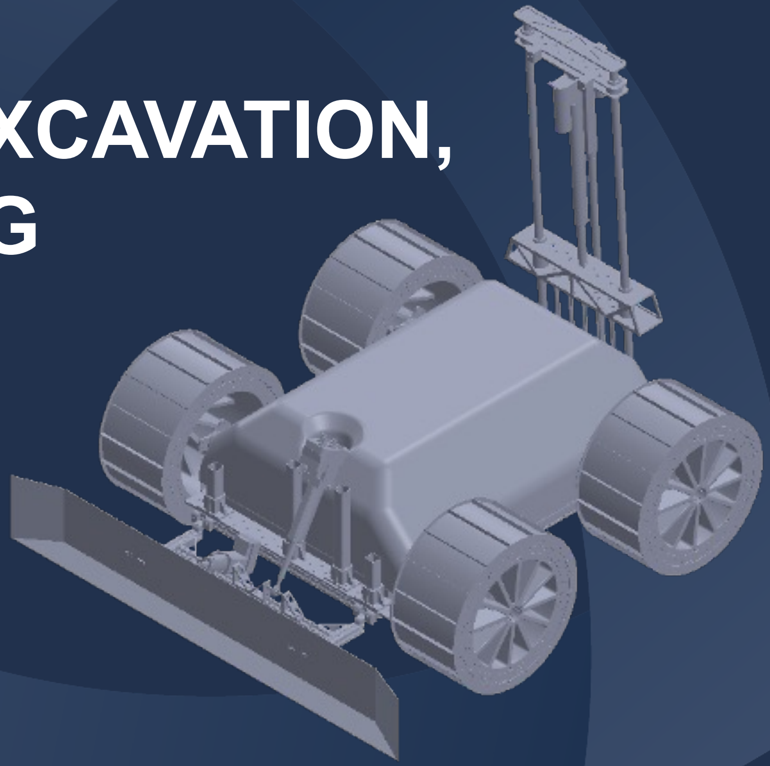
ASPECT

AUTONOMOUS SITE PREPARATION: EXCAVATION, COMPACTION, AND TESTING



LSIC Excavation & Construction Meeting
May 31, 2023

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Team

MINES

Chris Dreyer – PI, Regolith Mechanics
Andrew Petruska – State Estimation
Neil Dantam – Autonomy and Planning
Jamal Rostami – Regolith Manipulation
Kevin Cannon – Simulated Lunar Surface
George Sowers – Infusion

NASA Glenn Research Center
Phil Abel – NASA Technical Officer

Michigan Technological University

Paul van Susante – Compaction

Lunar Outpost

AJ Gemer – Mobility Platform
Justin Cyrus and **Joe Kendrick**

BECHTEL

Ann Esbeck – Terrestrial Experience

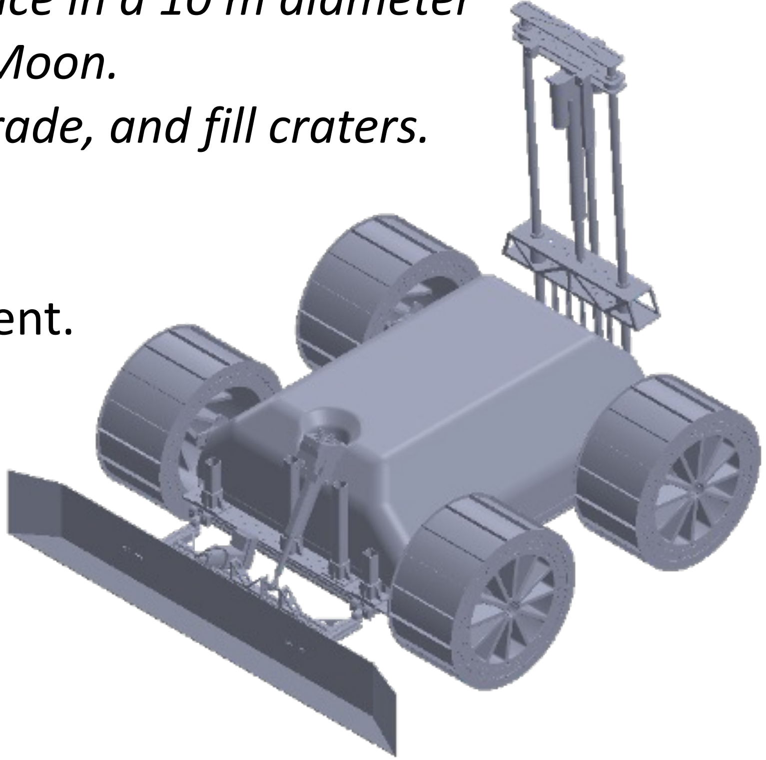
ASPECT - AUTONOMOUS SITE PREPARATION: EXCAVATION, COMPACTION, AND TESTING

Project Summary

Develop a push-button autonomous real-time task-to-motion planning vehicle capable of preparing a lunar surface for landing pad construction. Testing and verify performance in a 10 m diameter testbed with an 83 kg vehicle which represents a 500 kg vehicle on the Moon.
Tasks are to compact the surface to 90% relative density, move rocks, grade, and fill craters.

Anticipated Outcomes

- Demonstration of site preparation in a lunar relevant test environment.
- Demonstration of sustained autonomous task and motion planning.
- Site preparation time per area.
- Infusion plan to put the ASPECT solution on a path to flight.



LuSTR Requirements

- Terrestrial rover mass to be ≤ 83kg.
  - 1g reaction forces = reaction forces of 500 kg rover on the Moon
- Demonstrate site preparation of a 10m diameter and up to 1m deep simulated lunar surface
  - LuSTR prescribes the start and end states:
    - Starting state: # of and size of craters, # and size of rocks, slope to be leveled
    - End state: over the 10 m dia. level to <1°, <1 cm RMS, 90% relative density.


Image Credit NASA

The LuSTR21 solicitation specified several system and test requirements

Inherent challenges of site preparation on the Moon …and solutions we are investigating

- Low lunar gravity reduces available reaction mass
  - Minimize regolith movement
  - Carefully manage cutting and traction forces
  - Move only loose, low density, regolith
- Autonomy is necessary
  - Site preparation occurs before human arrival
  - Not to use teleoperation
  - Anticipate a series of individual steps

