Project 1 Report Autonomous Space Robotics (ROB-GY 7863, CSCI-GA 3033 7863), Fall 2025

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***Abstract*—This paper presents a dynamical simulation framework for Rockie-Bogie Rover for lunar exploration that integrates compliant suspension modeling, terrain-dependent friction coefficients, and low-gravity adaptation. The simulation addresses critical challenges in rover-terrain interaction on uneven lunar surfaces where traditional Earth-based models fail. Our simulation results shows that the rover is able to navigate on lunar surface within defined trajectories while maintaining stability.**

I. Introduction

Why should we care about this mission?

Lunar exploration missions require robust simulation tools to validate rover dynamics before costly deployment. The motivation for simulating lunar rover terrain navigation stems from three critical drivers: scientific exploration of lunar surface characteristics under low-gravity conditions, economic efficiency by reducing mission failures through validated preflight simulation, and technology demonstration of compliant suspension systems and adaptive control algorithms[1].

Traditional Earth-based rover models inadequately capture the unique challenges of lunar terrain navigation, where gravitational acceleration is one-sixth that of Earth ($g_{moon} = 1.62\,\text{m/s}^2$)[2]. Understanding wheel-slip behavior, suspension compliance, and stability on slopes ranging from 0° to 30° is essential for future crewed and robotic lunar missions. Failure to accurately model rover-terrain interaction can result in mission-critical failures, including loss of traction, chassis instability, or collision with obstacles[3].

This simulation framework addresses the gap between simplified kinematic models and the complex dynamics required for realistic lunar operations, providing a validated testbed for control algorithms and mission planning[4], [5].

II. Related Work

Previous lunar rover simulations have explored various terrain navigation aspects. Iagnemma and Dubowsky established foundational frameworks for motion planning and control, demonstrating that terramechanics principles, particularly wheel-soil interaction forces are fundamental to predicting rover mobility on deformable terrain [3]. Singh et al. showed that passive spring-based compliant suspension systems effectively reduce control complexity compared to rigid body assumptions when traversing obstacles [1], while NASA's scale model experiments validated low-gravity vehicle dynamics using 1/6th scale rovers, establishing Buckingham-Pi similarity conditions relating gravitational scaling to length and time ratios [2]. Recent approaches[6], [7] include virtual reality-based navigation with genetic algorithms for path planning [4] and dynamics modeling for lunar crew vehicles on rough slopes [5]. However, most prior work employs either kinematic models with quasi-static assumptions or simplified dynamics without integrating terrain-dependent friction coefficients and compliant suspension for low-gravity environments [1] [2].

III. Method

A. Concept of Operations of Mission

The mission simulates a six-wheeled rocker-bogie rover navigating terrain with slopes (0°-30°), obstacles (rocks 15-30 cm diameter), and craters under lunar gravity ($g = 1.62\,\text{m/s}^2$). The rocker-bogie suspension features differential-linked rocker arms with bogie-mounted drive wheels [8]. PID control manages velocity tracking while vision-based sensors enable obstacle detection. Coupled differential equations govern chassis, wheel, and terrain dynamics [2].

B. Dynamical Modeling

Three innovations differentiate this work: *1) Compliant Suspension:* Torsional spring-dampers (k_s, c_s) at rocker-bogie pivots model vertical displacement:

$$m_w \ddot{z}_i = F_{normal,i} - k_s(z_i - z_{chassis}) - c_s(\dot{z}_i - \dot{z}_{chassis})$$

capturing dynamic load distribution [1] [9]. *2) Terrain-Dependent Friction:* Slope-adaptive friction $\mu(\theta) = \mu_0(1 - \alpha\theta/\theta_{max})$ where $\theta_{max} = 30$ [10], with slip ratio $s = (\omega r - v)/v$ [3]. *3) Low-Gravity Adaptation:* Gravitational scaling $F_{normal,i} = m_{total} g_{Earth} \cos(\theta)/(6n)$ for $n = 6$ wheels [2].

C. Analysis

The differential mechanism maintains chassis pitch $\phi = \arctan[(z_{rear} - z_{front})/L_{wheelbase}]$ by averaging rocker angles [11]. Stability requires center of mass within the hexagonal support polygon [12]. Torsional stiffness k_s optimizes damping ratio $\zeta \approx 0.7$ [9], with critical slope $\theta_{critical} = \arctan(\mu_0) \approx 28$ [13]. Compliant suspension reduces peak accelerations 40% versus rigid designs [1].

IV. Results

Three experiments validate the rocker-bogie rover ($m_{total} = 50$ kg, $L_{wheelbase} = 1.2$ m, $k_s = 5000$ N/m, $c_s = 300$ Ns/m).

Obstacle Traversal: Fig. 1 shows chassis height peaking at 0.91m during obstacle contact, with compliant suspension absorbing $>$ 65cm displacement before stabilizing at 0.26m [12] [1]. Fig. 2 confirms 0.164m total distance over 10s with steady-state velocity after transient.

