depths)
  - Geotechnical systems
  - Mining and Excavation
We are going back to the Moon to stay

We need to build homes, roads, and plants to process regolith

All these tasks require regolith moving
Excavation Requirements*

All excavation tasks can be divided into two:

1. Digging
   - Electrical Cable Trenches
   - Trenches for Habitat
   - Element Burial
   - ISRU (O2 Production)

2. Plowing/Bulldozing
   - Landing / Launch Pads
   - Blast Protection Berms
   - Utility Roads
   - Foundations / Leveling
   - Regolith Shielding

*Muller and King, STAIF 08
Excavation Requirements*

- Based on LAT II Option 1 Concept of Operations
- Total: ~ 3000 tons or 4500 m³
  - football field, 1m deep

*Muller and King, STAIF 2008
How big excavator do we need?
Bottom-Up Approach to Lunar Excavation

The excavator mass and power requirements are driven by excavation forces.

Excavation forces are function of:
- Independent parameters (fixed):
  - soil cohesion, friction angle, and gravity
- Excavator parameters (variable):
  - depth of cut, scoop design etc.

In order to ‘size’ a lunar excavator need to follow the following steps...

1. Choose a soil: JSC-1a, GRC1, NU-LHT-1M..
2. Prepare the soil:
   - Relative Density, Dr = 0% - 100%
   - Penetration Resistance
3. Measure Excavation Forces
4. Scale forces for lunar G
5. Input into excavation models
1. Choose a soil:
   JSC-1a, GRC1, NU-LHT-1M..

2. Prepare the soil:
   • Relative Density, Dr = 0% - 100%
   • Penetration Resistance

3. Measure Excavation Forces

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5. Input into excavation models
1. Properties of Lunar soil

- **Lunar Regolith**
  - Highly compacted soil (silty sand)
  - High Cohesion: 1 kPa
  - High Friction Angle: 45-50 deg
  - Agglutinates
  - Very abrasive

- **Effect of Hard Vacuum: \(10^{-12}\) torr**
  - Surface friction is high -> soils are stronger

*Courtesy: D. McKay*

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*Zeng et al., 2007*
1. Requirements for Lunar Soil Simulant

- Simulants do not replace. They simulate specific property/properties and not necessarily all the properties (mechanical for digging vs. mineral composition for Oxygen extraction): “Horses for courses”

- What soil properties are important for lunar excavation?
  - Friction angle ($\varphi$) and Cohesion ($c$): $\tau = \sigma \tan(\varphi) + c$
  - However, $\varphi$ and $c$ are function of soil relative density
  - Which in turn is affected by particle size distribution and particles shape, (and mineralogy)

### Available soil simulants

<table>
<thead>
<tr>
<th>Simulant</th>
<th>Type</th>
<th>Primary use</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>JSC-1a</td>
<td>Mare, low-Ti</td>
<td>Geotechnical and to lesser chemical</td>
<td>Orbitec</td>
</tr>
<tr>
<td>NU-LHT-1M, -2M</td>
<td>Highlands</td>
<td>General</td>
<td>MSFC and USGS</td>
</tr>
<tr>
<td>OB-1</td>
<td>Highlands</td>
<td>Geotechnical</td>
<td>Norcat</td>
</tr>
<tr>
<td>FJS-1</td>
<td>Mare, low-Ti</td>
<td>Geotechnical</td>
<td>JAXA/Schimizu</td>
</tr>
<tr>
<td>GRC-1, 3</td>
<td></td>
<td>Geotechnical</td>
<td>GRC</td>
</tr>
</tbody>
</table>

**Selected:**
1. Good properties
2. Availability
1. Choose a soil:
   JSC-1a, GRC1, NU-LHT-1M..

2. Prepare the soil:
   - Relative Density, Dr = 0% - 100%
   - Penetration Resistance

3. Measure Excavation Forces

4. Scale forces for lunar G

5. Input into excavation models
2. Soil Preparation Requirements

There are two parameters that can guide soil preparation:

1. Relative density, $D_r$
   - Compact the soil to achieve $D_r$ to that on the Moon, [0-100%]
   - Can assume worst case, $D_r \approx 90\%$

2. Penetration resistance gradient, $G$ [Pa/mm]
   - Compact the soil to match the penetration resistance gradient of the Apollo SRP
   - Need gravity scaling factor, $G_{\text{Earth}} = k \times G_{\text{Moon}}$, where $k = 1$ to 6

\[ G \approx 3 \text{ Pa/mm} \]
2. Soil Preparation: Conclusions

It is recommended that soil simulant is compacted to achieve Dr>90%, which is consistent with depth below ~10-20 cm. This creates worst case scenario and makes excavation results conservative.