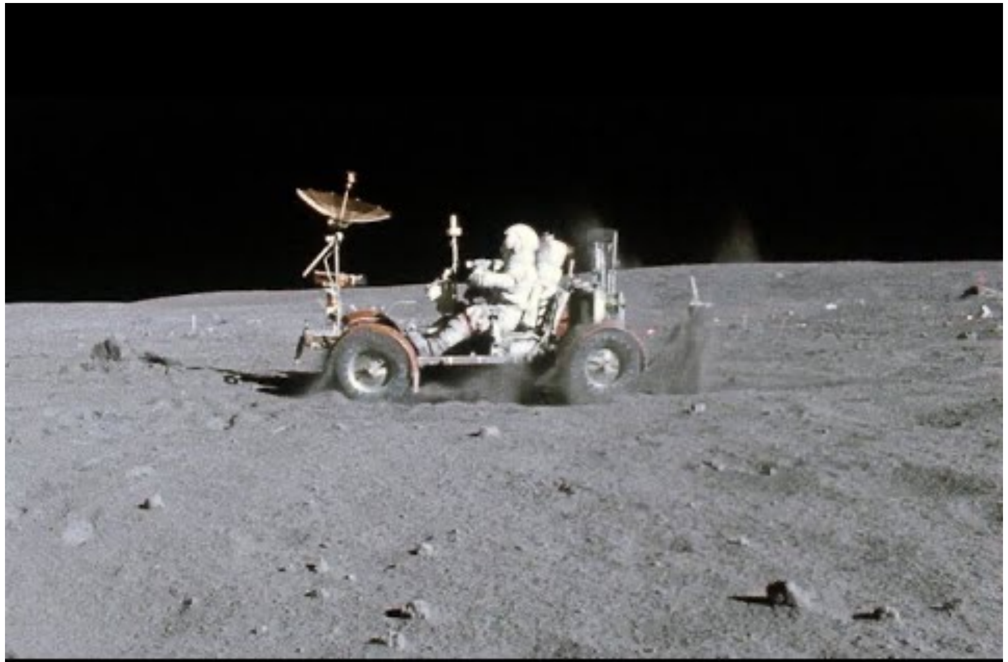
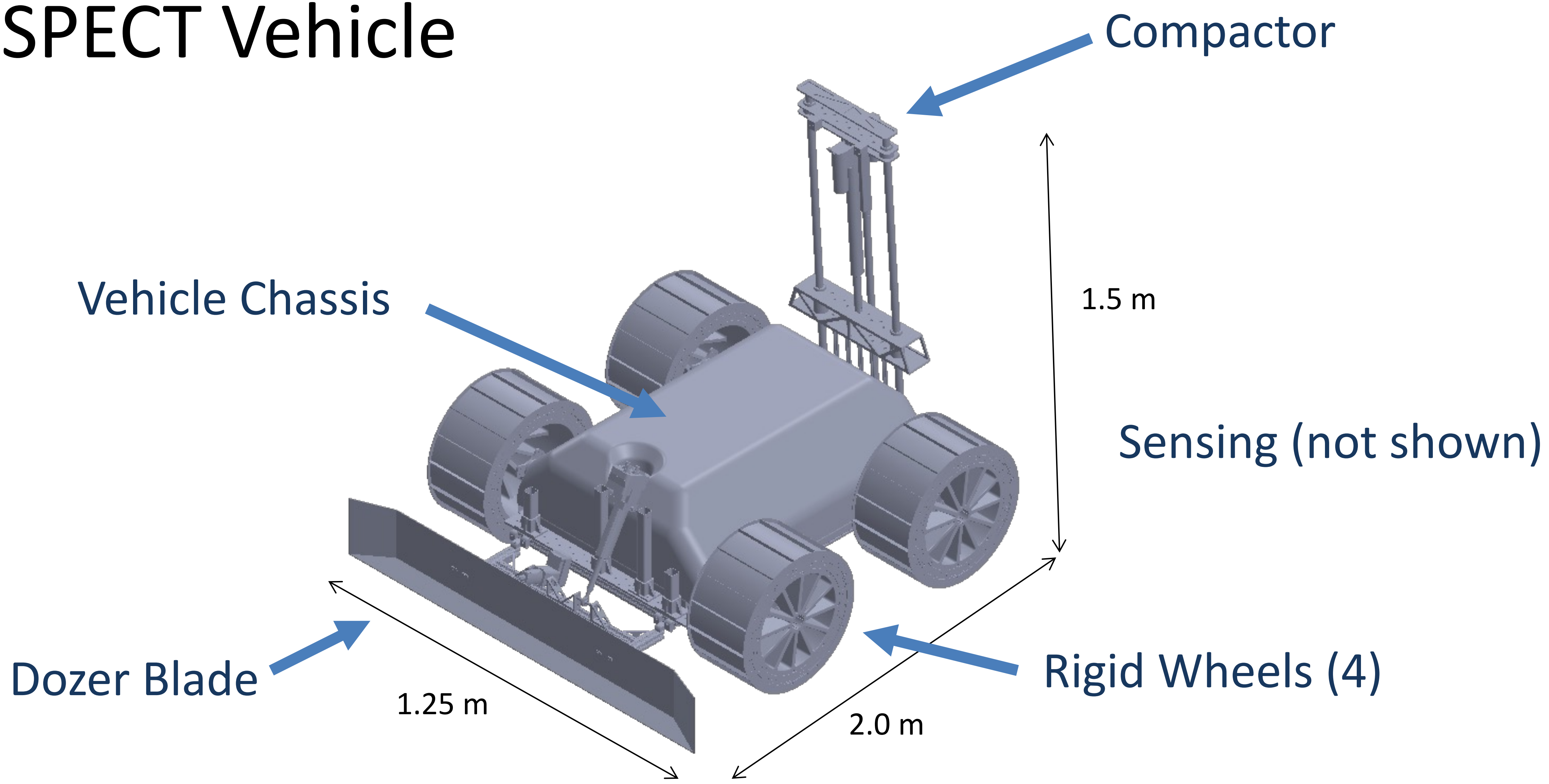


Image Credit NASA

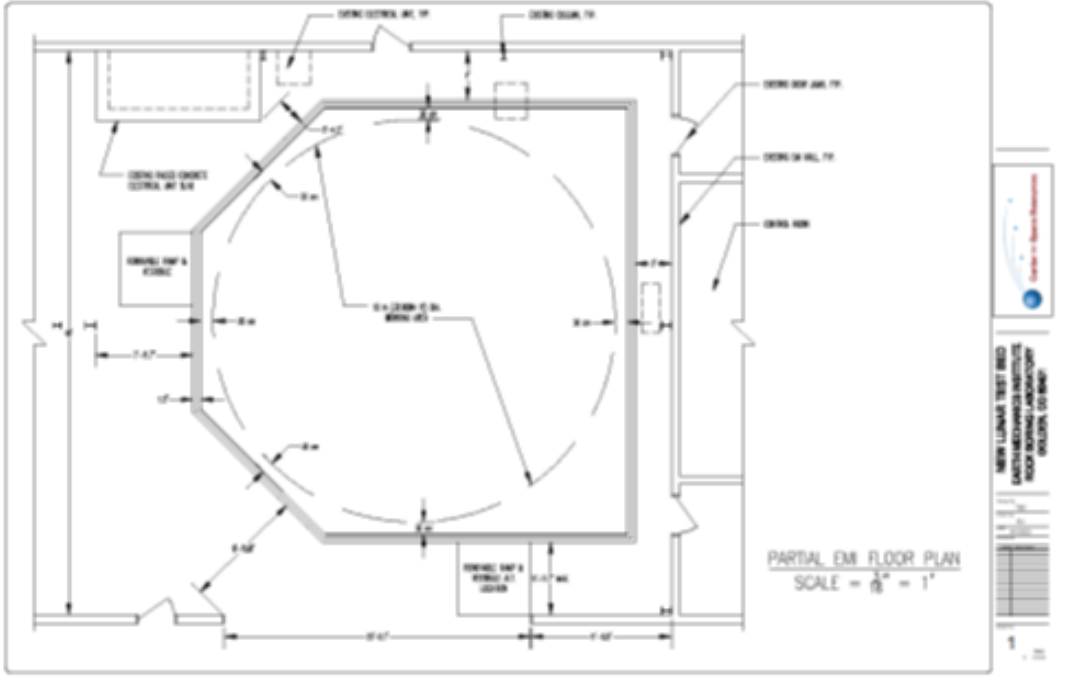
ASPECT Vehicle

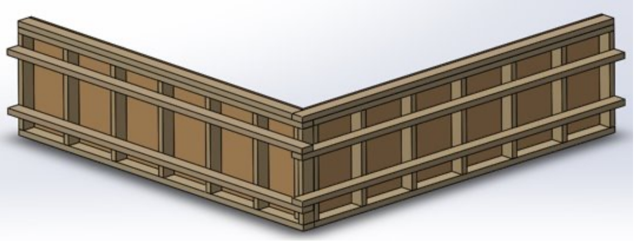


ASPECT LuSTR Testbed

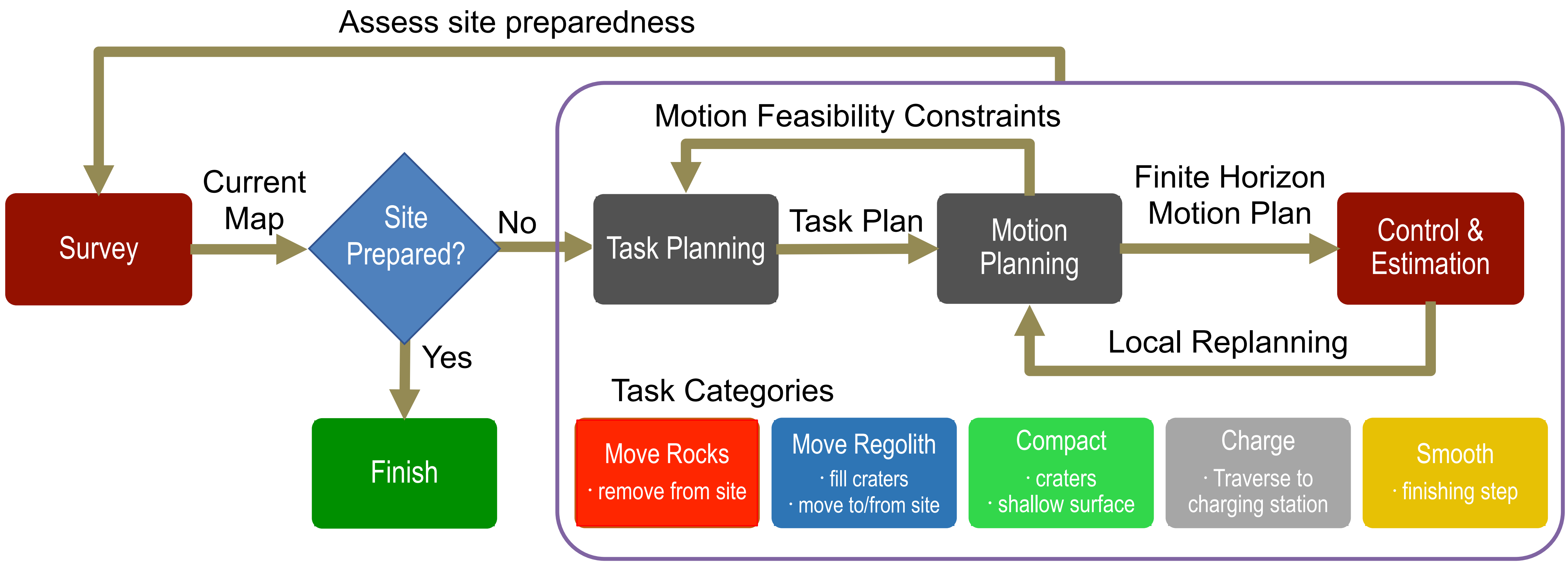
- In Earth Mechanics Institute on campus
- Area > 100 m^2
- Dust enclosure and mitigation
- Simulant: variant of CSM-LHT-1, based on Greenspar anorthosite
- Rocks: pumice for low mass simulation

