REV-LE

Regolith Excavation Vehicle for Lunar Exploration

C3 Cosmic: Final Outbrief

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Ram Vedula, Wayne Williams, Brooke Wolfram

Team Overview

- Senior capstone design aerospace design project
- Team REV-LE,

  Texas A&M University
- REV-LE makes the moon ready for touchdown and construction


Joshua Cole
Compaction


David Fumero
Electronics/Power


Miranda Kang
Team Lead


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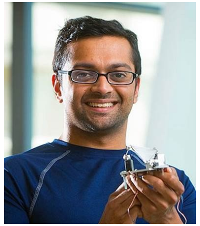
Software & Autonomy


Ram Vedula
Structures


Wayne Williams
Robotics and Manufacturing


Brooke Wolfram
Systems


Tim Kienberger
Cosmic Mentor


Dr. Manoranjan Majji
Advisor

Mission Overview

REV-LE

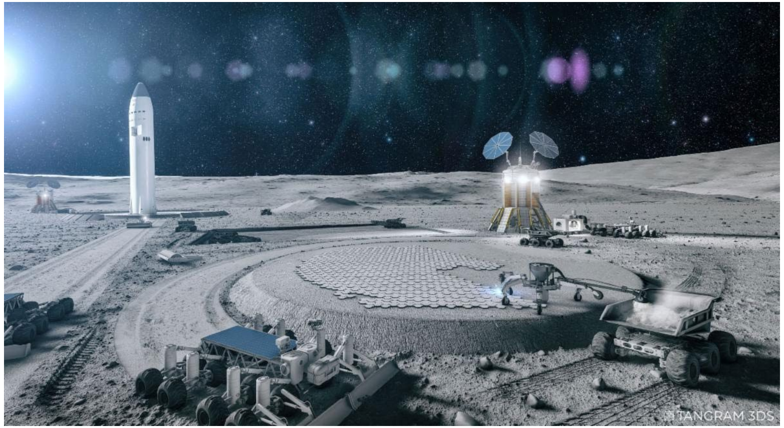
Executive Summary

Background and Motivation:

- Lunar regolith: abrasive, adhesive, unstable, erosion-prone
- Dust plume kick-up and surface instability threaten landers and hardware
- Artemis-era lunar infrastructure requires prepared, stable surface sites
- Current lunar rover efforts rarely address autonomous site preparation

Solution:

- REV-LE: autonomous rover for leveling, rock clearing, and regolith compaction
- Supports safer landing zones and future lunar infrastructure
- Moderate compaction can increase regolith strength by 2–4×



Design Process Overview

Problem Definition

The problem provided by C3 Cosmic helped determine the system's main stakeholders and primary needs.

System Concept Review

From primary needs, developed goals to determine mission success. Trade study conducted to determine system concept and conops.

System Requirements Review

Fleshed out design by creating system and subsystem level requirements, as well as creating diagrams displaying the system architecture.

System Definition Review

Conducted trade studies to size the subsystems while ensuring they meet requirements, and introduced a risk assessment.

Preliminary Design Review

Design subsystems and reflect whether the final design meets the system requirements and stakeholder needs.

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Stakeholders

Primary Stakeholders	
Lunar lander companies (SpaceX, Blue Origin, Intuitive Machines, Firefly, Future Systems, etc.)	Lunar habitat companies (ICON, Sierra Space, Lockheed Martin, Boeing, etc.)
Lunar mobility companies (Lunar Outpost, Intuitive Machines, Astrolab, NASA JPL,etc.)	End operator of system (Internal team or NASA)
Lander provider (Astrobotic)	NASA & Other International Space Agencies (JAXA, ESA, ISRO, etc.)
Federal Aviation Administration	Federal Communications Commission

Stakeholders were identified by considering the full lifecycle of our system and determining the parties directly affected by its site preparation.

Needs, Goals, and Requirements

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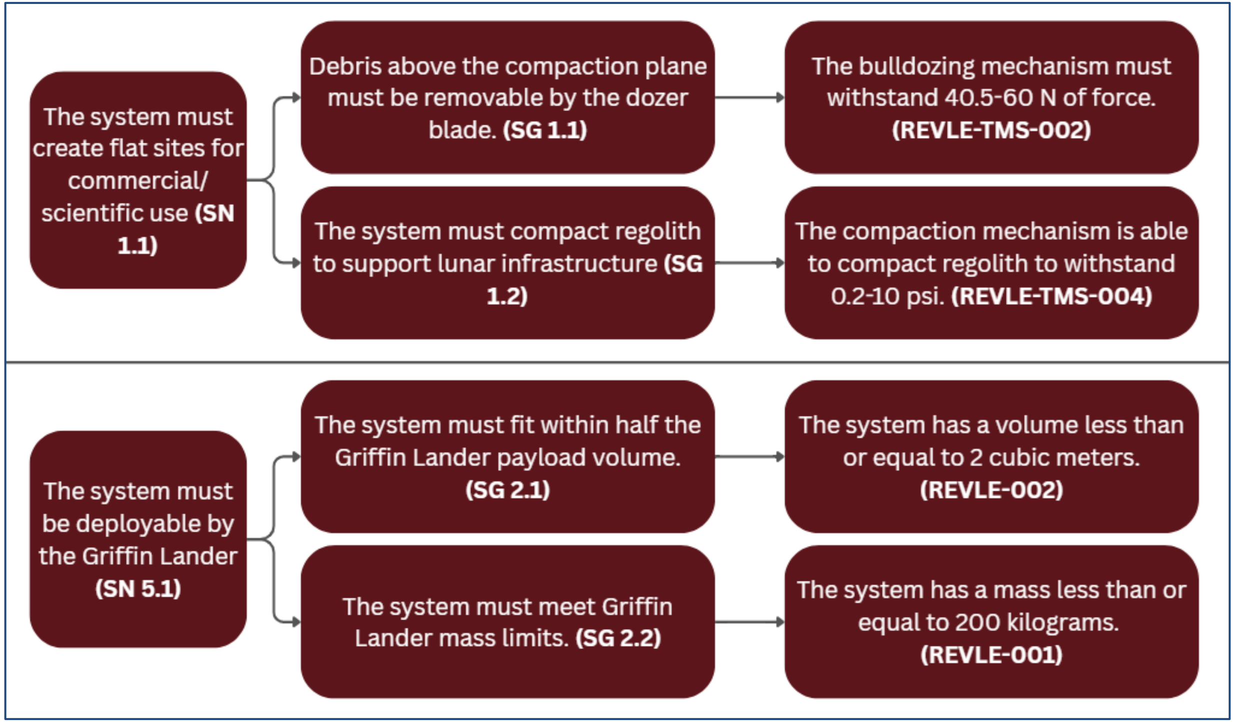

