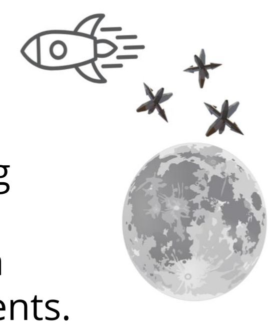
ASTROJACKS: A.R.M.S. (Autonomous Remote Mapping System)

Jet Propulsion Laboratory
California Institute of Technology

MOTIVATION / OBJECTIVE

The Problem:
- Satellite remote sensing of the Moon offers wide-area data but lacks direct, on-site validation called *ground truthing*.
- Traditional ground-truth instruments are heavy and expensive.



The Proposed Solution:
- A previous mars sample-return concept demonstrated deploying small, auxiliary payloads alongside main mission objectives.
- Sensor packages detach from ASTROJACK and deployed across a designated lunar-area, providing direct ground-level measurements.

<u>**Objective:**</u> Provide a proof-of-concept for low-cost, lightweight distributed sensor packages capable of:
- Ground Analysis: classifying ground hardness.
- Communication: maintaining robust, drop-node-tolerant data-transfer between nodes.
- Localization: computing relative node locations.

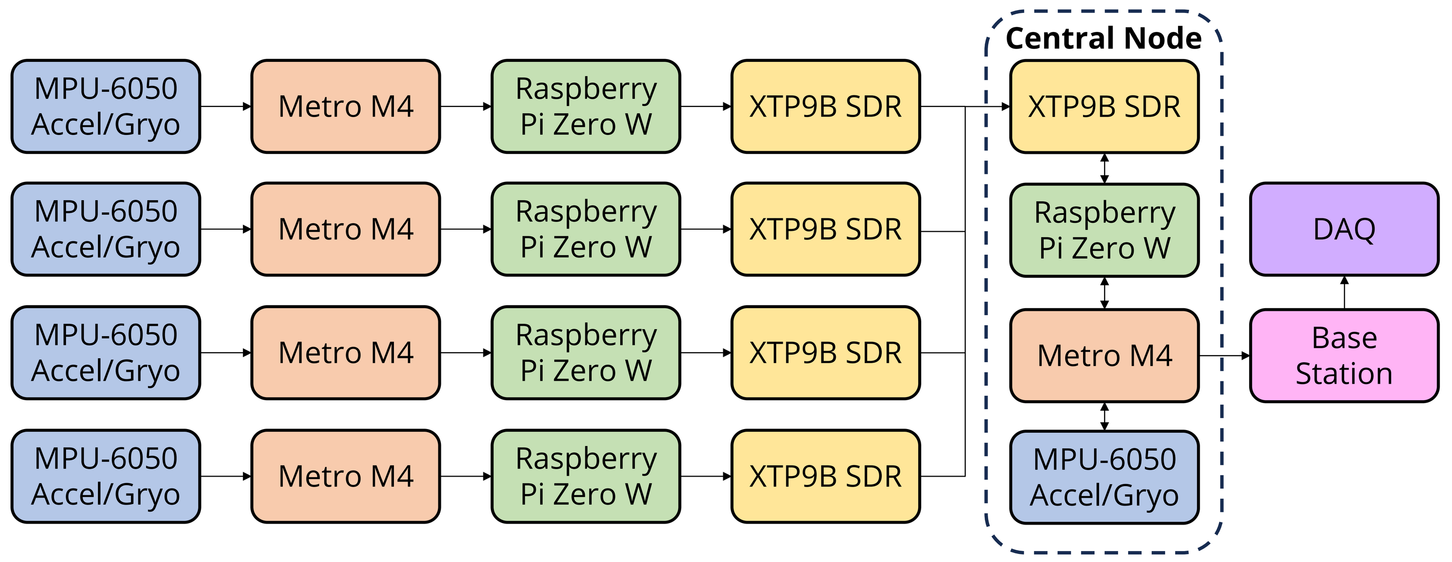
*Deployed sensors highlighted in purple.