Existing testbed



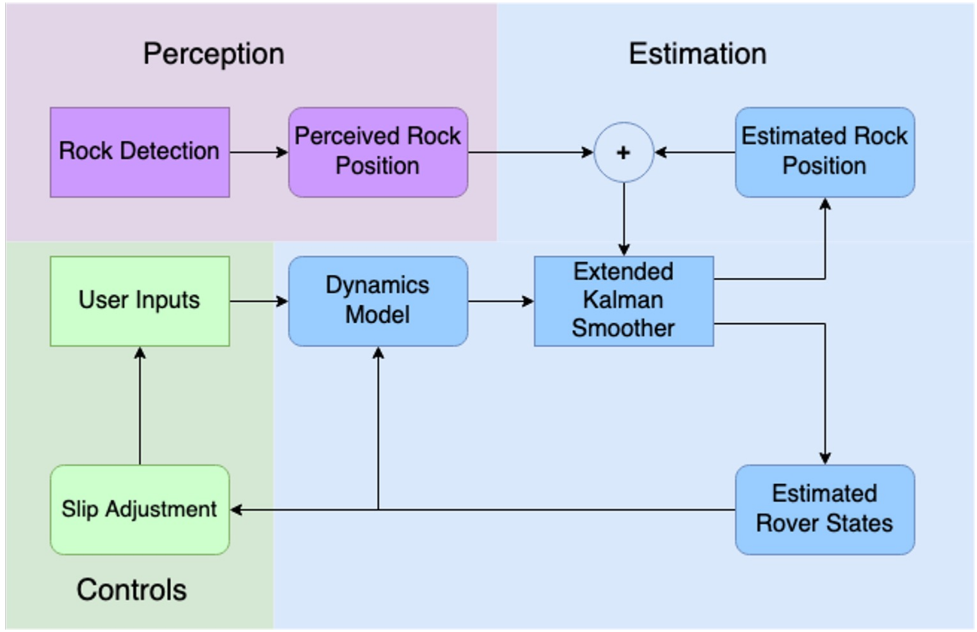


Estimation and Execution Integration



Visual SLAM for Rover Navigation

- Navigation challenges on moon
  - No existing navigation infrastructure
  - Regolith and lower gravity cause wheel slip
- Visual SLAM
  - Perception: Leverage distinct rocks as static lunar landmarks
    - Use color segmentation in RGB image to identify rocks
    - Use depth measurement to compute 3D position of rocks
  - State estimation: Get pose of rover and rocks concurrently using EKS (Extended Kalman Smoother)
    - Estimate and compensate for rover wheel slip using slip dynamics model

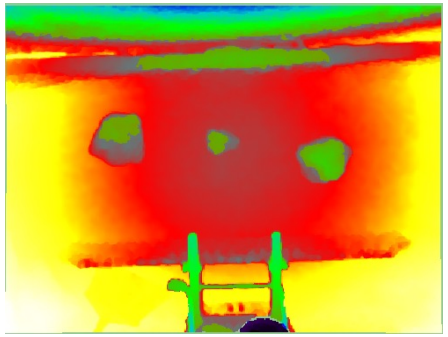


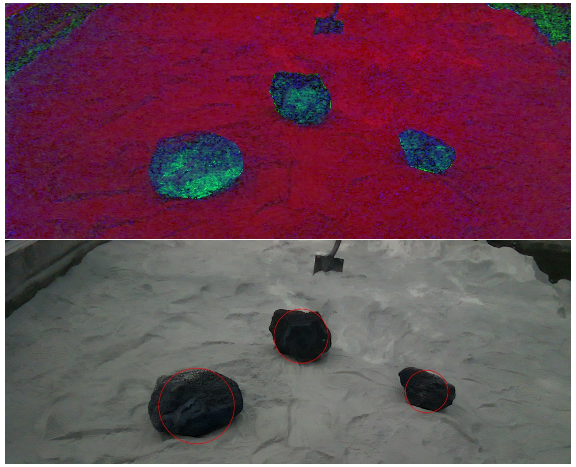
Visual SLAM for Rover Navigation

- Navigation test setup
  - Teleoperated Clearpath Husky rover with Intel RealSense L515 Lidar sensor
  - Regolith simulant chamber with rocks
- State estimation test
  - Fixed ArUco tags used as ground-truth for known trajectory
  - Successfully recovered trajectory and estimate rock landmark positions using visual SLAM
- Future work
  - Autonomous navigation using visual SLAM. Implement rock detection measurement model into estimation framework

Student and Husky in regolith testbed

L515 Lidar rock image





HSV image for rock detection using CV, and corresponding red-circled rocks

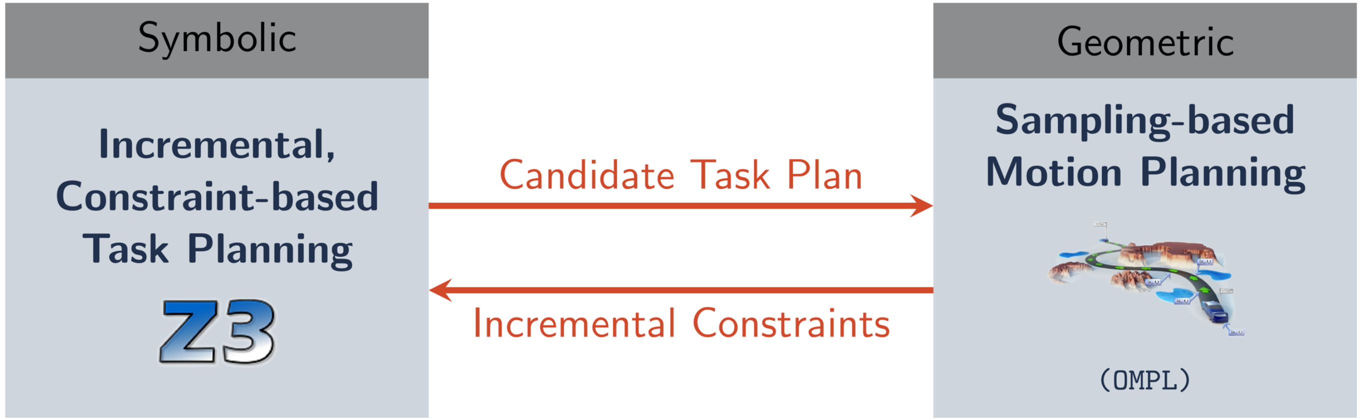
A Task and Motion Planning Approach

Task Planning

- What are the high-level actions or steps?
- Approaches: search, constraint-satisfaction.

