Toward Density-Aware Granular Loco-Manipulation for Obstacle-Aided Mobility on Steep Slopes

Parnia Shokri and Feifei Qian
Department of Electrical and Computer Engineering, University of Southern California
Los Angeles, CA, USA   Email: {pshokri, feifeiqi}@usc.edu

***Abstract*—Granular terrains such as desert sand, lunar regolith, and Martian soil remain challenging for mobile robots because loose substrates cause slip, sinkage, and loss of support. Recent work has shown that a robot can exploit localized avalanches to reposition obstacles and improve traversability, but existing methods do not explicitly account for obstacle density, even though density can strongly influence burial, stability, and downslope motion. In this extended abstract, we present a preliminary study toward *density-aware granular loco-manipulation*. Using same-geometry dome-shaped obstacles with different densities, we track their motion on a sandy slope under repeatable robotic appendage actions, including vertical intrusion and horizontal dragging. Experimental measurements show that lighter obstacles tend to rise toward the surface and undergo larger downslope displacement, whereas denser obstacles tend to sink and stabilize under repeated disturbance. These results motivate treating density as a latent state that can be inferred from motion history and incorporated into future prediction and planning.**

I. Introduction

Granular environments are common in terrestrial and extraterrestrial exploration, including deserts on Earth and regolith-covered terrain on the Moon and Mars [1]–[3]. These substrates are difficult for robots because the ground can deform significantly under contact, often causing slip, sinkage, and reduced traction [1], [4], [5]. On steep sandy slopes, these effects become even more severe, making reliable mobility difficult [6], [7].

A promising alternative is to exploit granular interaction rather than avoid it. Recent work has shown that robot actions can intentionally trigger localized avalanches to reposition obstacles and improve traversability, which motivates a view in which locomotion and terrain manipulation are coupled through granular loco-manipulation [8], [9].

However, an important latent property remains missing from this formulation: obstacle density. Even when two obstacles have the same shape and size, density may substantially affect whether they float upward, sink deeper into the substrate, continue moving downslope, or stabilize under repeated disturbance. This distinction is important for obstacle-aided mobility [8], [10], as well as operations such as construction [11], [12] and excavation [11], [13]. A dense object that settles and becomes stable may serve as a useful stepping stone, whereas a light object may remain mobile and should instead be displaced away. In this work, we present preliminary experiments and a modeling direction toward density-aware granular loco-manipulation.

II. Prior Work and Motivation

Recent work has established a new view of mobility on steep granular slopes: instead of treating the terrain as something to avoid or passively adapt to, a robot can actively exploit granular flow to reshape the environment and reposition obstacles in ways that improve traversability. Collectively, this line of work has shown that avalanche-driven obstacle manipulation can be learned from data, that obstacle motion on granular slopes can be predicted from terrain state and robot actions, and that in more realistic settings locomotion and manipulation must be planned jointly because robot actions affect both obstacle motion and the robot's own state [8], [9].

However, these advances still treat obstacle behavior mainly as a function of geometry, terrain state, and action. A key remaining question is whether obstacles with the same shape and size can behave differently under repeated granular disturbance because of latent physical properties such as density. In particular, density may affect whether an obstacle rises, sinks, stabilizes, or continues moving downslope, which in turn changes whether it should be treated as a useful support or as something to be displaced. This motivates the present study, which asks whether density leads to systematic differences in burial and downslope transport when shape is held fixed. This is relevant to planetary rover mobility, where robots may need to use rocks or embedded objects as stable supports on deformable regolith-covered slopes.

III. Experimental Setup

To investigate this hypothesis, we designed a controlled physical experiment using 3D-printed half-spherical obstacles with identical external geometry but different internal mass distributions. The four obstacle conditions are: hollow (12 g), resin-filled (43 g), steel-ball-filled (150 g), and lead-shot-filled (215 g). Motion-capture markers are attached to each obstacle to enable 3D tracking during interaction on a sandy slope.

A 2-DOF robotic appendage (a "flipper") executes a repeatable circular pattern near the obstacle to produce localized disturbance and granular flow, as shown in the lower panel of Fig. 1. This setup preserves the avalanche-driven interaction mechanism while letting us isolate the effect of density. In contrast to the full quadruped setting, the flipper platform offers a simpler and more controlled way to observe how obstacle motion changes with repeated granular interaction. Although the flipper does not capture full quadruped dynamics, it preserves the local appendage–granular interaction