SYSTEM REQUIREMENTS

Key Milestones
- Implement ground-hardness classification via accelerometer data and onboard software.
- Develop peer-to-peer communication protocol over SDRs.
- Build RSSI-based distance estimation between two nodes.
- Extend localization and communication to a network of 3+ nodes.
- Design and fabricate enclosure to house and protect system electronic components from dropping.

High Level System Requirements
- Classify surface hardness (soft/hard) via ≥1kHz accelerometer sampling and onboard machine learning algorithm.
- Communicate wirelessly across ≤500m with reliable, low-latency transmission and error checking.
- Determine relative location of each node using RSSI-based distance estimation and localization within 50m of uncertainty per 100m.

SYSTEM DIAGRAM

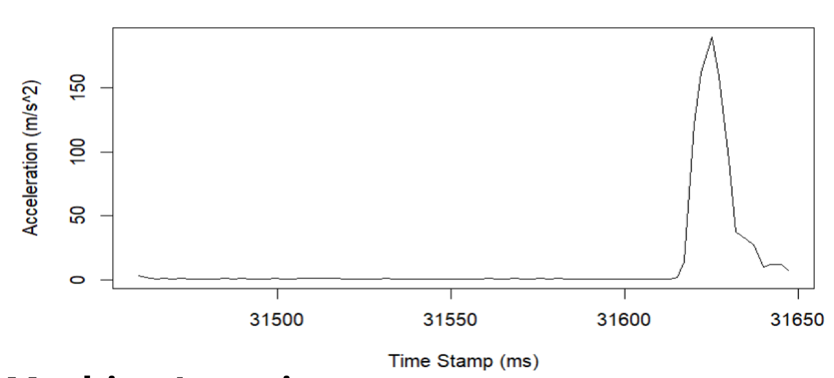


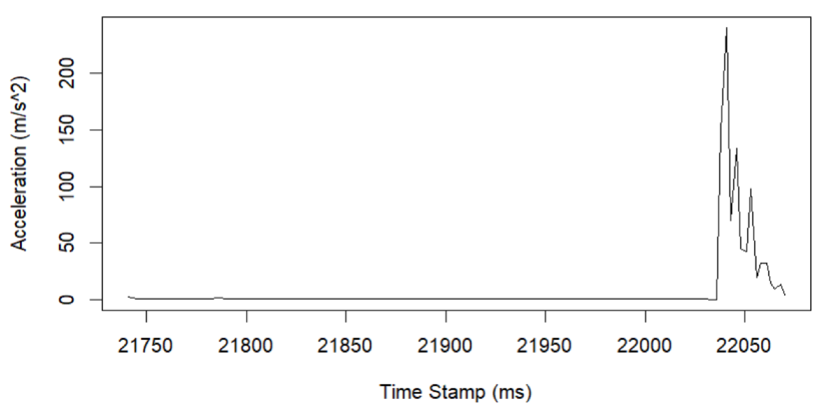
*In the event that the central node goes offline, the next available ARM will take it's place

GROUND ANALYSIS

Ground Analysis
- Detect free-fall/steady-state acceleration for start/stop conditions.
- Record ≥1 kHz accelerometer data via microcontroller.
- Determine drop characteristics including peak acceleration and impact duration.

Landing Type	Peak Acceleration	Impact Duration	Characteristics
Soft Landing	< 200 m/s^2	Longer	Gradual Deceleration
Hard Landing	> 200 m/s^2	Shorter	Sharp Spiky Deceleration

