A Dual-Simulator Framework for Physics Based Locomotion and Vision Based Navigation of Planetary Rovers

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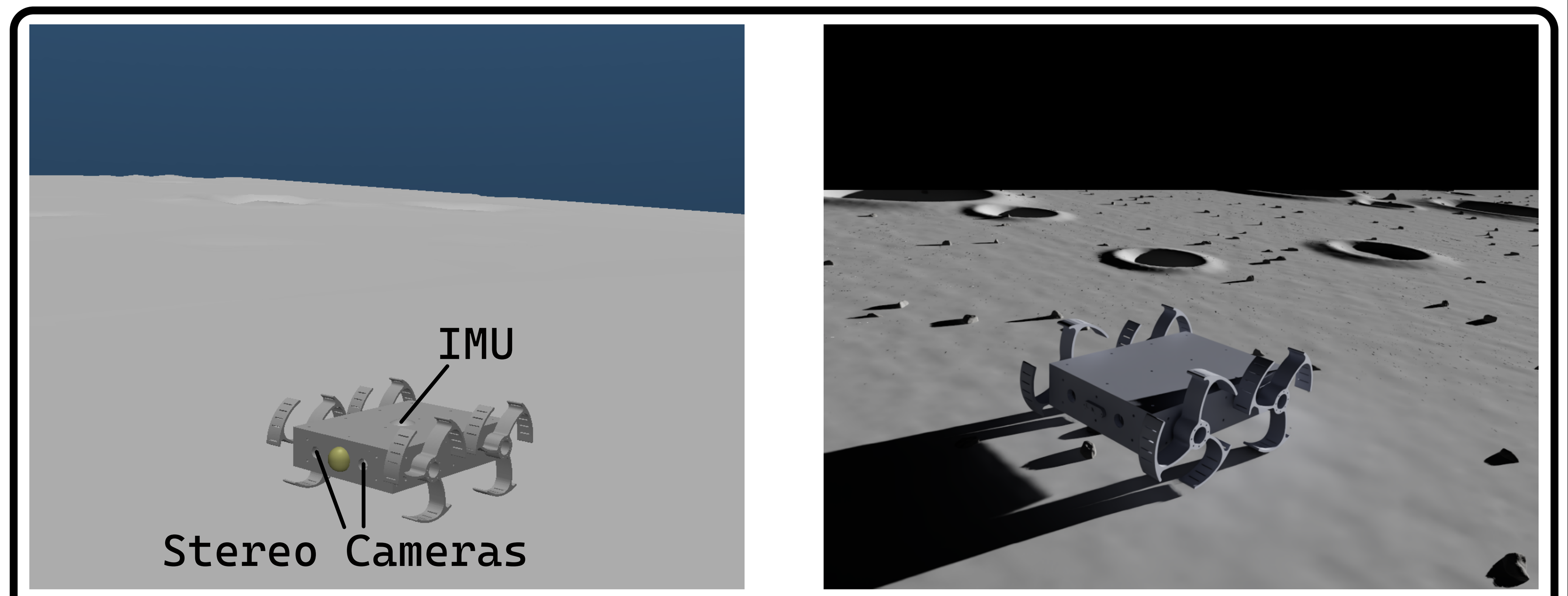
The simulation challenge in lunar robotics

Extreme conditions (low gravity, abrasive regolith, rough terrain) make Earth-testing resource-intensive.

Existing simulators force a critical trade-off:
Physics-oriented: Accurate contact dynamics, low visual fidelity.
Photorealism-oriented: High-fidelity rendering, poor multi-contact physics.



MuJoCo Isaac Sim

A dual-simulator framework combining MuJoCo and Isaac Sim within a spatially consistent lunar environment.

A Dual-simulator framework

Physics & gait control (MuJoCo)