Motion Planning

- What are the paths to execute each task action?
- Approaches: search, sampling, optimization



Task Planning

Planning Domain

```
; Compact the soil at a given location
(:action compact
    :parameters (?t - location)
    :precondition (and
        (not (has-rock ?t))
        (rover-at ?t)
        (not (compacted ?t))
    )
    :effect (and
        (compacted ?t)
        (not (smoothed ?t))
    )
)
```

Symbolic Planner

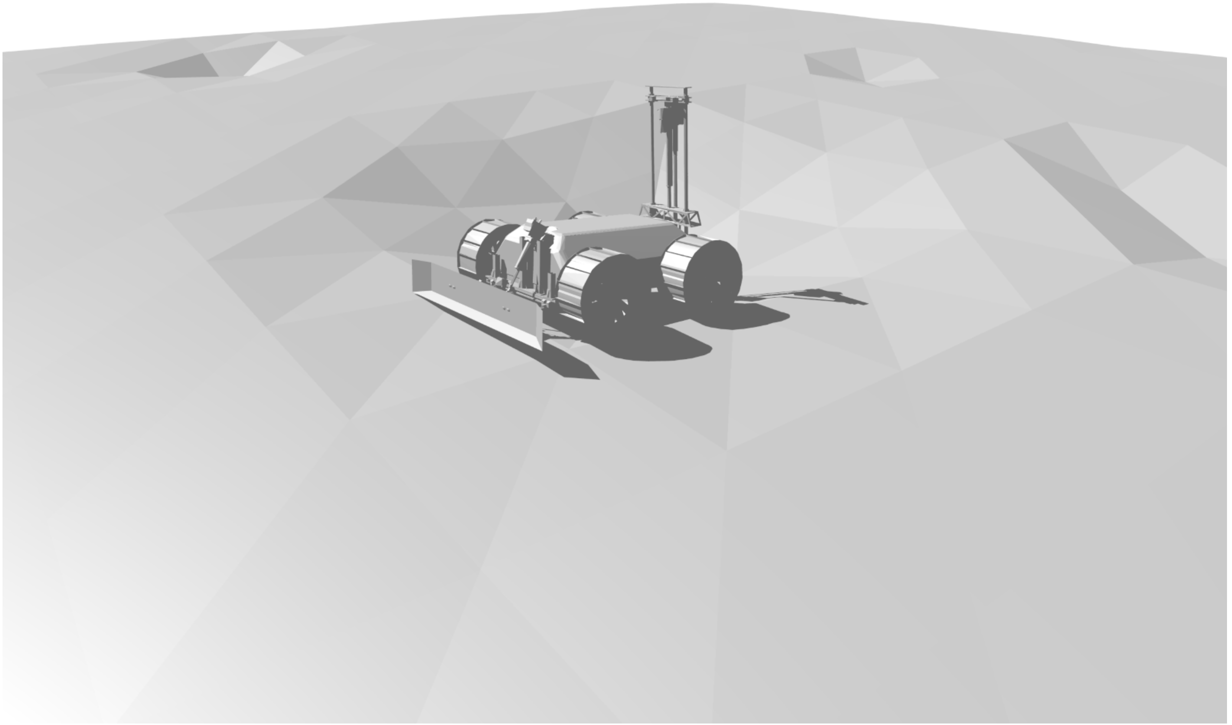
```
TMSMT> (pddl-sat "/planning/domains/simple-compact.pddl" "/planning/goals/clear-2x2.pddl"
'((trace . nil) (:max-steps . 20) (:solver-type . :z3)))
Unrolling at step 1...
Unrolling at step 2...
Unrolling at step 3...
Unrolling at step 4...
Unrolling at step 5...
Unrolling at step 6...
Unrolling at step 7...
((TMSMT/PDDL::COMPACT TMSMT/PDDL::LOC_00_00)
 (TMSMT/PDDL::MOVE TMSMT/PDDL::LOC_00_00 TMSMT/PDDL::LOC_01_01)
 (TMSMT/PDDL::COMPACT TMSMT/PDDL::LOC_01_01)
 (TMSMT/PDDL::MOVE TMSMT/PDDL::LOC_01_01 TMSMT/PDDL::LOC_01_00)
 (TMSMT/PDDL::COMPACT TMSMT/PDDL::LOC_01_00)
 (TMSMT/PDDL::MOVE TMSMT/PDDL::LOC_01_00 TMSMT/PDDL::LOC_00_01)
 (TMSMT/PDDL::COMPACT TMSMT/PDDL::LOC_00_01))
T
TMSMT>
```

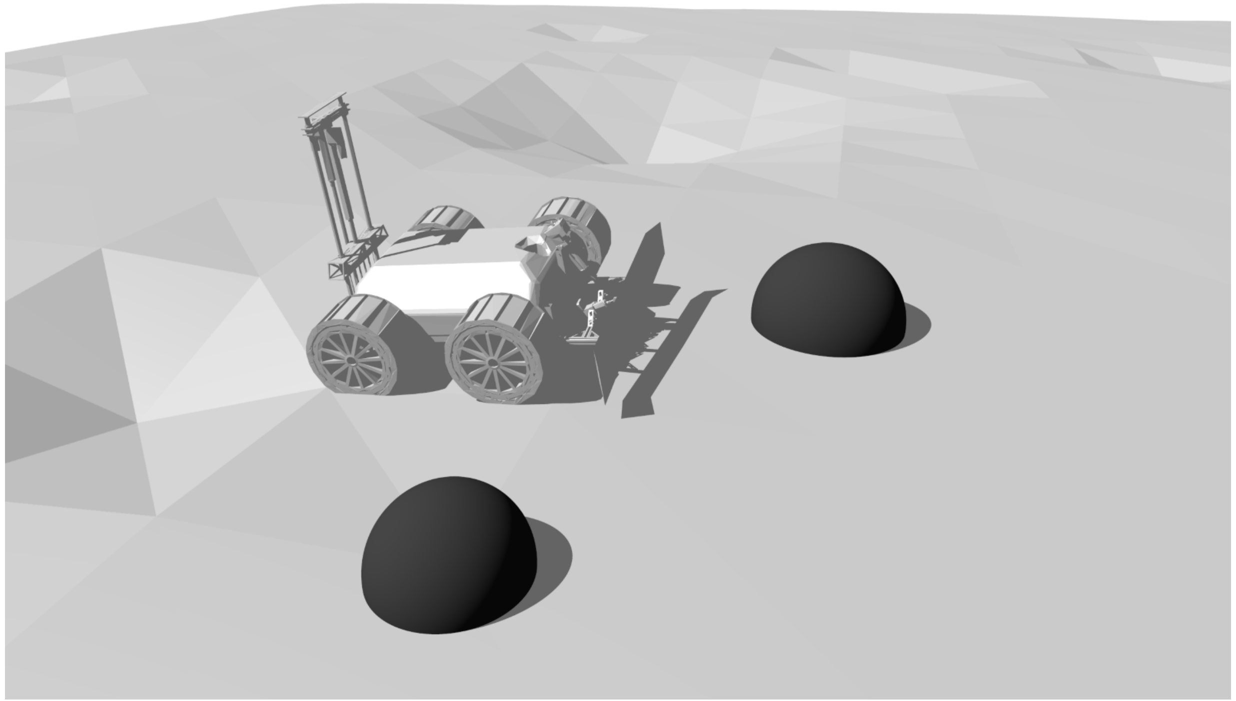
Task Plan

```
# Task Domain: domains/simple-compact.pddl
# Task Domain: goals/clear-2x2.pddl
a COMPACT LOC_00_00
a MOVE LOC_00_00 LOC_01_00
a COMPACT LOC_01_00
a MOVE LOC_01_00 LOC_01_01
a COMPACT LOC_01_01
a MOVE LOC_01_01 LOC_00_01
a COMPACT LOC_00_01
```

Developing a visualization to verify planning

Actual surface map will be imported into the visualizer and planner





Vehicle Chassis and Mobility Platform

Frame/Structure Subsystem

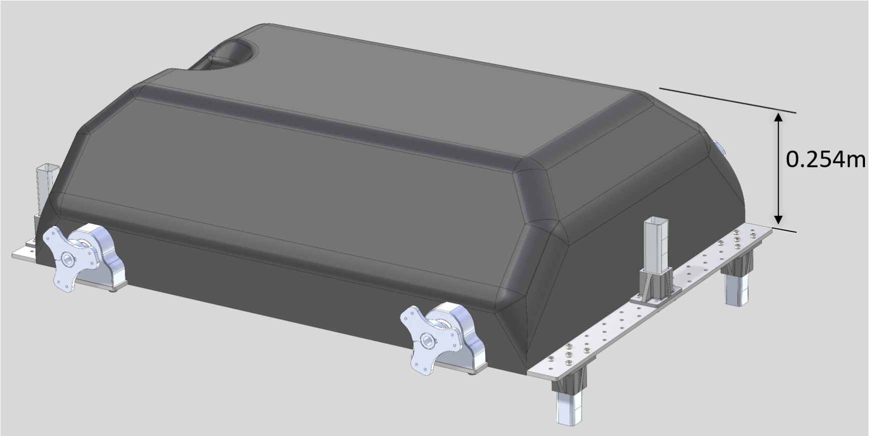
- Load bearing frame
- Electronics Box enclosure
- Outer Body Enclosure
- Light weighting using carbon fiber