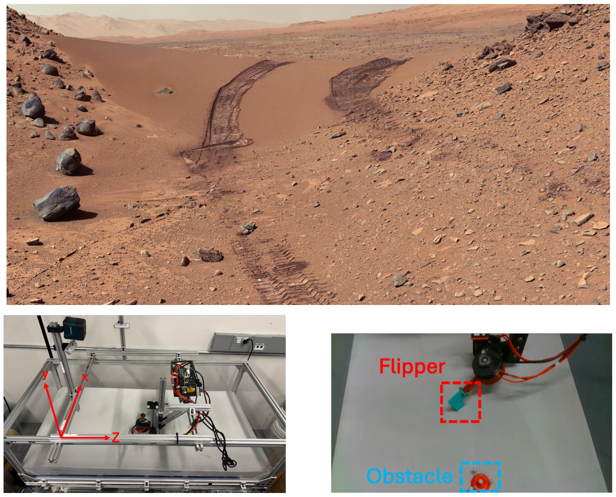


Fig. 1: Planetary and laboratory granular terrains. *Top:* A sandy, rocky planetary surface representative of the environments motivating this work. *Bottom:* Experimental setup used as a controlled laboratory analog. Left: fluidized-bed trackway with the mounted flipper. Right: zoomed-in view of the local interaction region, showing the flipper, embedded obstacle, and reference frame.

that drives obstacle motion. In a full quadruped, a similar interaction could occur when the robot maintains support with its stance legs while using one leg to sweep near the obstacle, so the qualitative density-dependent burial and mobility trends may transfer if intrusion depth and relative placement are similar. Differences may arise if the robot body shifts during interaction, causing the leg to follow a slightly different path relative to the sand, if the stance legs load or disturb the surrounding granular bed, or if obstacle motion affects robot stability and introduces feedback into the interaction.

Figure 1 bottom left panel shows the experimental setup and local interaction region. A 2-DOF robotic appendage (a "flipper") with a 4×7 cm paddle is lowered to a fixed intrusion depth such that the paddle is fully submerged in the sand during actuation. The obstacle is a 3D-printed dome-shaped obstacle with a base radius of 1 in (25.4 mm) and a height of 1.25 in (31.75 mm), initially embedded 25.5 mm into the sand. The flipper then executes a repeatable closed-loop motion defined by a fixed sequence of commanded joint-angle waypoints (θ_1, θ_2), where θ_1 controls adduction and θ_2 controls sweeping. The action is a submerged 2-DOF sweeping primitive. In each session, the same action is performed over $N = 7$ trials, with 3s pause between successive trials, to generate localized disturbance and granular flow near the obstacle. During each trial, we record motion-capture measurements of the obstacle pose and RGB observations from two viewpoints to track the resulting obstacle motion and surrounding surface deformation.

IV. Experimental Results

Experimental measurements revealed systematic density-dependent obstacle motion under repeated flipper disturbance. In the incline-aligned frame, positive $\Delta y'$ indicates upward motion toward the surface, while positive $\Delta z'$ indicates downslope motion. The strongest trend appears in the surface-normal direction: the empty obstacle moves upward, with net $\Delta y' \approx +1.2$ cm, whereas the filled obstacles move downward into the bed, with net $\Delta y' \approx -2.1$ cm for resin, -2.6 cm for steel, and -3.1 cm for lead (Fig. 3a). This sign change suggests that density strongly affects whether an obstacle resurfaces or becomes increasingly buried under repeated disturbance. Along the slope, the empty obstacle also travels the farthest, with net $\Delta z' \approx 23.5$ cm, followed by resin at approximately 19.5 cm, steel at approximately 13.2 cm, and lead at approximately 14.4 cm (Fig. 3b). Thus, while the surface-normal rising-versus-sinking behavior is the clearest density-dependent effect, the downslope displacement also generally decreases from the lightest obstacle to the denser filled obstacles. This supports the interpretation that lighter obstacles remain more mobile, whereas denser obstacles tend to become buried and stabilized. This interpretation is reinforced by Fig. 4, which provides a complementary view of the absolute vertical position $y'(t)$ for the two extreme cases: the empty obstacle evolves over a wider range of relative leg–obstacle gaps and reaches closer to the leg across trials, whereas the lead-filled obstacle undergoes most of its vertical change in the early trial regions and then stabilizes. One possible explanation is that as denser obstacles sink deeper into the granular bed, increased confining pressure and shear resistance at the obstacle–sand interface suppress further motion. Other factors may also contribute: as the obstacle rises or sinks, the same commanded flipper motion can produce different effective interaction depths and flipper–obstacle distances. Repeated trials may also modify the local bed geometry by forming ridges, troughs, or loosened regions that either guide lighter obstacles downslope or help stabilize denser ones. For the empty obstacle, later increases in y' may also partly reflect tumbling or rotation on the slope, in addition to upward resurfacing.

These observations suggest that obstacle density is an important hidden factor in the motion dynamics. This leads to two complementary problems. The first is a forward model that predicts obstacle motion from the current obstacle state, terrain slope, action, and density:

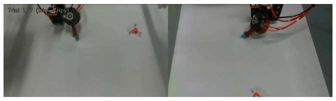
$$o_{t+1} = f(o_t, a_t, \phi, \rho), \tag{1}$$

where o_t is the obstacle state, a_t is the robot action, ϕ is the slope angle, and ρ is the obstacle density.

The second is an inverse estimator that infers density from the observed motion history under known actions and slope conditions:

$$\hat{\rho}_t = g(o_{0:t}, a_{0:t}, \phi). \tag{2}$$

Together, these would allow the robot to begin with a coarse prior over obstacle density, refine that estimate online, and improve prediction of future obstacle motion as interaction proceeds.