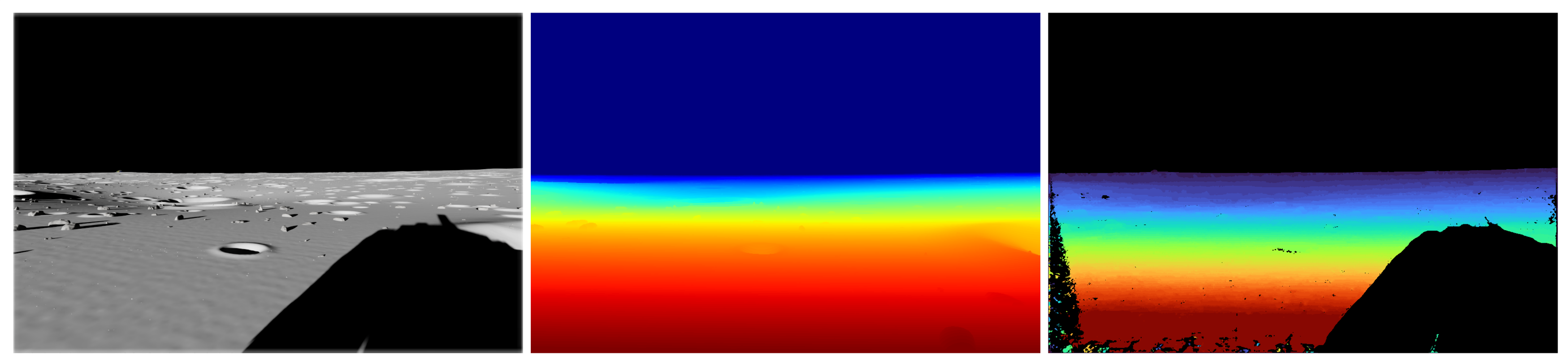
- RHex-inspired micro-rover with 3-spoke rigid legs.
- Phase-based periodic walking gait set to diagonal trot ($\phi_i \in [0,1)$).
- Dynamic body pose trajectories, joint states, and ideal IMU data.

Scene synthesis & sensor noise (Isaac Sim)

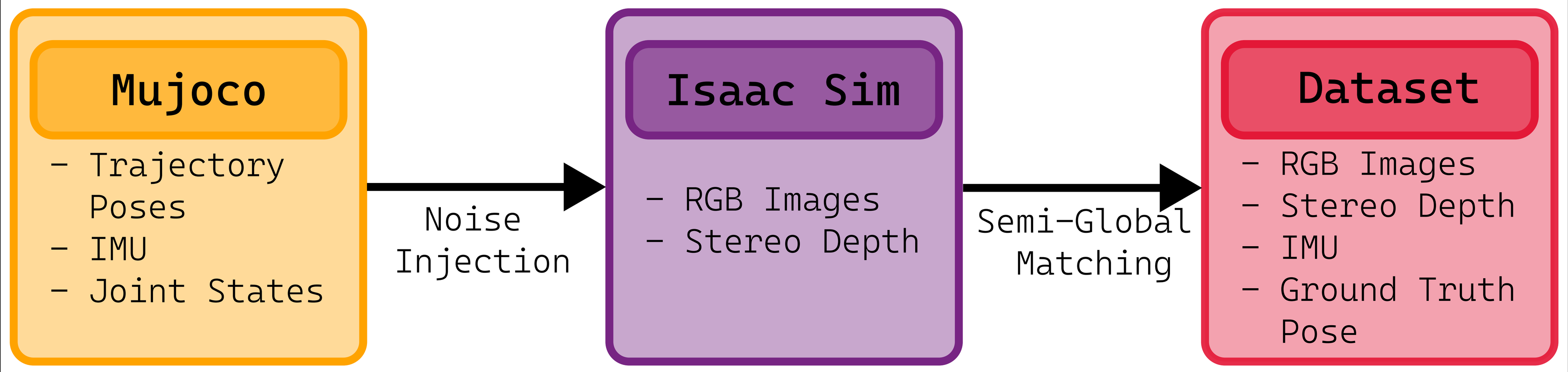
- Replicates polar regions with low sun elevations (0° to 15°) and sharp shadow boundaries.
- Augments ideal data with additive white noise and random walk drift.

$$\tilde{a}(t) = a(t) + b_a(t) + n_a(t)$$
$$\tilde{\omega}(t) = \omega(t) + b_g(t) + n_g(t)$$

- Implements Semi-Global Matching (SGM) on stereo pairs to inject hardware-realistic artifacts (occlusion holes, matching noise).