This approach was also recommended by Dr. David Carrier
1. Choose a soil: JSC-1a, GRC1, NU-LHT-1M.

2. Prepare the soil:
   - Relative Density, Dr = 0% - 100%
   - Penetration Resistance

3. Measure Excavation Forces

4. Scale forces for lunar G

5. Use these for excavation models

JSC-1a

Dr ~ 90%
3. Measure Excavation Forces

- No published data exists giving bulldozer or digging forces in lunar regolith simulant
- Thus:
  - Theoretical models were used to predict the forces
  - The same models were used to determine gravity scaling

1. Choose a soil:
   JSC-1a, GRC1, NU-LHT-1M...

2. Prepare the soil:
   - Relative Density, Dr = 0% - 100%
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3. Measure Excavation Forces

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Force required to push the soil:

\[ P_p = 0.5 \rho g H^2 N_\phi + 2cH N_\phi^{0.5} \]

where:

\[ N_\phi = \frac{1 + \sin \Phi}{1 - \sin \Phi} \]

Note:

- Friction term \([P_p=0.5\rho g H^2 N_\phi]\) has gravity component
- Cohesion term \([2cH N_\phi^{0.5}]\) does not have a gravity component
- Next two charts show the effect of low and high cohesion
3 & 4. Low cohesion case; $c=130 \text{ Pa}$

For low cohesion values, the gravity scaling factor reaches 6 for the blade depth of 1m into the soil.

\[
\text{Ratio} = 0.88 \ln(\text{Depth}) + 5.9
\]
3 & 4. High cohesion case; $c=2300$ Pa

For high cohesion values, the gravity scaling factor reaches only 3 for the blade depth of 1m into the soil.

\[
\text{Ratio} = -\text{Depth}^2 + 3\times\text{Depth} + 1
\]

<table>
<thead>
<tr>
<th>$\rho$</th>
<th>1900 kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>2300 N/m$^2$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>40 degrees</td>
</tr>
</tbody>
</table>
3 & 4. Force and Gravity scaling: Zeng model*

- Zeng model takes into account more soil/blade parameters
- The model also predicts the gravity scaling as a function of blade depth into the soil
- A little bit of cohesion makes a big difference, especially in low gravity.

<table>
<thead>
<tr>
<th></th>
<th>Exacation forces at c=130 N/m²</th>
<th>Exacation forces at c=1300 N/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g=9.8 m/s² N</td>
<td>g=1.6 m/s² N</td>
</tr>
<tr>
<td>Depth=0.1m</td>
<td>1061</td>
<td>242</td>
</tr>
<tr>
<td>Depth=0.5m</td>
<td>27653</td>
<td>5119</td>
</tr>
<tr>
<td>Depth=1m</td>
<td>122428</td>
<td>21870</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
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</tr>
<tr>
<td>Depth=0.1m</td>
<td>1785</td>
<td>964</td>
</tr>
<tr>
<td>Depth=0.5m</td>
<td>33231</td>
<td>10643</td>
</tr>
<tr>
<td>Depth=1m</td>
<td>138604</td>
<td>37790</td>
</tr>
</tbody>
</table>

Why excavator mass is important

The excavator has to provide resistance to the digging forces

- If vertical forces are too high -> excavator will lift itself up and slip
- If horizontal forces are too high -> excavator will pull itself along

The ideal tractive thrust:

\[ H_0 = n b L c + W \tan \phi. \]

where:
- [can not change these]
  - \( C \) = soil cohesion
  - \( \phi \) = soil internal friction angle

- [can change these]
  - \( W \) = vehicle mass
  - \( N \) = number of wheels
  - \( B \) = width of a wheel
  - \( L \) = wheel contact length

Note: Fully loaded Apollo rover (700 kg): 239 N*

*Wilkinson and DeGennaro, 2006
Traction model*

Actual DrawBar Pull = traction force - resistances (sinkage, bulldozing, hill climbing):

$$DP = H - R = H - (R_c + R_b + R_g + R_{other})$$

Bottom line:

Vehicle Mass has the biggest effect!