Mobility Subsystem

- Drivetrains x 4
  - Motors, gearboxes, driveshafts

Payloads Mounts

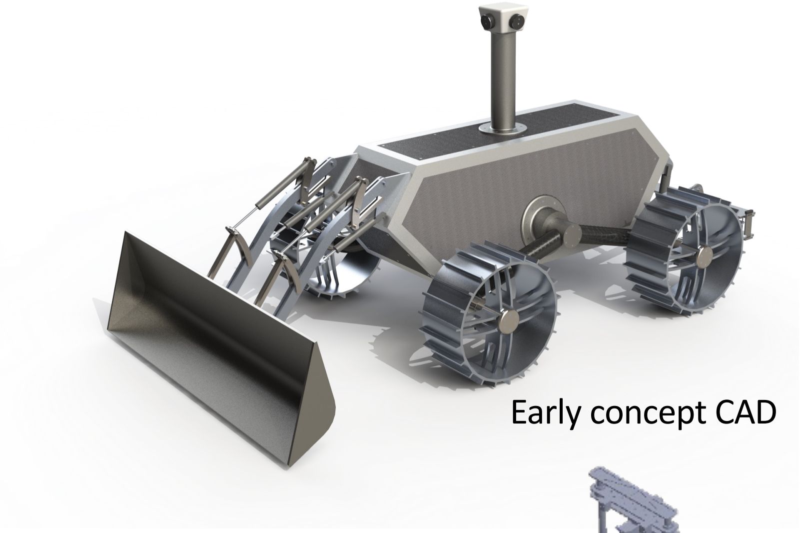
- Structural mounting points at either end

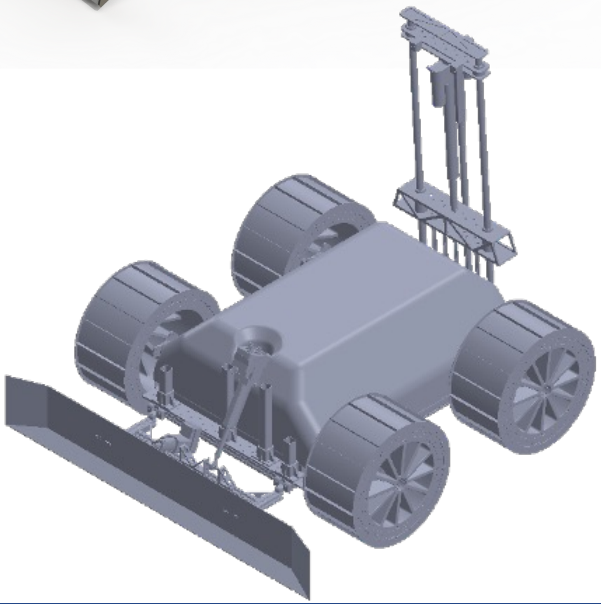


Lunar Outpost™

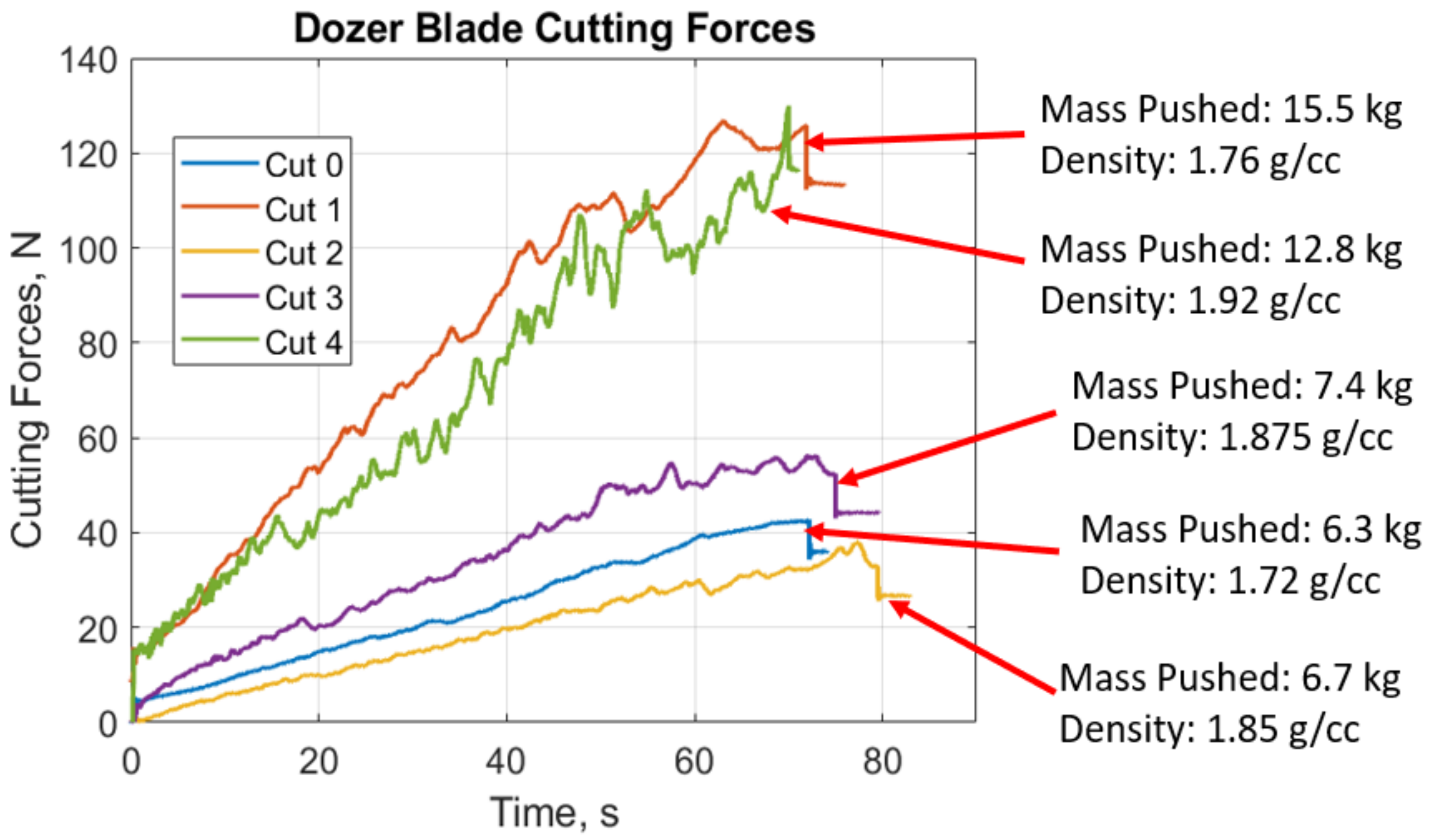
Regolith Manipulation Tools

- One bucket does it all
  - – Base principle: only move loose regolith
  - – Multi-purpose bucket – regolith manipulation, grading, and rock removal that minimizes forces through vibration
  - – Articulate the bucket to
    - Push regolith and rock – Blade vertical, forward drive
    - Lift regolith and rock – Blade low, forward drive and lift
    - Smooth – Blade low, rearward drive
    - Rip – Blade negative rotation, rearward drive
- Bucket and wheels designed together
  - Careful management of cutting/traction forces