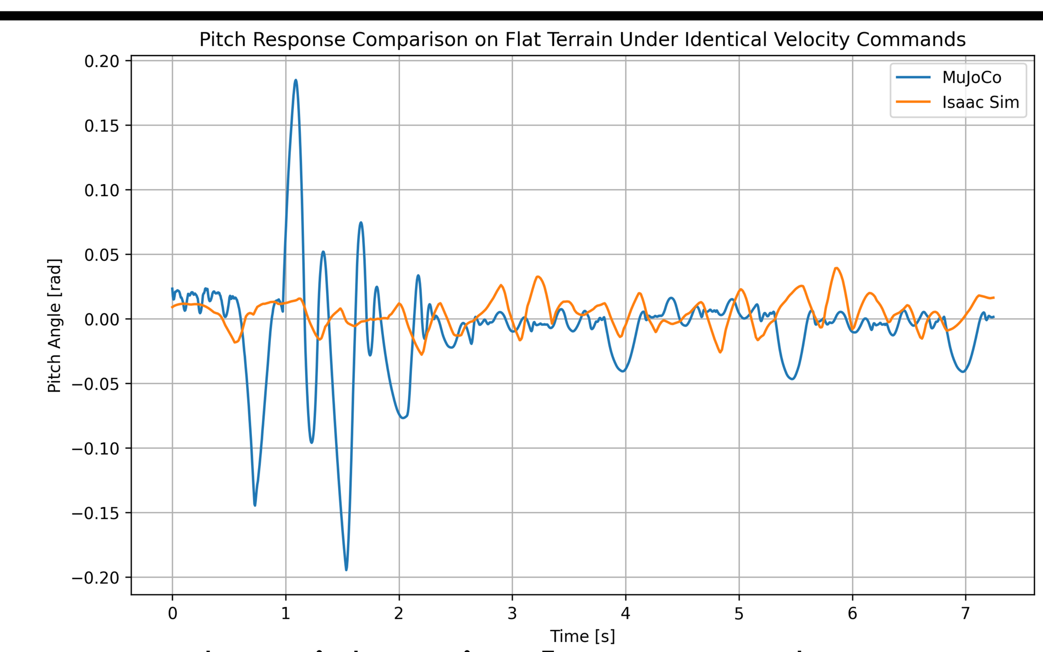
RGB observation Disparity map SGM disparity map



Experimental results

Locomotion Validation

The Test: Comparison of body pitch response under identical velocity commands on flat terrain.



Pitch response under identical commands:
MuJoCo: Captures the initial body jerk and periodic spoke-leg impact oscillations.
Isaac Sim: Produces a smoothed trajectory omitting these critical contact dynamics.

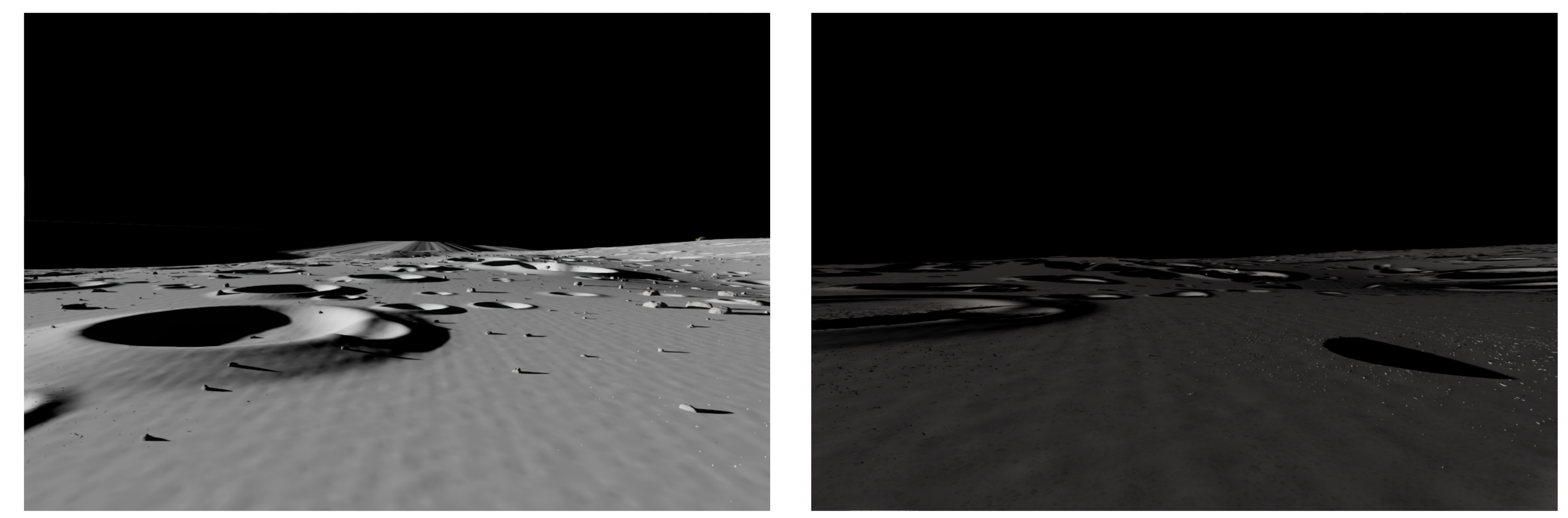
Key Finding:

- MuJoCo captures critical structural dynamics (initial body jerk and periodic spoke impact oscillations) observed on real hardware.
- Isaac Sim produces an overly smoothed response.