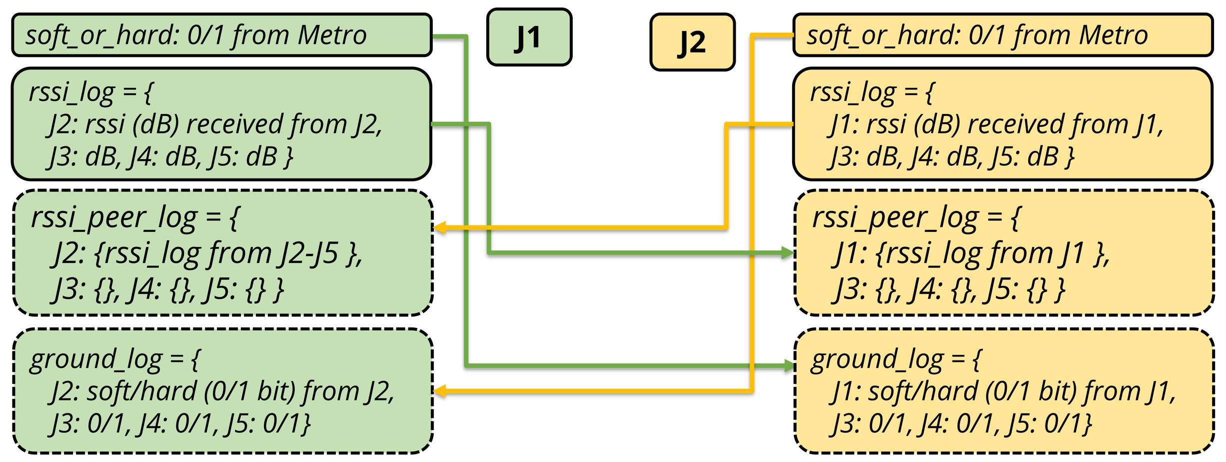


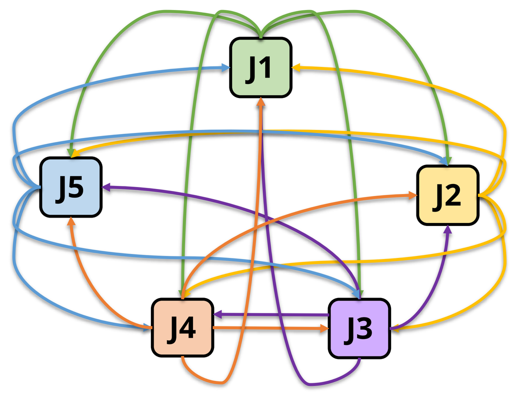


Machine Learning
- A TensorFlow-based linear neural network serves as the base model. While typically power-intensive, it is optimized into a low-power TinyML format suitable for deployment on resource-constrained platforms like the Raspberry Pi.

COMMUNICATION

Wireless Communication is implemented through a **peer-to-peer, multi-nodal mesh network**. Each node:
- Sends and receives 25-packet bursts containing local ground classification (*soft_or_hard*).
- Stores *soft_or_hard* majority bit from all peers.
- Stores and sends distance estimations of all peers through packet-extracted, averaged RSSI values (*rssi_log*).
- Stores *rssi_logs* from peers (*rssi_peer_log*) to form distance matrix used for localization.





Packet transfer of the full network.

LOCALIZATION

Node to Node Distance
- Distance approximation between nodes utilizes **received signal strength indicators** (RSSI) from packet data.
- This method requires experimental calibration to the desired environment (path loss exponent: n).

$$Distance = d_0 \cdot 10^{\left(\frac{RSSI_0 - RSSI_{measured}}{10 \cdot n}\right)}$$

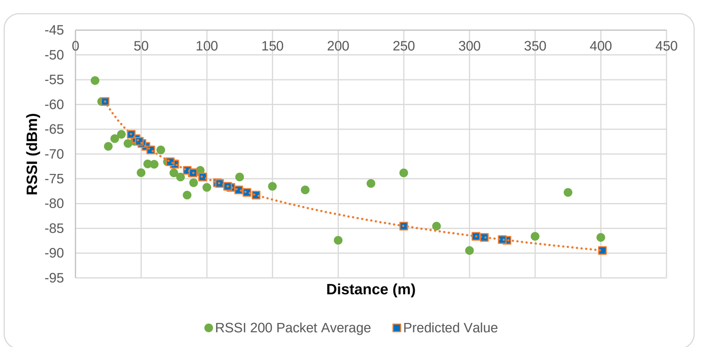


Figure demonstrates the relation between dBm (RSSI) and the meters both observed and predicted by our model