Early concept CAD



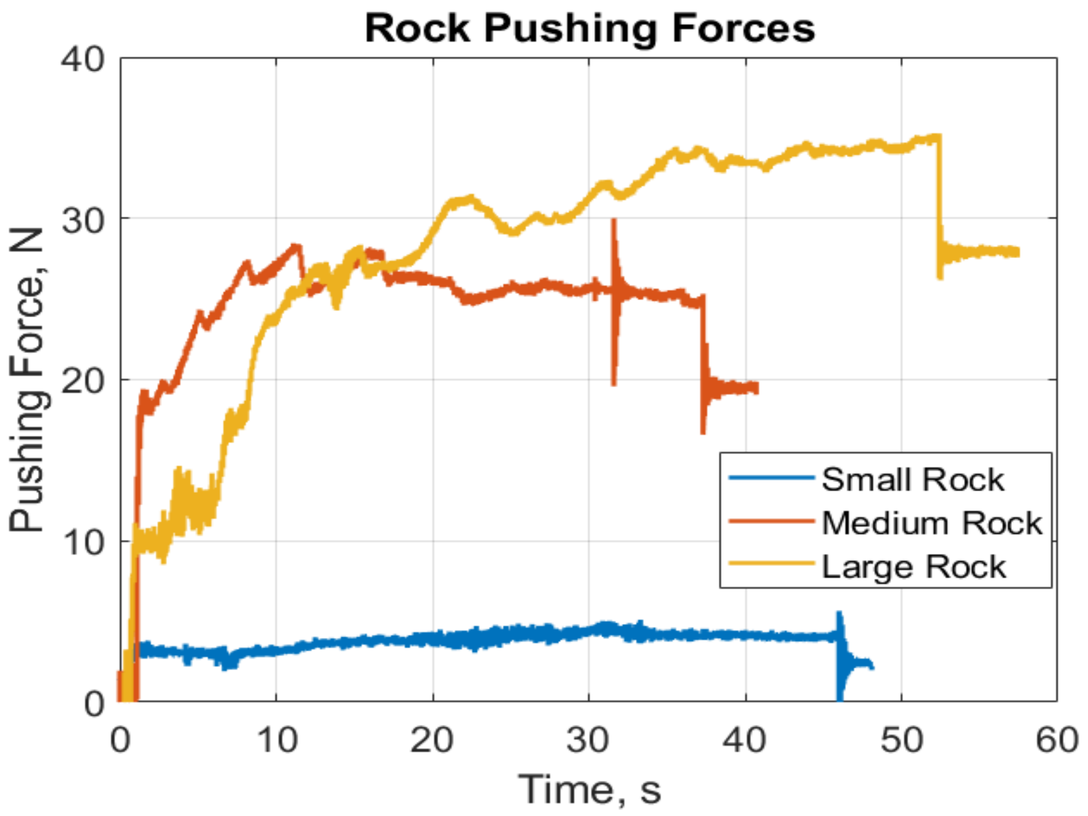
Dozer Blade Testing



Results are generally in agreement with Balovnev Blade analysis.

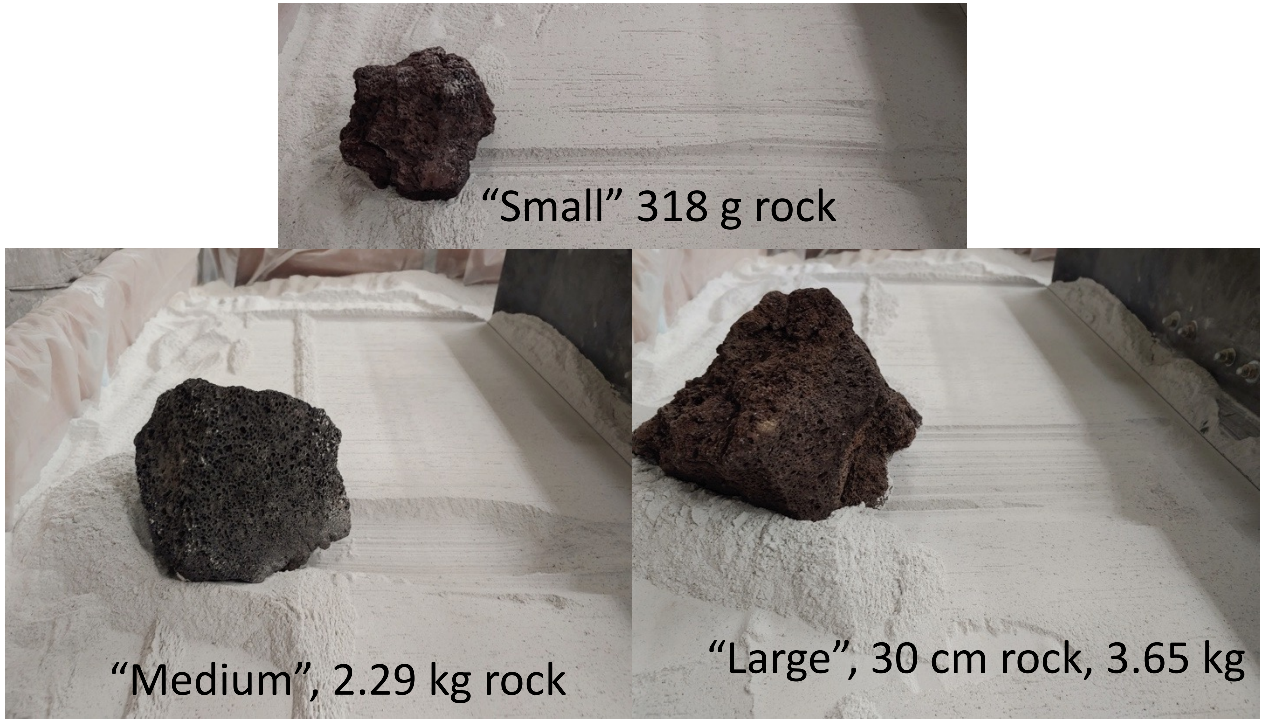
Cutting force vs. time for five sequential cuts with cut depth from 3 to 8 mm. Each cut covered a distance of 80 cm.

Rock Pushing



Pushing force for each of the rocks tested, with rock masses of 318 g, 2.29 kg, and 3.65 lg.

Pumice rock, approx. 0.8 g/cc density



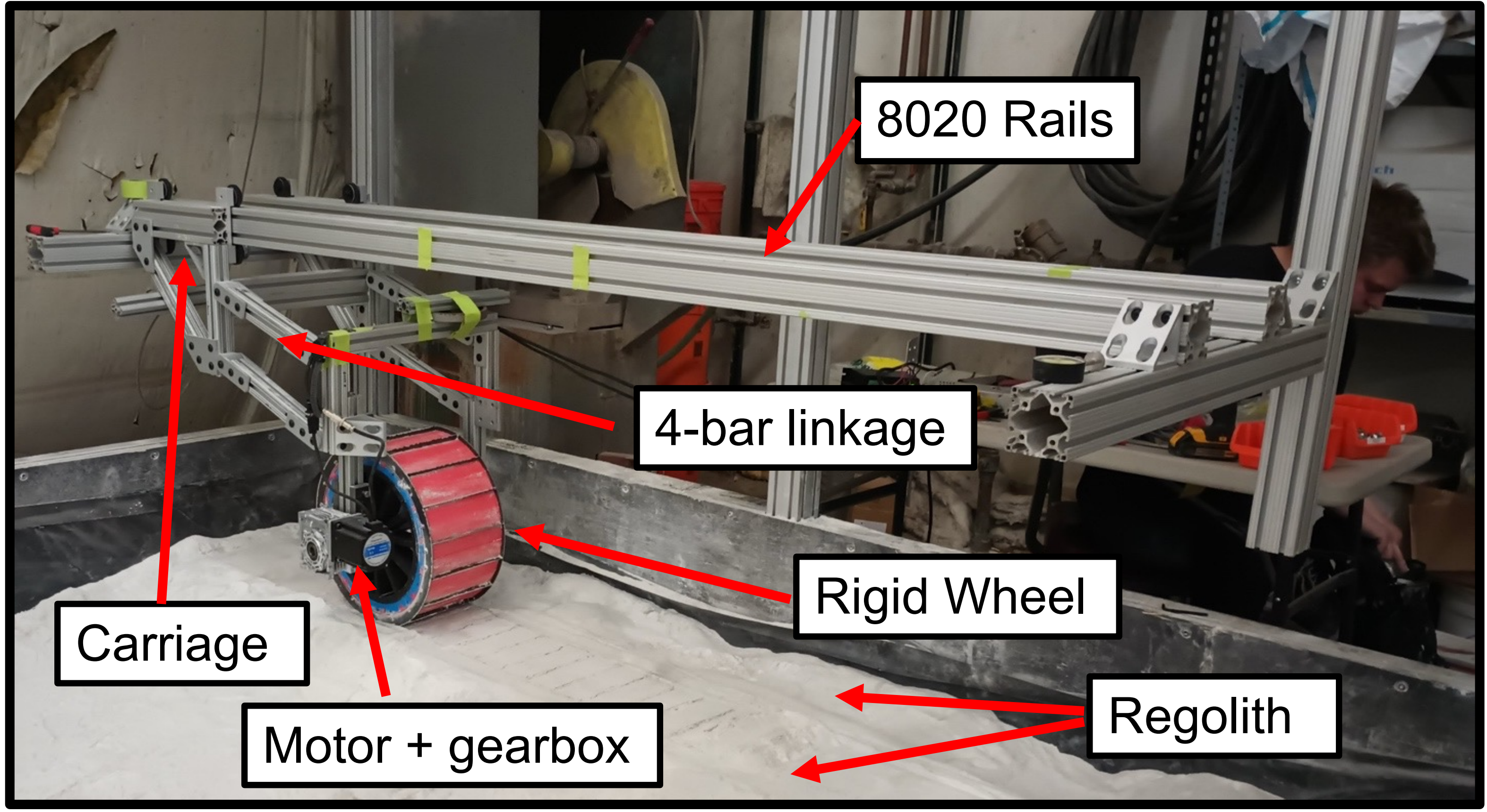
Tests show that pushing force is < 40 N for even largest rock (30cm)