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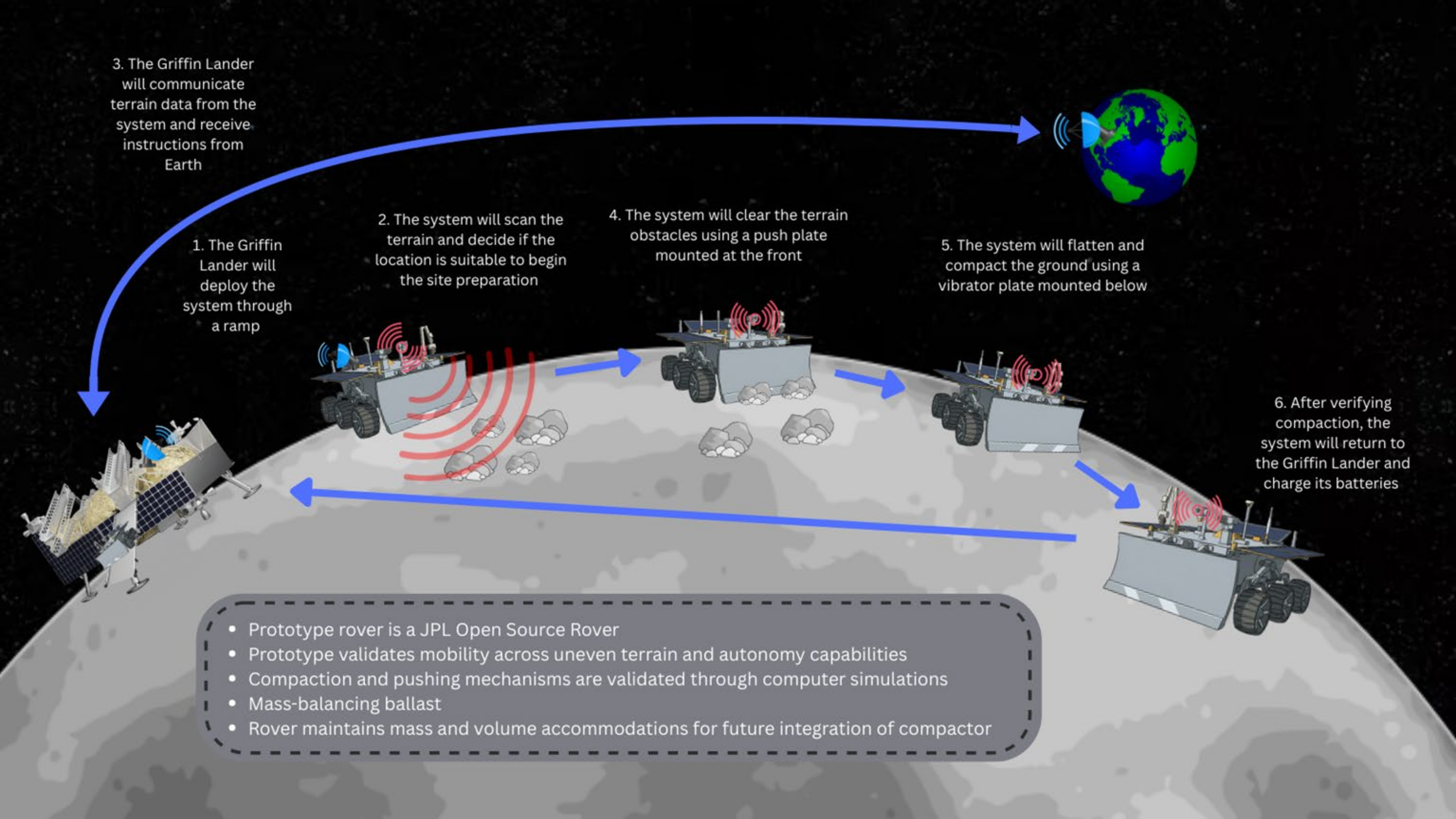
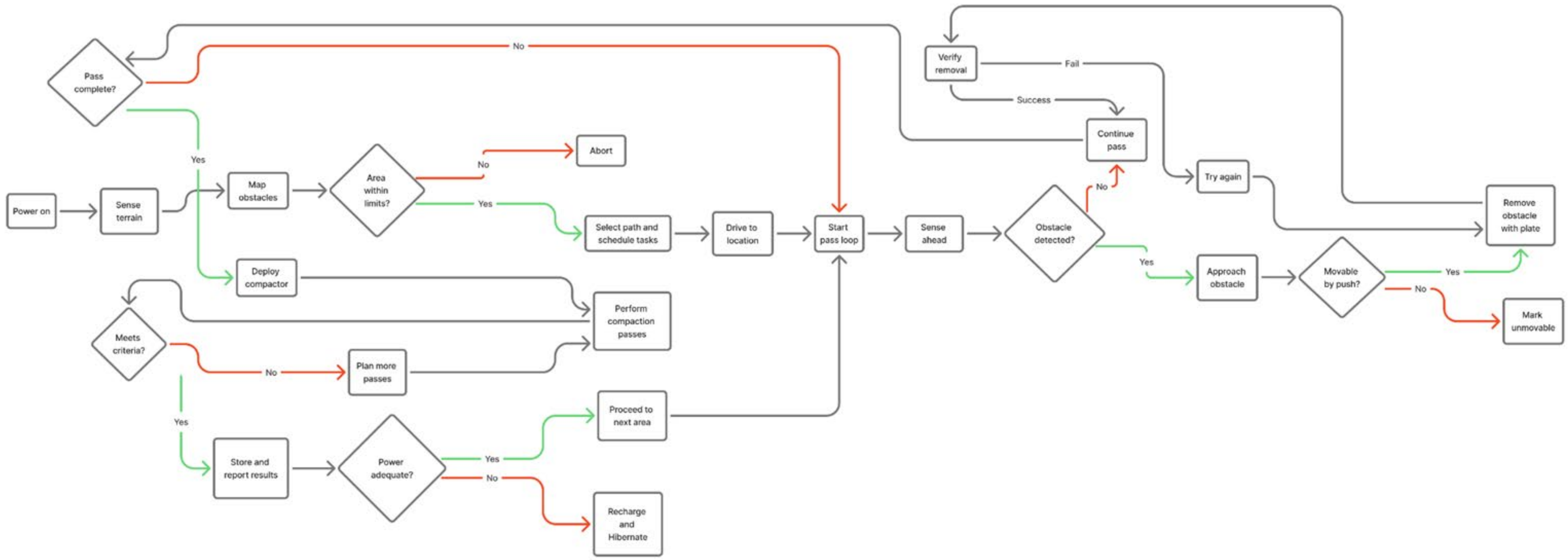
System Concept and Architecture