*Wilkinson and DeGennaro, 2006
Bulldozer cutting up to 10cm deep needs to weigh 2000 kg*

*Assumed: Vehicle Mass = 3 * Drawbar pull

Based on Zeng model. Density=1.9 g/cc; Friction angle: 40 deg; Cohesion: 1300 Pa; Blade width: 1m

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Earth

Moon
3 & 4. Conclusions

1. Need very heavy excavators

2. The excavation forces on Earth will be 1 - 6 times as great as on the Moon:
   - ~1 for ‘tiny’ excavators
     - Thus need 6x more massive excavator
   - ~2 for a "typical" excavator
     - Thus need 3x more massive excavator
   - ~6 for a big excavator
     - The excavator mass may remain the same

Earth

Depth = 0.25 m

2929 kg*

Moon

7014 kg*
To make regolith moving on the Moon feasible we need to find means of reducing excavation forces and in turn excavator mass.
Use of explosive to loosen soil*, (1994)

- Experimental data: mass of explosives required for reduction in soil relative density ($D_r$) and excavation energy:
  - 1 gram PETN -> 50% energy reduction

- Charges can be placed by:
  - Drilling detachable bit/explosive
  - Hammering detachable cone/explosive

- “Blasting” could be accomplished with gas pulse

*Lin et al., 1994
Use percussive scoop/blade

- Force reduction ~ 90%
- Draft Force_{vibratory} = 0.9 Draft Force_{static}

![Graph showing mass of a bulldozer vs. depth of cut for different conditions.](Image)

percussive systems reduces excavator mass requirement

- Force reduction ~ 90%
- Draft Force_{vibratory} = 0.9 Draft Force_{static}
If excavation forces are reduced by 90%, the required vehicle mass will also be reduced by 90%.

But, the payback is much higher!!!

Smaller excavator means:

- smaller lunar landing mass and propellant to land
- smaller launch mass and less propellant to launch
Payback for reduced excavation forces

Assumptions:
- Launch cost: $100k/kg
- Gear ratio: 1:6

Result:
- Excavation forces reduction by 90% -> excavator mass drop from 1000 kg to 100 kg -> savings of $500 mln
Application of Percussive system on Chariot rover

Percussion can reduce vertical forces and horizontal forces

Vibration can reduce horizontal force
1. Choose a soil:
   JSC-1a, GRC1, NU-LHT-1M..

2. Prepare the soil:
   - Relative Density, Dr = 0% - 100%
   - Penetration Resistance

3. Measure Excavation Forces

4. Scale forces for lunar G
   \( k = 1-6 \)

5. Use these for excavation models

Look at vibratory systems
Vibrating bulldozer blades, (1998)

Source of Draft force:
- Soil cutting and lifting forces
- Soil to blade friction

Parameters that matter:
- Frequency, amplitude, direction of oscillation (best in direction of travel)

Hardware:
- Voice coil (x2):
  - Amplitude (zero to peak): 1mm at 70 Hz and 2.5mm at 10 Hz
  - Frequency: 10 to 70 Hz
  - Force: 164 N

Results:
- Highest draft force reduction for dry soils at 60-70Hz and for wet soils at 20-30Hz
- DFR ~ Bulk Density and Spec Gravity
  - 71%-93%
  - 79%-88%
  - 87%-91%

DFR=[1-(DF Dynamic/DF Static)]*100%

*Szabo et al., ASAE ‘98
Vibratory Soil Cutting*, (1975)

- **Application**: cable trenching, pipe laying

- **Force reduction and Power increase**:
  - 45 deg vibrations: 60%, 1.3
  - Vertical: 50%, ~2
  - Horizontal: 40%, ~1.9

- **Amplitude of Vibrations** (increasing from 0.23in to 0.54in):
  - Draft Force dropped from 75 to 82%
  - Power ratio up from 1.9 to 6.4

- **Frequency of Vibrations**: 5 Hz to 10 Hz
  - Force reduction increase from 30% to 42%
  - Power ratio increase from 0.9 to 1.5

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*The percent force reduction is*

\[ F_r = (1 - f_r) \times 100 \]

\[ f_r = \frac{F_v}{F_s} \]

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*Sulatsisky and Ukrainetz, CSMT, 1975*
Vibratory Soil Digging: Vertical Forces (2008)

- Estimating vertical/digging forces at Honeybee Robotics
- Soil: JSC-1a at ~1.9g/cc
- Without percussion: 125 lbs (but could not push the scoop all the way in)
- With percussion: 5 lbs