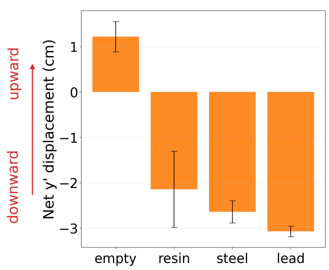
(a) Empty obstacle, Trial 1/7

(b) Empty obstacle, Trial 6/7

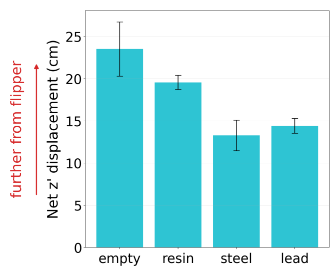
(c) Lead half-sphere, Trial 1/7

(d) Lead half-sphere, Trial 6/7

Fig. 2: Qualitative comparison of empty and lead-filled half-sphere behavior over repeated trials on a sand tank with inclination angle 23°. Top row: empty half-sphere. Bottom row: lead-filled half-sphere. The numbers shown in each panel indicate trial progression.



(a) Net y' displacement



(b) Net z' displacement

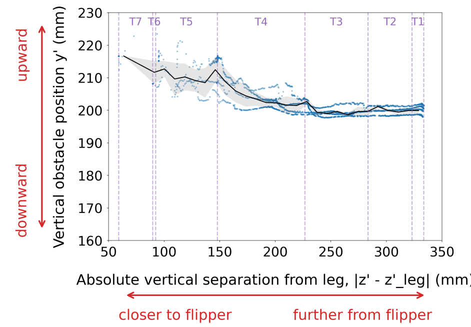
Fig. 3: Net obstacle displacement versus obstacle type/density for the empty, resin-filled, steel-filled, and lead-filled obstacles. Bars show the mean total displacement across $n = 5$ sessions, and error bars denote ± 1 standard deviation. Here, y' denotes surface-normal displacement, with positive values indicating upward motion toward the surface, and z' denotes along-slope displacement, with positive values indicating downslope motion.

V. Going Forward: Toward Density-Aware Avalanche Prediction

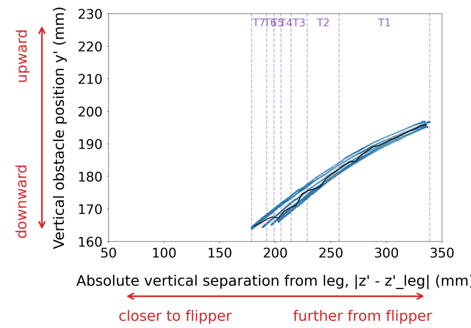
Our longer-term goal is to incorporate obstacle density into avalanche-based prediction models such as DiffusiveGRAIN [9]. In the simplest setting, density is known in advance and can be provided as an additional conditioning variable to the environment predictor. The model would predict terrain and obstacle motion from the current terrain state, robot action, and obstacle density. This would extend existing predictors beyond purely geometric representations.

In practice, obstacle density will often be unknown. A more useful formulation is therefore to estimate it online from motion history and feed that estimate back into the motion predictor. Starting from a prior estimate, the model would update its density belief from the observed obstacle response under known actions and use the refined estimate to improve prediction of subsequent obstacle and terrain evolution.

A natural next step is a coupled prediction-and-inference model, where a forward predictor estimates terrain and obstacle motion while an inference module updates the density estimate from observed responses. This could be implemented by training a density-aware predictor directly, or more data-



(a) Empty half-sphere



(b) Lead-filled half-sphere

Fig. 4: Obstacle vertical position $y'(t)$ versus absolute relative leg gap $|z_{\text{obs}}(t) - z_{\text{leg}}|$ for empty and lead-filled obstacles. Blue points are pooled mocap samples across sessions and trials, the black curve is the mean trend, and the gray band denotes ± 1 standard deviation. Purple dashed lines indicate trial-specific relative-z regions, where T_1 to T_7 corresponds to each robot action/trial.

efficiently, by augmenting a pretrained avalanche predictor with a lightweight density-estimation and correction module.

Density matters directly for mobility planning. If an obstacle is inferred to be dense and likely to settle into a stable configuration, the robot may use it as a foothold or stepping stone. If an obstacle is inferred to be light and unstable, the planner may instead use avalanche dynamics to displace it away from the intended path. In other words, density-aware prediction can support both environment understanding and decision-making.

VI. Conclusion

We presented a preliminary step toward density-aware granular loco-manipulation for steep-slope mobility. Building on prior work in avalanche-based obstacle repositioning, we identify obstacle density as a missing latent factor that may determine whether an object becomes a stable locomotion aid or an unstable obstruction. Our initial experiments with same-geometry, different-density obstacles suggest systematic differences in burial and downslope motion under repeated interaction. These observations motivate future models that jointly infer density from motion and use that estimate to improve obstacle prediction and planning in granular environments.

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