3. The Griffin Lander will communicate terrain data from the system and receive instructions from Earth
1. The Griffin Lander will deploy the system through a ramp
2. The system will scan the terrain and decide if the location is suitable to begin the site preparation
4. The system will clear the terrain obstacles using a push plate mounted at the front
5. The system will flatten and compact the ground using a vibrator plate mounted below
6. After verifying compaction, the system will return to the Griffin Lander and charge its batteries
• Prototype rover is a JPL Open Source Rover
• Prototype validates mobility across uneven terrain and autonomy capabilities
• Compaction and pushing mechanisms are validated through computer simulations
• Mass-balancing ballast
• Rover maintains mass and volume accommodations for future integration of compactor

Functional Flow Block Diagram

REV-LE



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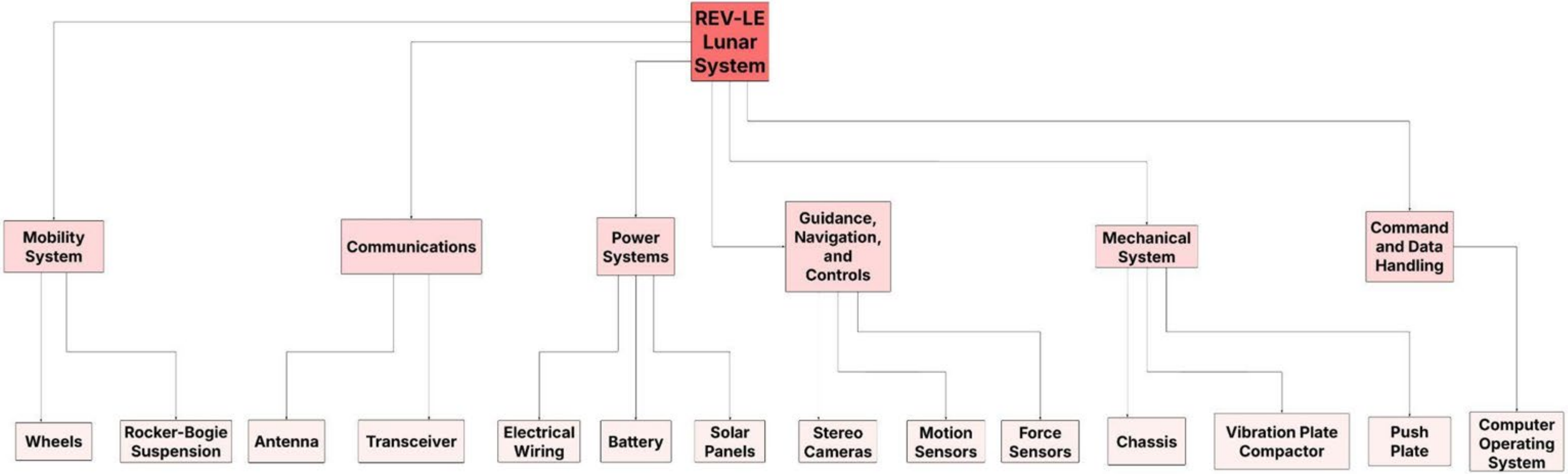
System Architecture



System Design

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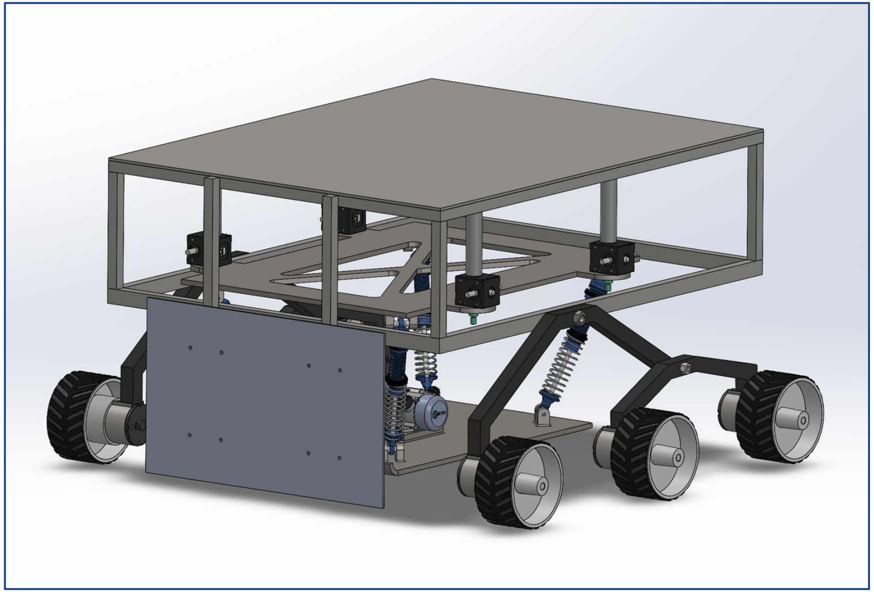
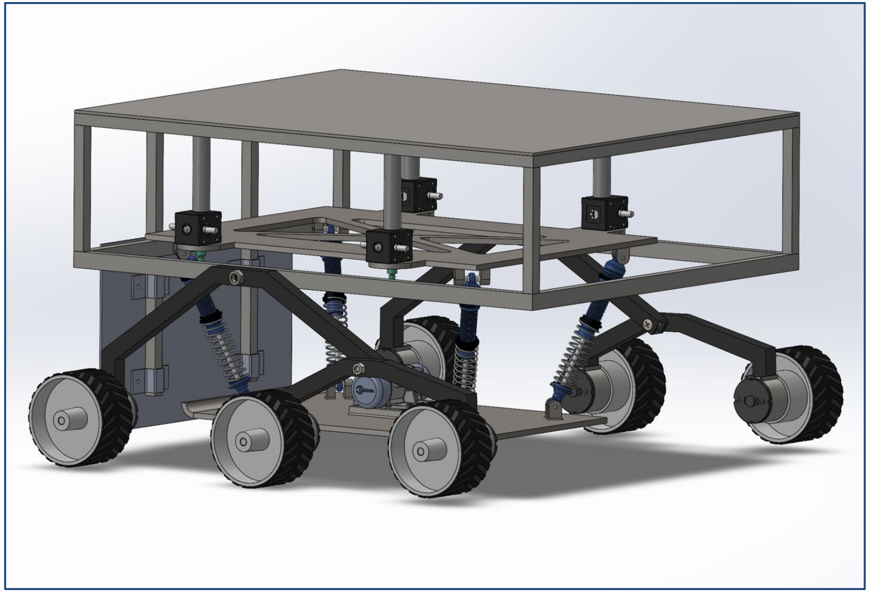
Rover Assembly