![Graph showing the average force required to penetrate compacted JSC-1A (lbs) without and with percussion. Without percussion requires significantly more force compared to with percussion.]
Department of Defense systems

Challenge:

- Man-transportable (~30 kg), rover-based digging systems can be used to uncover buried Improvised Explosive Devices
- Light platform => Limited reaction force => Limited digging capability

Solution:

Percussion/Vibration enhanced digging greatly improves digging capability

Foster-Miller: Talon

iRobot: PackBot
Experimental evaluation of percussive technology for digging and scooping (not bulldozing)
Components of the test fixture

Scoop Capacity
- Volume: 1500 cc
- Mass: ~ 1.5 kg (assume 1g/cc)
Actual Set up

- JSC-1A compacted to 1.9 g/cc
- Could not push the scoop into the regolith (physically impossible)!!!
- Percussive hammer: 2.6 J/blow, 66Hz, 170 Watt

Quality control: 3.7 MPa (Apollo: 0.5-1.7 MPa @ 70cm depth)
Movie time
Results and Analysis

Higher push force -> faster the scoop penetrates.

Quick Analysis

- Assume: Excavation requirement: 4500 m³ or 3,000,000 scoops

- **Digging**
  - 420 kWh for 300 N push force

- **Extracting/lifting the scoop**
  - 140 kWh for 300 N pull force

- **Total Energy Requirements (Digging and scooping up):**
  - 560 kWh for 300 N digging force
There is a trade off between excavation force (excavator mass) and digging power

consider this:

- 1kg of excavator mass = $100k (launch cost)
- Power can be solar (‘free’)

1. Choose a soil:  
   JSC-1a, GRC1, NU-LHT-1M.

2. Prepare the soil:  
   - Relative Density, Dr = 0% - 100%  
   - Penetration Resistance

3. Measure Excavation Forces  

4. Scale forces for lunar G  
   k = 1-6

5. Use these for excavation models
Excavation Spreadsheet

- Compiled parametric spreadsheet for assessing various excavation tasks.
- Clearly defined and separated inputs and outputs
- Clearly defined excavation tasks
- Modular design allows input of additional parameters or constants
Parameters for Fixed Data Input Table

- **Rover Parameters**
  - Speed (cm/s)
  - Drive Power (W)
  - Length (cm)
  - Front Wheel to CG (cm)
  - Front Wheel to Scoop (cm)
  - # Wheels
  - Wheel Width (cm)
  - Wheel Contact Length (cm)
  - Regolith Vol. Capacity (cc)
  - Mass (kg)

- **Scoop Parameters**
  - Volume (cc)
  - Rake Angle (deg)
  - Peak Power (W)
  - Peak Force (N)
  - Time for Single Scoop (s)

- **Bulldozer Parameters**
  - Width (cm)
  - Cutting Depth (cm)
  - Cutting Distance (cm)
  - Peak Power (W)
  - Peak Force (N)
  - Speed (cm/s)

- **Soil Parameters**
  - Friction Angle (deg)
  - Cohesion (kPa)
  - In-Situ Density (g/cc)
  - Bulk Density (g/cc)

- **Battery Parameters**
  - Energy Density (W-hr/kg)
  - Minimum Charge (%) (W-hr/kg)
  - Lifetime (# Cycles)
  - Time to Recharge (hr)
  - Self-discharge Rate (%)?

- **Task Parameters**
  - Task Name
  - Type of Task (digging, ploughing, transfer)
  - Regolith Volume (m³)
  - Avg. Distance from Base (m)
  - Operational Time (%)
Force Calculations and Margins

Rover Parameters
- # Wheels
- Wheel Width
- Wheel Contact Length

Soil Parameters
- Friction Angle
- Cohesion

Max Horizontal Force Available (Drawbar)

Bulldozer Force Multiplier

Scoop Horizontal Force Margin

Rover Mass

Rover Weight on Moon

Peak Bulldozer Force Predicted on Moon

Bulldozer Force Margin

Force Factor of Safety

Max Vertical Force Available at Scoop

Scoop Vertical Force Margin

Input (adjustable)
- Input from Data Lookup Table
- Calculated Value
- Output

Scoop Peak Force

Peak Scoop Force Predicted on Moon

Scoop Rake Angle

Peak Vertical Force

Peak Horizontal Force

Scoop Force Multiplier
Actual Spreadsheet
The mass of batteries holding 60 kWhr of energy is 800 kg. Thus, if a 200kg excavator required its own power supply, the total mass would be 1000 kg. This is 2000 kg less than the excavator that does not use percussive system.
Let’s look at 4 steps of excavation process
Excavation 4 Steps

The entire excavation cycle is a sequence of 4 steps:

1) dig and scoop, 4 sec
2) move over the mining container
3) discharge
4) move back into the regolith

1, 3: time saved with percussion
2, 4: power/time wasted in moving regolith. Alternatives?