Wheel Testing

- Wheel test rig designed to characterize drawbar pull and slippage
- 4-bar linkage allows vertical compliance

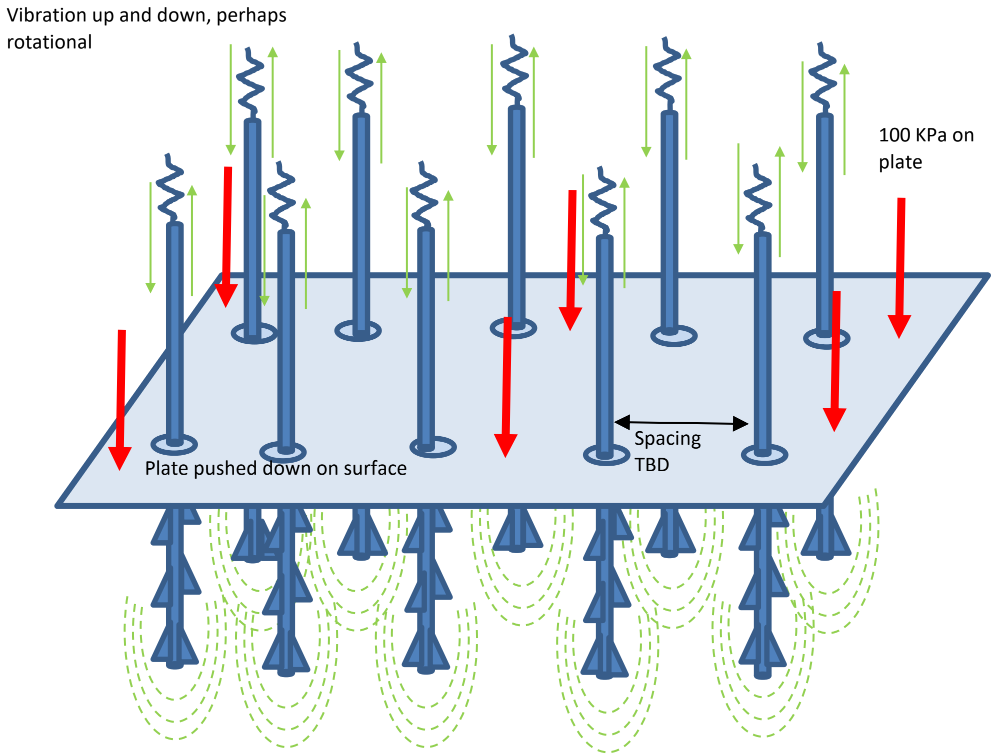
Drawbar pull testing

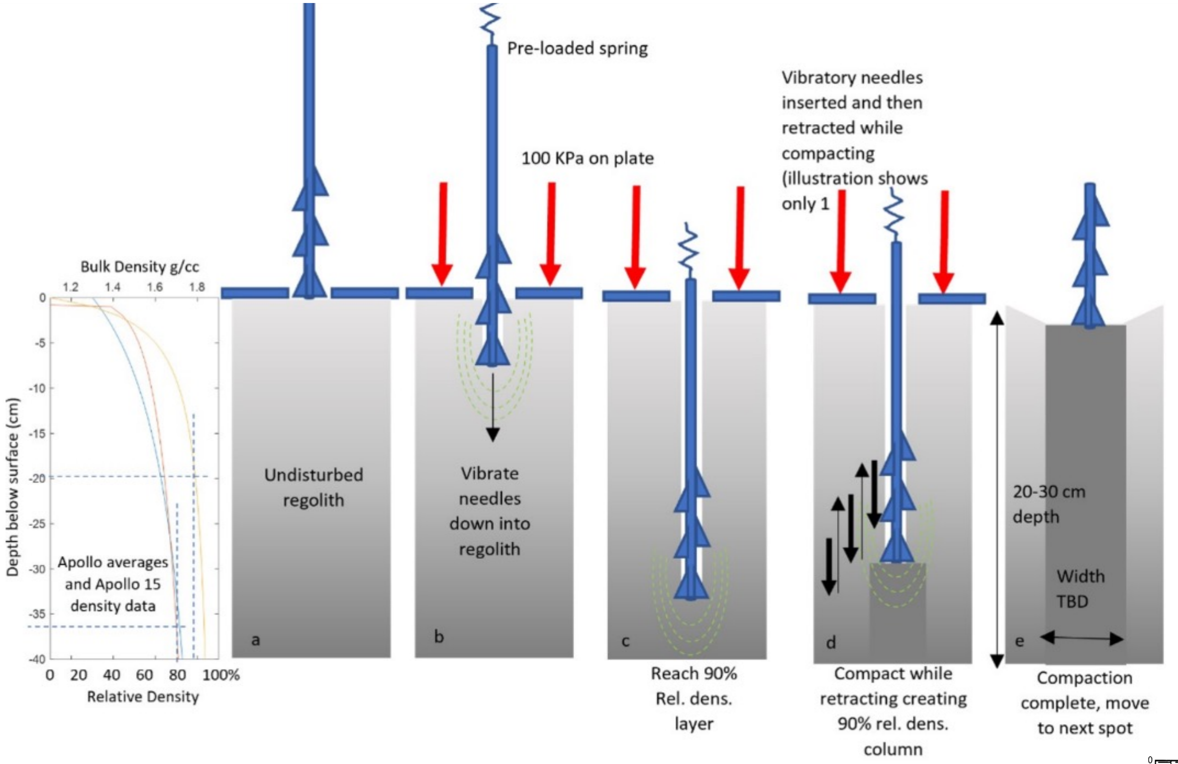
- 68N/wheel w/ 20.75 kg load/wheel at 14.4% slip, 5 cm/s
- Good agreement with terramechanics model (Bekker)



With baseline wheel, a 4-wheel vehicle can pull 272 N, which exceeds maximum bucket loading

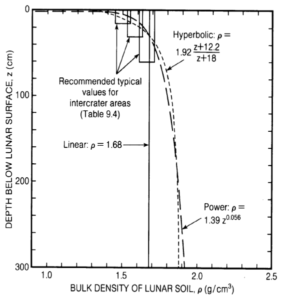
Compaction - Concept





The proposed compaction mechanism showing downward pressure plate and vibratory needles (left), showing one vibratory needle in its downward position (center) and after completing compaction (right)

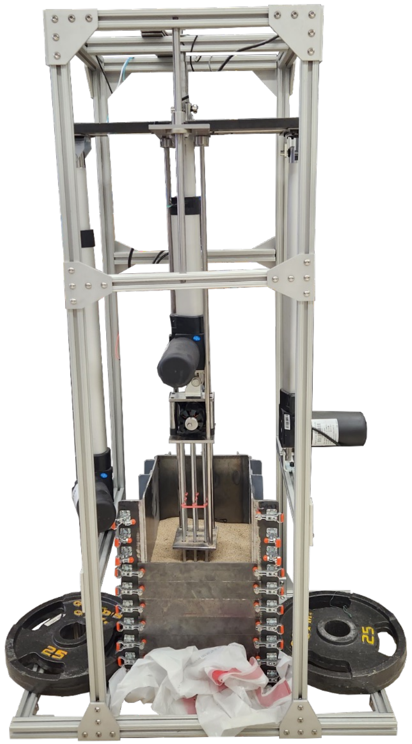
- 90% relative density naturally reached between 20-37 cm depth.
- Need to compact top 20-30 cm – estimated pressure 100 kPa
  - Based on compressibility measurements of lunar samples at 90% rel. den.