Visual SLAM Evaluation (ORB-SLAM3)

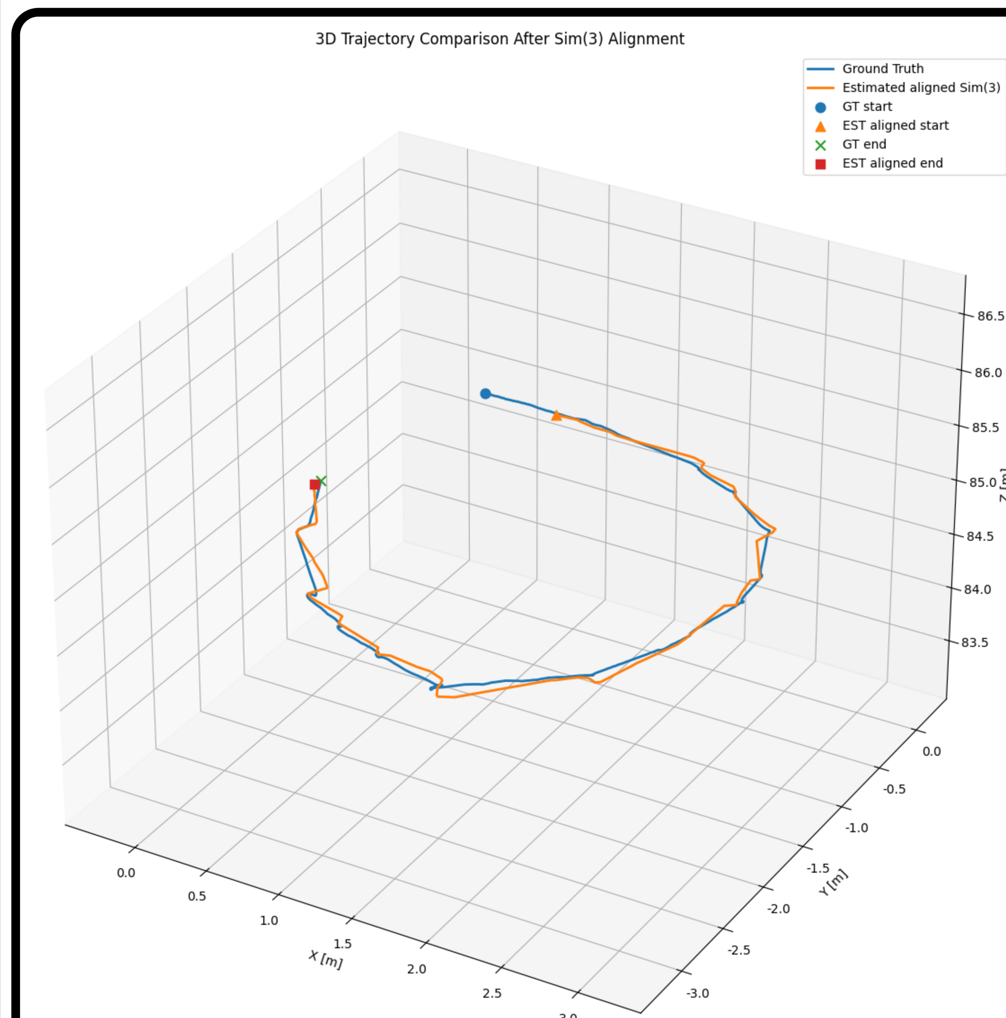
Synthetic datasets benchmarked across three controlled lunar terrains:

- Baseline → Sub-decimeter accuracy for both.
- Feature-sparse → Sparse landmarks maximize pose drift.
- Low albedo → Stereo maintains robust metric scale.



Baseline terrain with high feature density Feature-sparse terrain with low albedo

Scenario	Mono. ATE [m]	Mono. Scale	Stereo ATE [m]	Stereo Scale
Baseline terrain	0.0519	23.068	0.0507	0.967
Feature-sparse terrain	0.1365	48.532	0.1445	0.833
Low albedo terrain	0.0511	4.745	0.0263	0.965



3D trajectory comparison after **Sim(3)** alignment. The estimated trajectory closely matches the ground truth path generated by the dual-simulator pipeline, demonstrating the framework's utility for evaluating visual SLAM under controlled lunar conditions.

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