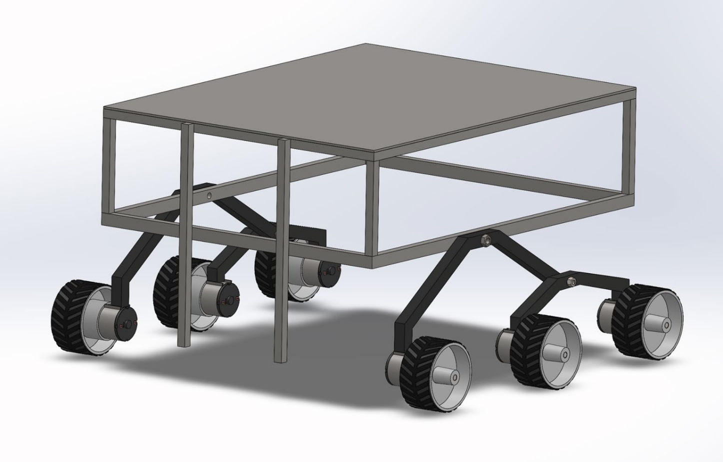




Chassis

System/Subsystem Requirements:

- REVLE-001: The system shall have a mass less than or equal to 200 kilograms at launch
- REVLE-TMS-003: The TMS system shall be able to withstand temperatures ranging from -208 to 250°C



System Overview:

- Steel Chassis with Rocker Bogie Suspension System
- Material: 4130 Steel (tubing), A36 Steel (Sheet metal)
- Tubing Dimensions: 1"x1" square tube, 1/16" thick
- Sheet Metal Dimensions: 28" x 36", 0.1875" thick
- Volume: 37" x 41" x 22"
    - Conforms to Griffin Lander Payload Requirements
- Mass estimate: 98 lbm (44.5 kg)
- Manufacturing Methods: Waterjet, Bandsaw, Welding

Suspension

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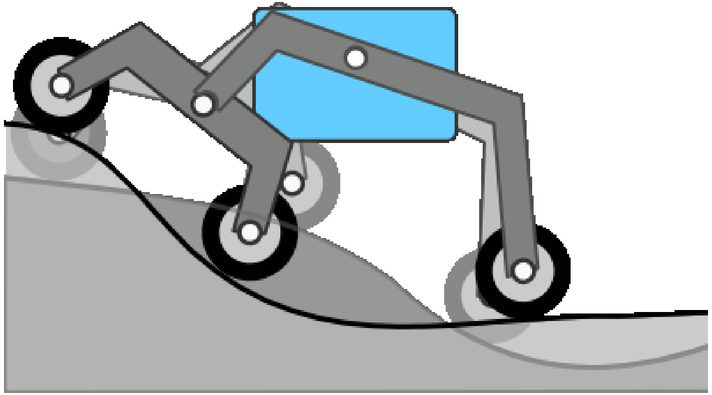
System/Subsystem Requirements:

- REVLE-001: The system shall have a mass less than or equal to 200 kilograms at launch
- REVLE-TMS-003: The TMS system shall be able to withstand temperatures ranging from -208 to 250°C

System Overview:

- 6 Wheel Rocker Bogie Suspension
- Material: 4130 Steel (tubing)
- Wheel Radius: 0.18 m
- Min Clearance: 0.10 m
- Traverse slope capability: ±25°



Suspension Trade Study

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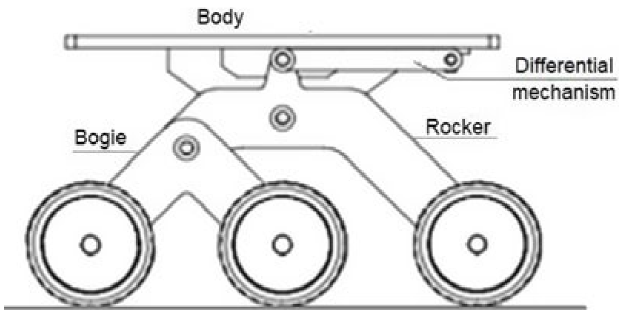
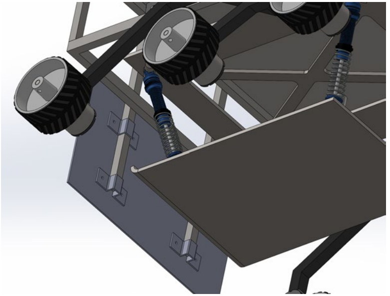
Selection Criteria	Weight	Scale	Rocker Bogie	Active	Independent	Solid axle
Mobility & Obstacle Clearance	0.3	1-5	5	5	4	2
Stability	0.2	1-5	4	5	3	2
Mass	0.15	1-5	3	2	3	5
Power Consumption	0.15	1-5	4	1	3	5
System Simplicity	0.1	1-5	4	1	3	5
Robustness	0.1	1-5	4	3	2	1
Totals	1		4.15	3.35	3.2	3.1



Bulldozer Plate

System/Subsystem Requirements:

- REVLE-005: The system shall compact and clear greater than or equal to 250 square meters of surface per operational lunar day
- REVLE-TMS-002: The TMS system’s bulldozing mechanism shall be able to withstand between 40.5 and 65 N of resistive normal force on the blade without yielding or buckling with a FOS of 1.5



	Mode	Frequency [Hz]
1	1.	197.63
2	2.	231.27
3	3.	233.92
4	4.	263.95
5	5.	311.48
6	6.	311.83

System Overview:

- Material: Al-7075-T6
- Plate Dimensions: 7 gauge thick, 20” x 12” plate
- Brackets: ⅛” thick, 1” wide/high, 3” long
- Mass estimate: 4.4 lbm (2 kg)
- Preliminary Resonance Mode Estimate: 197.63 Hz
- FOS against Yielding: > 29
    - Decided against using thinner sheet metal due to manufacturing concerns

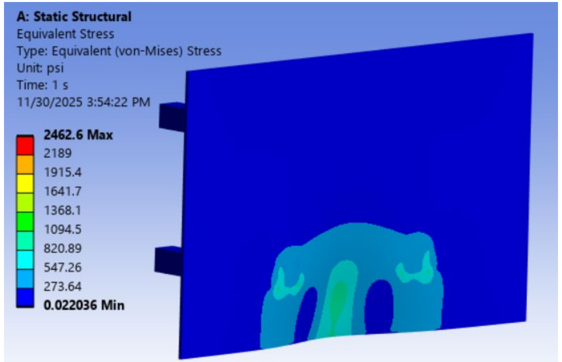


Plate Compactor

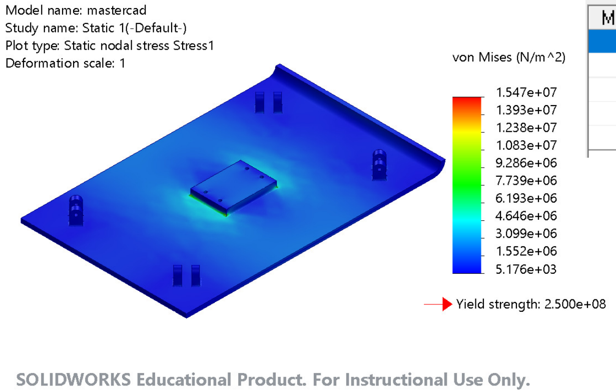
REV-LE

System/Subsystem Requirements:

- REVLE-002: The system shall have a volume less than or equal to 2 cubic meters in launch configuration.
- REVLE-TMS-001: The TMS system of REVLE shall have a mass between 100 and 180 kg.
- REVLE-TMS-004: The TMS system's vibration compaction mechanism shall be capable of producing greater than or equal to 2.8 kpa of compaction pressure.

System Overview:

- Material: ASTM A36 Steel
- Plate Dimensions: 22"x14"x0.35"
- Static + Vibratory Force: 605.7 N
- Compaction Pressure: 2.996 KPa



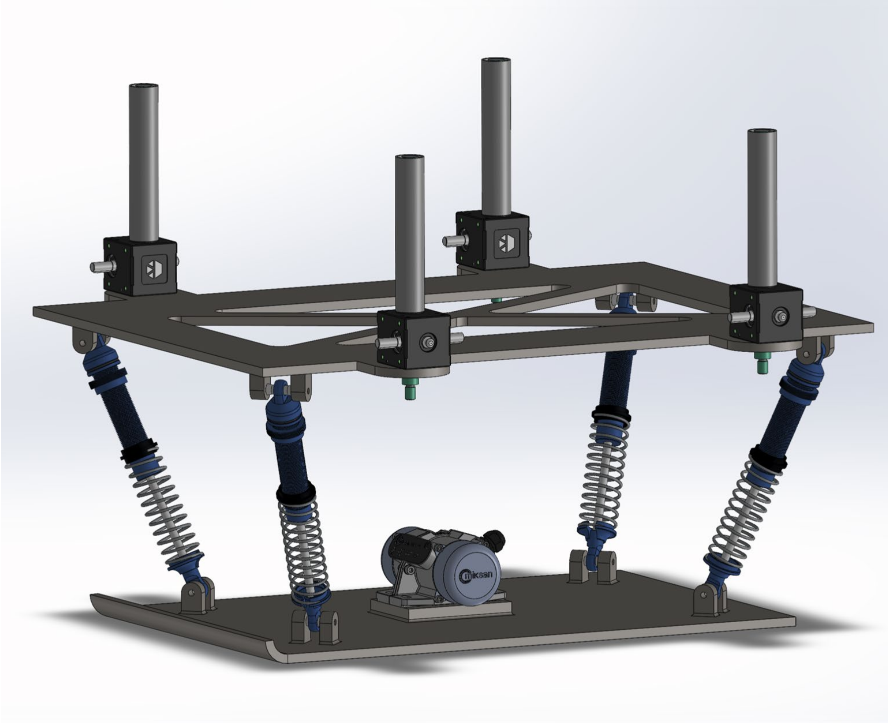
Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	8.2558	1.314	0.76106
2	17.011	2.7074	0.36935
3	17.102	2.7218	0.3674
4	24.148	3.8433	0.2602
5	29.504	4.6957	0.21296

Trade Studies - Compaction Method

REV-LE

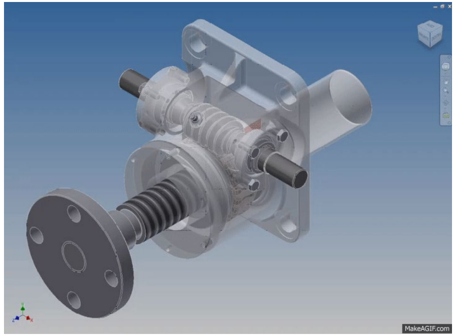
Selection Criteria	Weight	Scale	Regolith Filled Smooth Drum Roller	Padfoot Roller	Sintered Blocks	Plate Compactor	Weighted Smooth Drum Roller
Power Consumption	0.2	1-3	3	3	1	3	3
Mass	0.1	1-3	3	1	3	3	2
Complexity	0.25	1-3	1	3	1	3	3
Reliability	0.2	1-3	2	3	1	2	2
Effectiveness	0.25	1-3	3	0	3	3	3
Totals	1		2.3	2.05	1.7	2.8	2.7

Plate Compactor



Design Decision:

- 4 axial coilover shocks damp the vibration loads to the rest of the chassis and rover
- Screw jack mechanism translates the plate compactor upwards and downwards with respect to the chassis
    - Retracted away from ground for rover mobility, extruded and pressed into the ground for compaction
- Micro vibration motor provides vibratory motion



*Screw jack mechanism

Thermal Protection System

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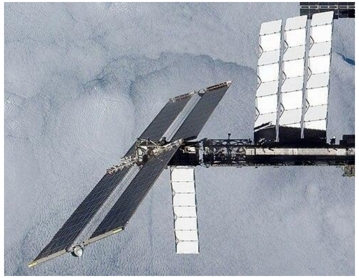
System/Subsystem Requirements:

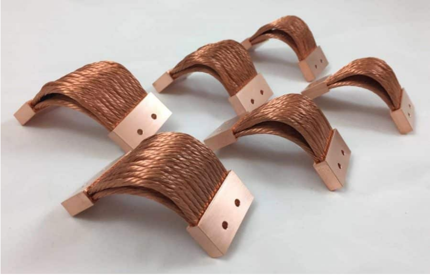
- REVLE-TMS-003: The TMS system shall be able to withstand temperatures ranging from -208 to 250°C
- REVLE-001: The system shall have a mass less than or equal to 200 kilograms at launch

System Overview:

- Radiator Panel: The top panel shall be used to radiate heat away from heat producing components.
- Thermal Straps: The heat producing components shall be connected to the panel using conductive thermal straps.
- Radiative Paint: The full structure shall be painted with a radiative paint to minimize heat absorption through radiation.