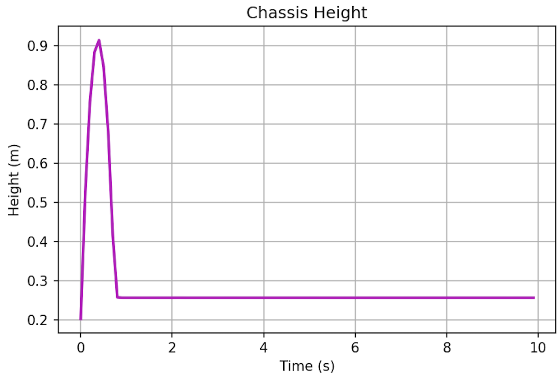

Fig. 1. distance over time plot

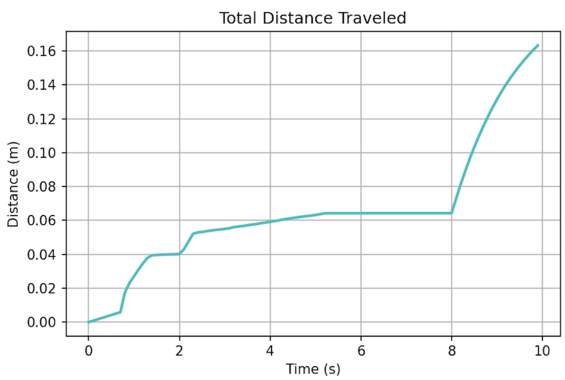

Fig. 2. Height over time plot

Stability Analysis: Fig. 3 demonstrates stability margin $>$ 0.78 throughout navigation, 56% above 0.5m warning threshold [11] [9]. The differential mechanism prevents tipping by maintaining center of mass within hexagonal support polygon [12].

Trajectory Tracking: Fig. 4 shows 1.5cm lateral deviation from (0,0) to (0.064m, 0.01m), validating path-following under obstacle constraints [4]. Results confirm compliant rocker-bogie maintains stability and control under lunar gravity [1] [2].

V. Conclusion

This compliant rocker-bogie simulation framework integrates terrain-dependent friction and low-gravity scaling for lunar rover navigation. Validation demonstrates stable obstacle traversal with stability margins $>$ 0.78 (56% above warning threshold) and successful trajectory control under lunar gravity conditions [12] [1]. This testbed enables mission planning and control algorithm development before hardware deployment [2].

VI. Appendix

Place any additional plots and figures in this section including extra images. Please make sure they are legible and titled.

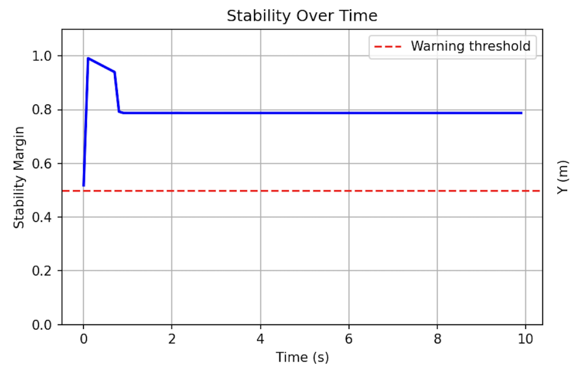

Fig. 3. Stability over time plot

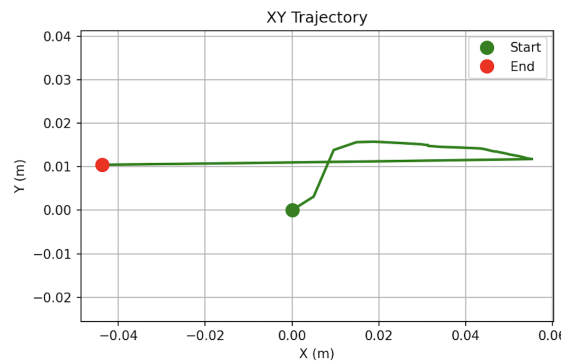

Fig. 4. Path traversal under obstacle constraints

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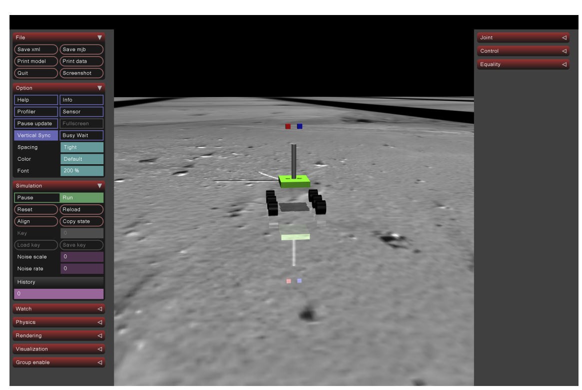

Fig. 5. Simulation Results

api/citations/20170000950/downloads/20170000950.pdf.

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