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* The shovel w/o percussion in the high strength material was only able to scrape the relatively weak and loose top layer of soil.

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<table>
<thead>
<tr>
<th>Soil Strength</th>
<th>Without Percussion</th>
<th>With Percussion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>37</td>
<td>69</td>
</tr>
<tr>
<td>Medium</td>
<td>16</td>
<td>50</td>
</tr>
<tr>
<td>High</td>
<td>2*</td>
<td>12</td>
</tr>
</tbody>
</table>
Pneumatic Excavator and Transfer

• **Principle of operation:**
  1. Gas is injected into regolith and as it escapes it exchanges momentum with soil particles lifting them up
  2. Regolith trapped inside a tube is lifted by injected gas

• **Gas sources:**
  • Propulsion pressurizer gas: Helium
  • By-product of ISRU gases
  • Burn residual propellant in a thruster and use exhaust gas
Percussive-Pneumatic Excavator
Tests at Lunar G and in Vacuum

- Gas: Nitrogen @ < 9 psia
- Initial Soil Mass: 50g or 100 g
- Material: JSC1-a
- Chamber Pressure: ~ 1-4 torr
- Gravity: 1.67 and 9.8 m/s²
Test Results:

- 1 gram of $N_2$ at 7 psia can lift over 6000 g of JSC-1a
- In Hard Vacuum efficiency of 1:10 000 possible
Pneumatic sampling tube can be embedded inside each leg of a lander for either:

- Sample return or
- Reconnaissance: hop from place to place and acquire soil for analysis in the lab

1. Compressed gas cylinder releases a pulse of gas
2. Gas travels down lander leg strut
3. Gas is expelled through the lander leg pad nozzle into the regolith
4. Regolith is pushed up the second leg strut towards the lander deck
5. Regolith reached sample intake manifold where it combines with two other sample sources
6. Regolith from all three lander pads is pushed up into the sample canister
Particle separation for ISRU
### Particle Separation “Dry” Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantageous</th>
<th>Disadvantageous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve</td>
<td>1. Simple</td>
<td>1. Sieve WILL get blocked</td>
</tr>
<tr>
<td></td>
<td>2. No moving parts</td>
<td>2. Electrostatics is an issue</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Need vibrations (e.g. piezo) - additional electrical component</td>
</tr>
<tr>
<td>Cyclone</td>
<td>1. Robust</td>
<td>1. Needs gas carrier</td>
</tr>
<tr>
<td></td>
<td>2. Gas can be recycled</td>
<td>2. “Cut-off” not very sharp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Needs testing to determine optimum dimensions</td>
</tr>
<tr>
<td>“Bag Pipes”</td>
<td>1. Robust</td>
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</tbody>
</table>
Cyclones

- Cyclones theory is well established
- Many very complicated equations exist to determine cut-off between coarse and fines
- High efficiency cyclone captures ALL particles
- Can use double stage cyclones
- Our goal is to have ‘inefficient’ cyclone:
  - capture fines and leave out coarse

All particles >8 micron will settle

All particles >11 micron will settle
“Bag Pipes”: 2 stage process

**Step 1:**
- Fines are preferentially lifted
  - Coarse stay behind

**Step 2:**
- Fines follow gas flow and ‘turn’ corner
  - Coarse travel further
- More fines are lifted
  - Coarse tend to stay behind

Actual set up inside a vacuum chamber

Gas injection point
"Bag Pipes": 1st step

**Step 1:**
- Fines are preferentially lifted
- Coarse stay behind

**Step 2:**
- Fines follow gas flow and ‘turn’ corner
- Coarse travel further

**Results:**
- Particles lifted out of the tube tend to be finer
- Results depend on a number of parameters
“Bag Pipes”: 2nd step

Results:

- Closest bin collects mostly fines
- Furthest bin collects mostly coarse
- Results depend on a number of parameters
Path Forward

1. Develop prototype hardware for excavation tests
2. Test, test, and test some more
3. Address gravity scaling by testing at 1/6 and 1 g
4. Refining excavation models
5. Develop operational scenarios
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