*ISS Radiator Panels



*Thermal Straps

Dust Mitigation

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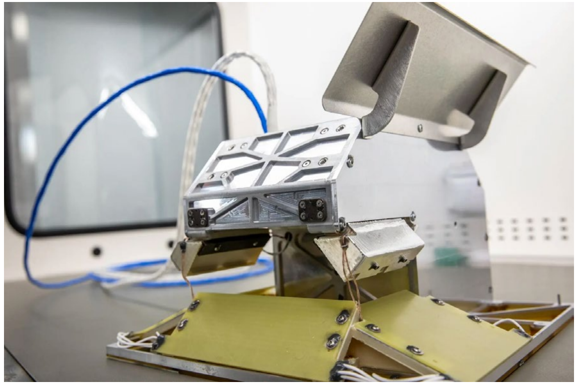
System/Subsystem Requirements:
- REVLE-001: The system shall have a mass less than or equal to 200 kilograms at launch
- REVLE-009: The system shall remove or prevent the accumulation of regolith particles on major subsystems during and after surface operations

Conclusion: Electrodynamic Dust Shield

Preliminary Sizing: (per screen)
- Mass: 0.2 kg
- Volume: 100 mm x 100 mm x 1 mm = 1e-5 m^3
- Power: 2-4 W



Communication Subsystem

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COM Subsystem Requirements:

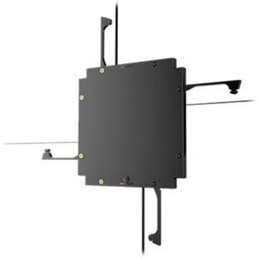
- REVLE-COM-001: The system shall be capable of transceiving communication from the Griffin Lander of signal strengths -100 to -10 dBm
- REVLE-COM-002: The system shall be capable of transceiving communication from the Griffin Lander of bandwidths 5-15 Mbps

Transceiver Decision:

- SpaceQuest TRX-U UHF Transceiver

Antenna Decision:

- EnduroSat: UHF Antenna III



Reason for Selection:

- Proven performance on spacecrafts (TRL 9)
- Excellent receiver sensitivity -(~120 dBm)
- Modest power draw (~250 mW RX)
- Omnidirectional

Electrical Power Subsystem

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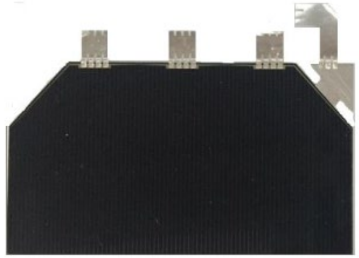
System/Subsystem Requirements:

- REVLE-EPS-001: The EPS shall provide a continuous power output of 500-1000 W for a duration of 4 hours during peak site-preparation operations, including operation of the roller compaction mechanism and bulldozing mechanism.
- REVLE-EPS-002: The EPS shall store 2.0-10.0 kWh of usable energy, enabling the rover to complete one full worst-case site-preparation cycle

System Overview:

- Lithium Ion battery
  - 48V and 52 Ah for 2.5kWh
  - 15-20 kg
- Gallium Arsenide Solar Panels
  - Spectrolab triple-junction
  - ≈ 1.77 m^2 for 700 W at 30% efficiency
  - ≈ 2-3 kg



C&DH Subsystem Component Selection

REV-LE

System/Subsystem Requirements:

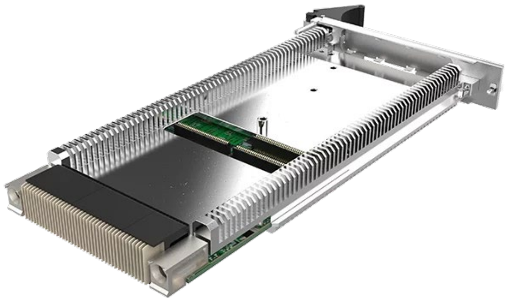
- REVLE-C&DH-001: The on-board processor shall contain 8-16 cores, 2-5 GHz
- REVLE-C&DH-002: The data handling system shall contain 16-32 GB of RAM
- REVLE-C&DH-003: The data handling system shall contain 1-2 TB storage

Flight Computer Decision:

- Aitech SP1 (2) -> Flight Computer

Non-Volatile Storage Decision:

- Aitech S993 -> Non-Volatile Storage



Specifications

- 3U Form Factor
- Cross strapped I/O
- < 105W, < 2.5 kg
- 1TB storage, 4 cores & 4 GB RAM per SP1
- Single SP1 ~ Single Jetson Nano

GNC Subsystem
Pose Estimation

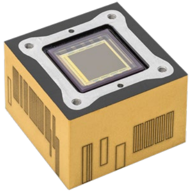
REV-LE

System/Subsystem Requirements:

- REVLE-GNC-001: The guidance subsystem shall identify its local 3D position within 0.25 meters.
- REVLE-GNC-002: The guidance subsystem shall identify its 3D orientation within 1 degree.

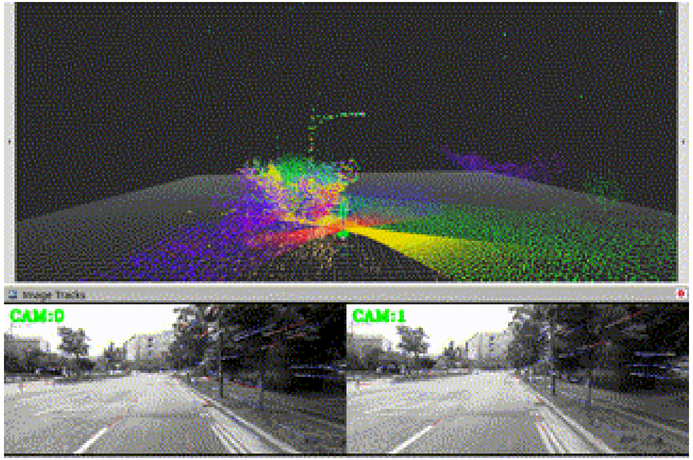
COTS Sensor Suite Specs & Modifications

- IMU: Northrop Grumman LN200S
  - .75kg, 12W
- Camera: 3D Plus 4Mpx RGB
  - 64g, 6W
  - 7 fps @ 12 bits, 1024 X 1024



Open Source Software Backbone

- RPNG-Multisensor-aided Inertial Navigation System (MINS)
  - Modular EKF: Camera, Wheel Encoder, IMU, GNSS
  - Modify GNSS to use ToF from Lander
  - Local Requirements Met Comfortably
  - Global translational error avg: ~1m for 1 km travel
  - Global orientation error avg: ~.25 degrees



Trade Studies - Pose Estimation

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Selection Criteria	Weight	Scale	FOG IMU + VIS cams + ToF w/ Lander	MEMS IMU + Star Tracker + Wheel Encoder + ToF w/ Lander	FOG IMU + Lidar + ToF w/ Lander
Reliability	0.3	1-5	5	2	5
Accuracy	0.2	1-5	5	5	5
Mass Efficiency	0.15	1-5	5	2	4
Power Efficiency	0.12	1-5	4	4	3
Compute Efficiency	0.1	1-5	2	4	3
Data Efficiency	0.1	1-5	2	4	2
Night Ops	0.03	1-5	3	5	5
Totals	1		4.22	3.33	4.11