Location Equations

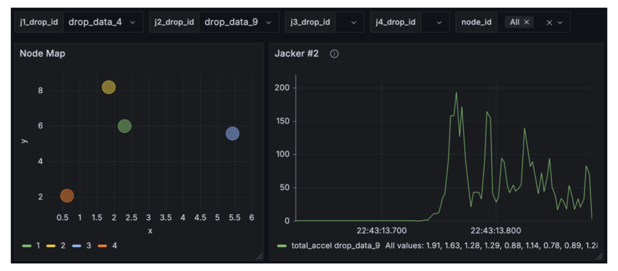
$$(x-p1_x)^2 + (y-p1_y)^2 + (z-p1_z)^2 = d1^2$$
$$(x-p2_x)^2 + (y-p2_y)^2 + (z-p2_z)^2 = d2^2$$
$$(x-p3_x)^2 + (y-p3_y)^2 + (z-p3_z)^2 = d3^2$$

Mapping Package Locations: Multilateration
- Takes in a node-to-node distance matrix as an input.
- Passes distances and nodes through systems of location equations.
- Uses the calculated distance to output (x,y,z) coordinate points.

DATA ACQUISITION AND VISUALIZATION

File Reception
- Sensor data logged in real-time by uploading structured CSV files received from sensor packages to an InfluxDB time-series database via python ingestion pipeline.

Data Visualization
- A Grafana dashboard dynamically visualizes acceleration data from each node with drop-specific filtering and timestamp tagging.

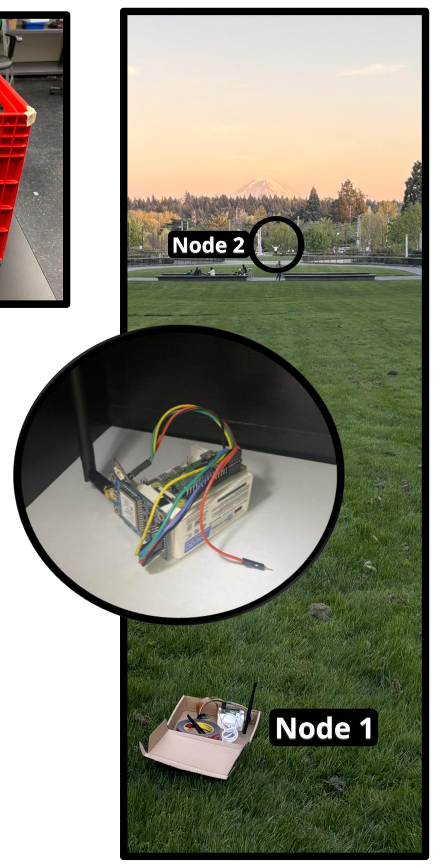


- 2D or 3D spatial telemetry rendered on an interactive map interface for remote monitoring and analysis of sensor package locations.

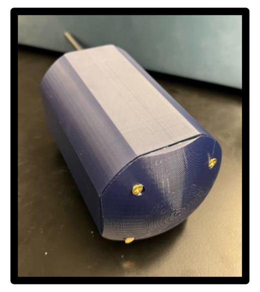
PHYSICAL IMPLEMENTATION & TESTING

Ground Analysis Testing:
- Initial drop tests were conducted by mounting fragile electronics inside a suspended milk crate.
- An accelerometer is secured to the base to capture impact data.

Comms & Localization Testing:
- Compact, self-contained telemetry units were assembled by integrating a battery, Raspberry Pi, and SDR into a single package connected through custom wire harnesses.



Final encasing:
- The final casings were 3D printed using ABS filament due to its availability, impact resistance, and researched thermal stability.



CONCLUSIONS

We aimed to design a lightweight, low-cost system that could autonomously characterize lunar soil and support future NASA missions with real-time, ground-truth data.
- **Ground analysis:** Captured impact characteristics and implemented surface classification using onboard ML.
- **Communication:** Enabled wireless transmission and visualization of gathered sensor data.
- **Localization:** Accuracy of localization is ∓ 25m per 100m, limited by the RSSI implementation as it is dramatically affected by multipath.

Future Works & Improvements
- **Improving localization accuracy** by exploring alternative distance approximation methods: Time of Flight, Ultra-wideband.
- **Reducing power consumption** through duty cycling or hardware level optimizations for longer field deployment.
- **Enhancing communication resilience** to reduce dropped telemetry.

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