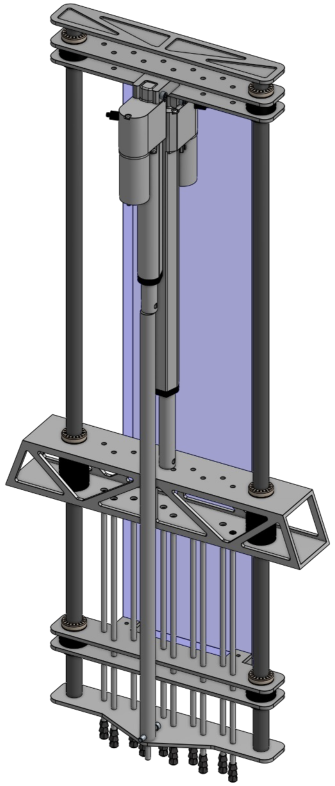
Lunar Source Book bulk density with depth derived relationship from Apollo core data

Compaction Development

Multi-pin and single pin testing

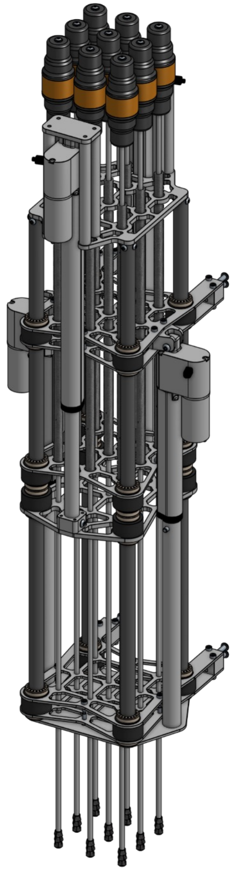


LuSTR Compactor Design

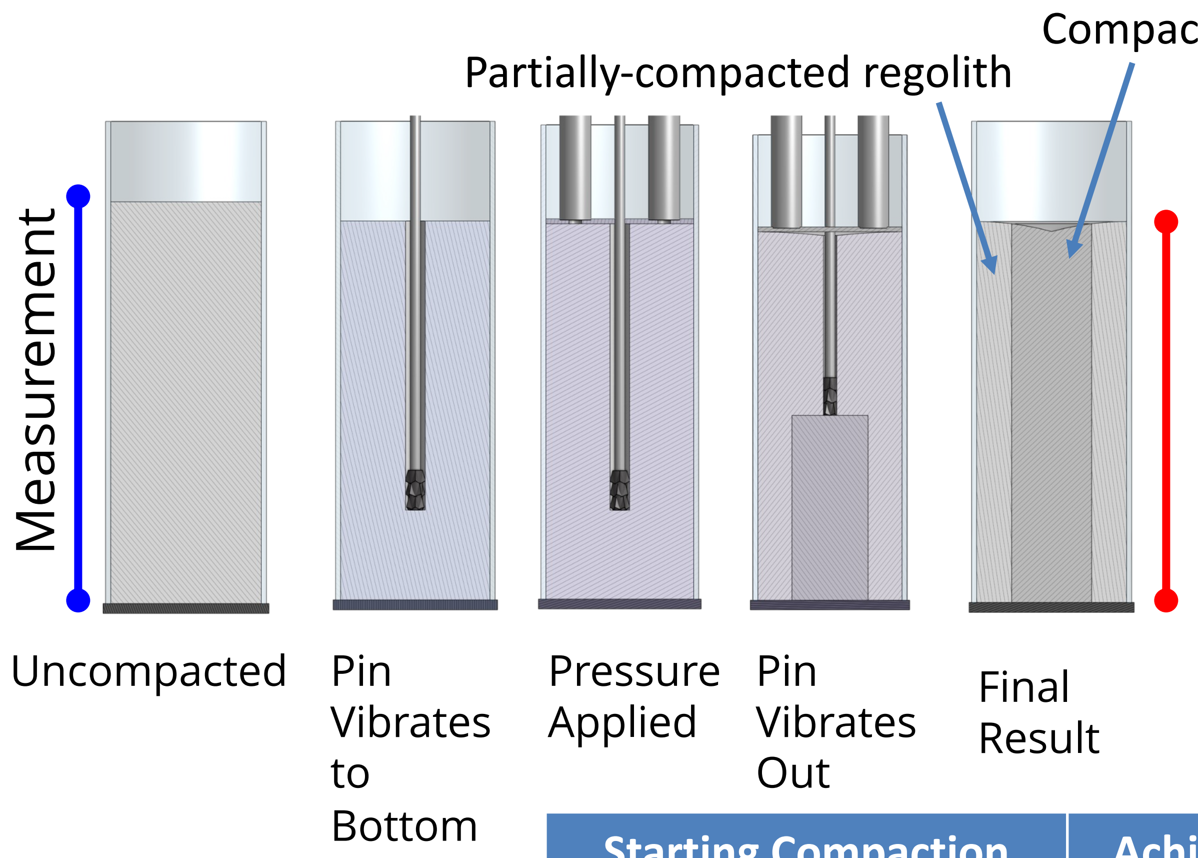


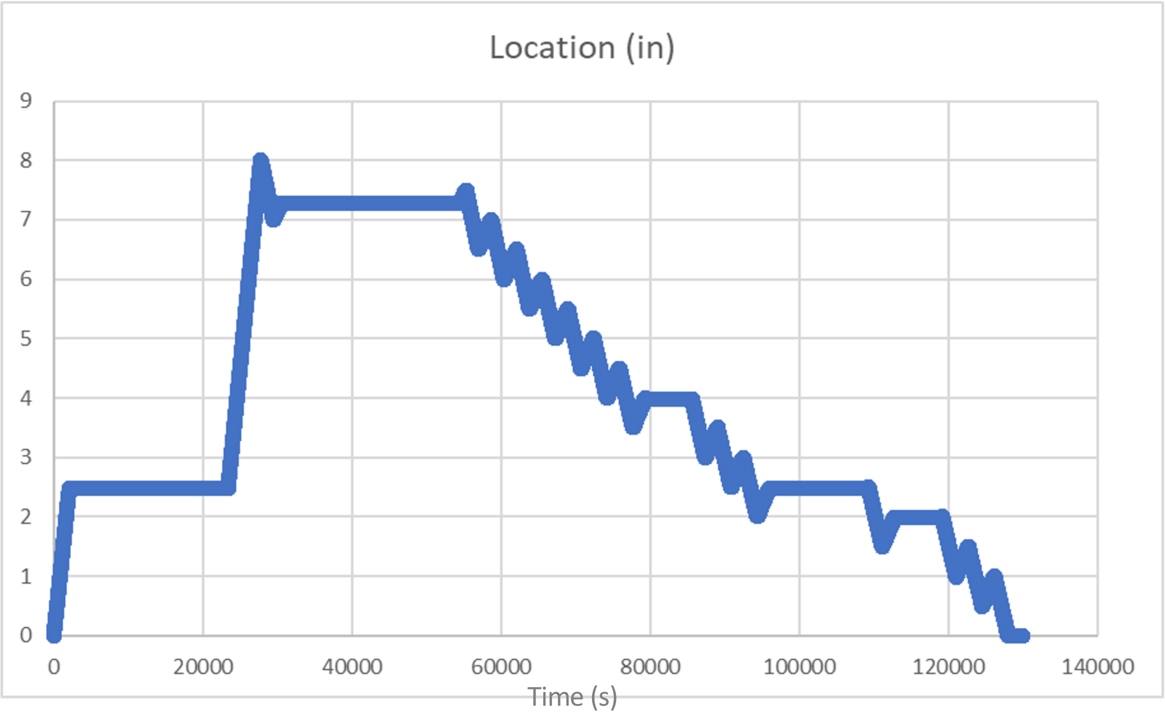
Lunar Infusion Compactor Design

MTU DTVAC



Testing Single Pin in Cylinders





Starting Compaction Relative Density	Achieved Compaction Lower Bound
49.22%	64.87%
39.13%	49.17%
17.54%	62.21%
17.49%	57.68%

- Investigating the parameter space – frequency (10's of Hz), dwell time, sequencing, plate pressure (~15 kPa)

Infusion

- Human lander scale site preparation
- Size up to 100 m diameter landing pad
- Support and ancillary equipment
- Path to flight

Thank you!

Questions?

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