GNC Subsystem
Path Planning

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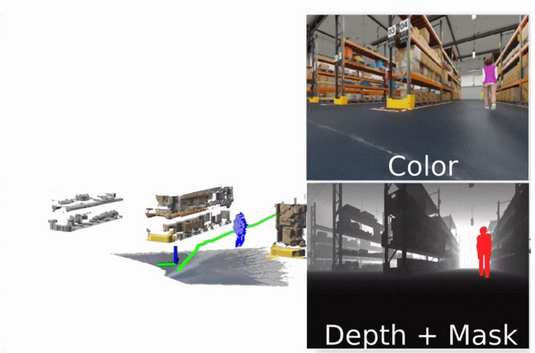
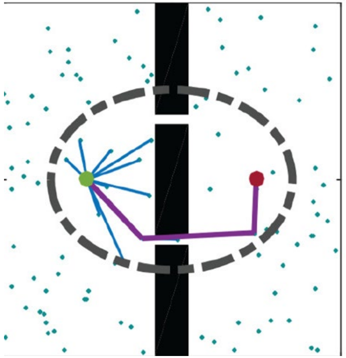
System/Subsystem Requirements:

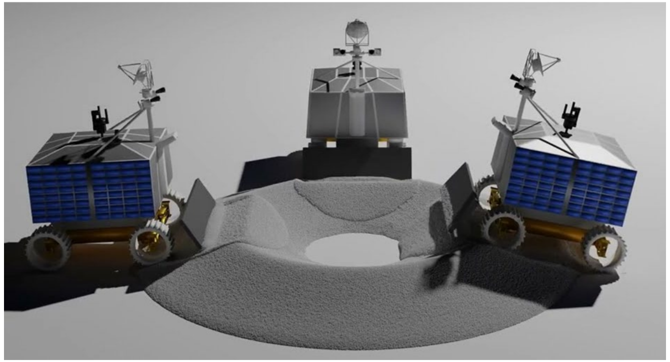
- REVLE-GNC-003: The navigation subsystem shall be able to continuously update path planning algorithms within 3 seconds of a new terrain information package

Open Source Software Backbone

- Isaac ROS NvBlox -> mesh, cost map (Euclidian Signed Distance Field) from pose and point cloud
- Open Motion Planning Library -> BIT* path planning for optimized route with deterministic timing (< 3s)
- Project Chrono -> Defining constraints through simulation in physics environment







Proof of Concept Prototype

The picture can't be displayed.

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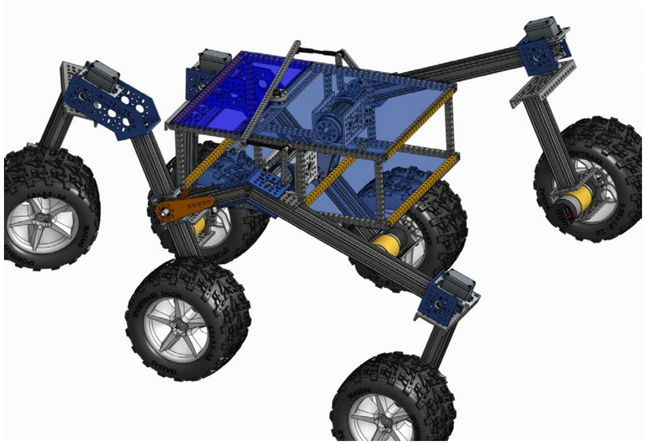
Prototype

- **Used NASA JPL Open Source Rover design to validate suspension and mobility**
  - Similar 6 motor 6 wheel rocker-bogie suspension
  - Proves mobility through validation tests on sand



JPL Rover System Specs:

- Wheel Radius: 72 mm
- 4-Wheel Steering
- Per-side wheel spacing: 0.216 m
- Max Vehicle Clearance: 144 mm
- Manufacturing Methods: entirely COTS

Gradeability and Obstacle Negotiation Test - PASS

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Successfully traversed an obstacle 20 cm high with a >20 degree grade

REV-MOB-001: Traverse slopes up to 20 degrees grade.

REV-MOB-002: Traverse obstacles up to 20 cm in height.

REVLE-MOB-003:
No wheel sinkage exceeding 10 mm in simulated environment.

Side-tip Risk Test - PASS

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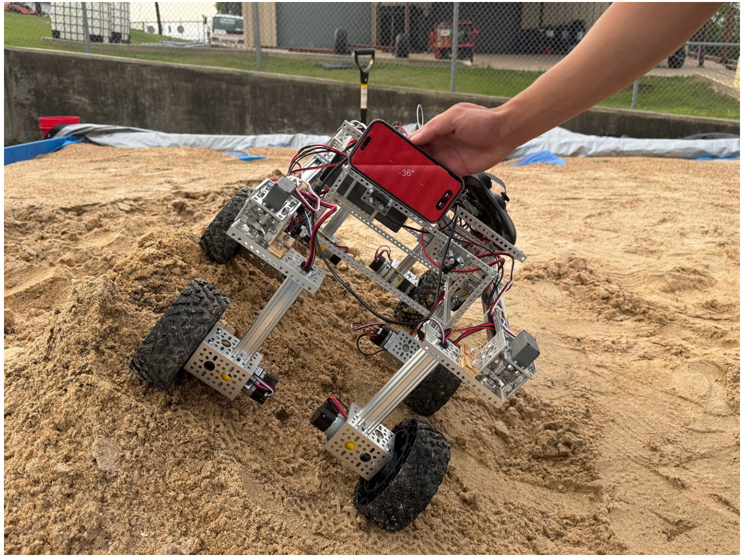
REVLE-MOB-004: No tip on slopes up to 35 degrees in both longitudinal and lateral



Slope Lateral Tilt - PASS

Slope Longitudinal Tilt - PASS

Compaction Simulation

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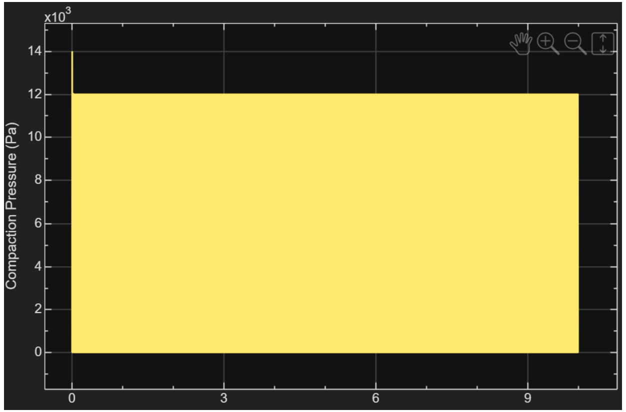
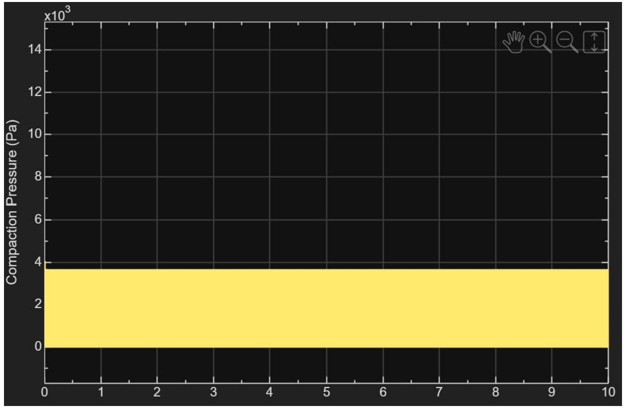
- Validated feasibility of vibratory plate compaction
- Soil modeled as linear elastic, soil parameters chosen for loose sand
- **Both static & dynamic pressure requirements met**

$$F_{soil} = kx + kxJ * x'$$



Total Pressure (~11 kPa)



Dynamic Pressure (~4 kPa)

Peak force from motor: 560 N

Perception & Autonomy

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Scope

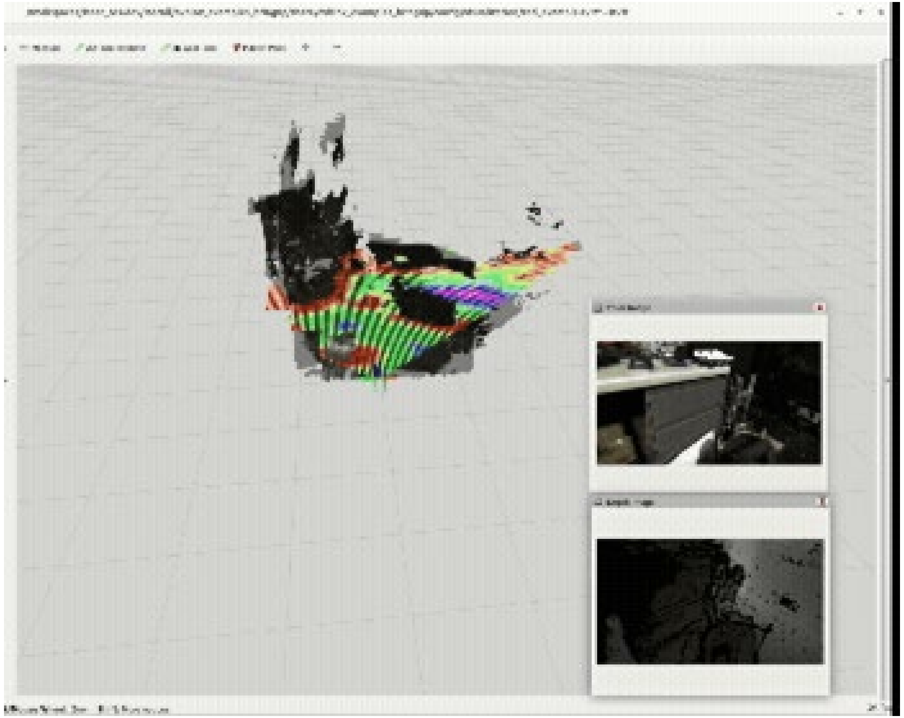
- Perception & Autonomy Stack Proven
- Demo Compute Heavy Perception on Flight-Analogous Hardware

Hardware

- Jetson Orin Nano Super Development Kit
- Zed Mini Camera
- Samsung 1TB SSD

Software

- Visual Inertial SLAM: NVIDIA cuVSLAM
- 3D cost mapping: NVIDIA NvBlox



Risk Assessment

Risk Assessment Matrix

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Likelihood of Occurrence	1 Negligible	2	3	4	5 Catastrophic
5 Frequent	Wheel Traction Loss (1.4)	Ice in Rover Crevasses (9.1)	Power system overload (3.1)	Error in Autonomy (5.1)	Dust Contamination (1.1)
4	Clearance blade wear reduces performance (4.2)	Deployment Mechanism fails to release (10.1)	Immovable Rock on compaction site (1.7)	Lidar or Navigation Sensor Failure (2.1)	Suspension Failure due to uneven terrain (1.5)
3	Sun glare affecting optical Sensors (2.2)	Density Verification Sensor Drift (4.3)	Solar Array Dust accumulation (3.4)	Failure of Rover Deployment (10.1)	Complex Terrain causing tip over (1.3)
2	Time Sync Errors (5.4)	Fault Management misclassification (5.3)	Loss of Comms (2.2)	Compaction Tool Failure (4.1)	Power Depletion before mission complete (3.2)
1 Rare	Failure of Hibernation Cycle (3.7)	Overcooling of electronics (3.6)	Rover Exceeds SWaP (6.1)	Rover cannot withstand landing (10.2)	System Overload from Actuators (3.1)

Consequence

Cost Estimation

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- Curiosity Rover
  - Development and Launch: $2.42 billion
  - First 98 weeks of operation: $116 million
  - 2014 operation costs onward (per year): $62 Million
- VIPER
  - Life-cycle cost estimation: $433.5 million
  - Commercial lunar payload service (CLPS): $235.6 million
- REV-LE
  - Development and Launch: **$1.27 billion**
    - Feasible in <5 years
  - Operating costs per year: **$62 million**

Next Steps

REV-LE

- Autonomous Controls
  - Test Path Planning & Control Algorithm
    - Generate random maps and configurations
      - Variable lighting, package losses, bit flips, poses, terrains,
    - Run Monte Carlo simulations in Isaac Sim
- Integration and Validation for:
  - Compaction mechanism
  - Bulldozer plate
  - Thermal protection

Lessons Learned

REV-LE

- What are the three most innovative ideas you had? Even if they weren't pursued.
  - Electric vibration plate compactor for lunar regolith
  - 3D printed regolith based concrete
  - Modular self-servicing construction and clearance rover
- Identify 3 technologies as most important to develop for this effort.
  - Autonomous path planning algorithms
  - Vibratory plate compaction characterization
  - Low gravity dust mitigation
- The three biggest challenges with the design process, even if you avoided them.
  - Scarcity of liquid water on moon that is normally used for compaction on Earth
  - Compaction ability hindered by mass budget and weaker lunar gravity
  - Troubleshooting of hardware and software for the PCBs

Thank you!

Any Questions?

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