Wheel-Based Trenching: Terramechanics of Nonprehensile Manipulation for Planetary Rovers

Catherine Pavlov and Aaron M. Johnson, {cpavlov amj1}@andrew.cmu.edu

Abstract—This paper presents a new behavior for planetary rovers using their wheels to dig a trench in soil. Such terrain manipulations can expand the range of missions that a rover supports, such as burying a cable or sampling lower layers of soil. Here we present a new terramechanics model of soil displacement around a wheel as it performs a trenching behavior. This model provides several insights to help avoid getting a wheel stuck: a deep trench does not require maximal sinkage; net traction forces can be used to bound feasible trenching operations; and using the rear wheel reduces the moment on the rover’s rocker. We verify this model experimentally by digging trenches with a rover, as in e.g. [5].

I. MOTIVATION/PROBLEM STATEMENT/RELATED WORK

In this work we develop new terramechanics models of sand displacement in order to enable controlled trenching behaviors with a planetary rover’s wheel. Planetary rovers have many constraints on their design, from the cost of launching platforms, to limited power and mass budgets. These constraints limit the number of actuators on the platforms and cause competition between mobility, computing, and scientific instrument systems. This naturally leads to the question, “How can we gain greater functionality from existing systems with minimal physical additions?”

Wheels are powerful actuators present on every existing planetary rover which are untapped for their manipulation potential. However, wheels can be used to perform nonprehensile manipulation (NPM), that is, manipulation of the terrain without a grasping end effector. Wheeled NPM can be used to increase mobility or locally terraform the terrain. These behaviors can enable higher level tasks such as leveling a landing site, digging a trench to lay cables, exposing lower soil strata for sampling, determining local soil properties, and getting a rover un-stuck[10, 8]. In this paper, we focus on digging a trench with the wheels of a robot, as in Fig. 1 and the video attachment. In order for a rover to autonomously dig trenches, we need to answer several key questions:

- What is the shape of soil deformed by a wheel as a function of driving (slip angle, slip ratio), platform, and soil parameters?
- How do we manipulate soil without getting stuck?

In this work we present a new terramechanics model of soil flow around a wheel (Sec. II), use that model to answer the above questions (Sec. III), and provide experimental validation of that model (Sec. IV). In the future, this model can be used to design motion controllers which can be employed in a kinodynamic planner to enable autonomous trenching with a rover, as in e.g. [5].

II. TECHNICAL APPROACH

Here we present a model mapping rover control inputs to deformed terrain geometry. The model consists of two parts: a terramechanics model mapping rover state to wheel-soil contact geometry and forces and a soil flow model mapping wheel-soil contact geometry to resulting soil deformation.

Terramechanics model: Different terramechanics models for wheeled vehicles exist for different settings [7 13 9 3 11 6 4], but all tend to be either fast but inaccurate (e.g. neglecting resistance built by soil piled in front of a wheel), or accurate but slow (e.g. Discrete Element Methods and Finite Element Methods). Of these, only the slower methods predict both forces on the wheel and resulting displacement of the soil [3 11 6]. Here, we use fast analytic fits to key terramechanics equations, as in [4] (enabling rapid evaluation of wheel-soil interaction forces), and extend this model to predict soil motion during trenching.

Soil flow model: When driving at steady state, all soil displaced by the wheel must flow around and back behind it, and so the volume of sand in any unit length along the track behind the rover must be equal to the volume of sand per unit length in front of the rover (assuming no compaction). As such, here we will consider an infinitesimal slice of soil volume and refer to it as a planar soil area. We classify this resulting area into pointy bottomed and flat bottomed [12], as seen in Fig. 1.

To calculate the planar profile of the resulting trench, we will use the constraints imposed by the angle of repose and by conservation of volume [2]. An additional assumption is required as to the symmetry between left and right piles of sand. For large and small wheel angles (β < 10° or β > 80°), the soil is assumed to split evenly around the wheel, creating a symmetric trench. For intermediate angles, the soil flow is assumed to split about the leading corner of the wheel. This model further assumes that soil transport due to the grousers is negligible compared to soil swept by the wheel’s profile, and as such a fixed and a rotating wheel will have identical trench profiles.

The calculation of the resulting profile is shown in Fig. 2. The area of soil to be moved is taken to be the projected area of the wheel, Fig. 2(c), as determined by the sinkage (h0) and slip angle (β). Soil is then placed to either side of the wheel based on the symmetry assumption, in the form of triangles with an angle of repose (φ) corresponding to that of the soil, Fig. 2(d). The soil then flows back into the trench, Fig. 2(e). The soil is assumed to move along the steepest gradient, only flowing inwards, maintaining the width of disturbed terrain found in
III. RESULTS

Numerical results based on this model were generated by testing different slip ratio and slip angle values using the parameters listed in Table I. These values were used to help answer the key questions outlined in Sec. I.

Trench Depth: Comparison of trench depth and wheel sinkage reveals that the deepest sinkage does not yield the deepest trench depth, as might be expected. This can be seen in Fig. 3a, where the bottom surface shows the wheel sinkage \( h_0 \) and the top surface shows the resulting maximal trench depth \( h_2 \) at different slip angles and slip ratios. Note that depth is reported as distance from the original surface, and so deeper trenches are lower on the vertical axis. The regions where the surfaces intersect are conditions that yield a flat bottomed trench. The deepest sinkage occurs at around \( \beta = 0^\circ \) while the deepest trenches occur at around \( \beta = 50^\circ \) to \( \beta = 60^\circ \) for almost all slip ratios. Thus we can maximize trench depth without maximizing sinkage.

Effect on driving: With this model we can bound the

![Fig. 1: Single-wheel testbed setup for trenching model validation (a). Wheel moves across level sand surface at fixed sinkage, slip ratio, and slip angle. Example vee-shaped trench with a pointed bottom (b) and a flat-bottomed (c).](image)

![Fig. 2: Definition of key terramechanics values (a-b) and illustration of soil flow model (c)-(g).](image)

![TABLE I: Sand parameters used in this paper.](image)
allowable slip angles and slip ratios for a trenching wheel in order to avoid it getting stuck. The net tractive force is calculated based on the driving parameters of the trenching and nontrenching wheels. Fig. 3b shows a plot of the trenching resistance versus slip angle (\( \beta \)) and slip ratio (\( s \)), and then driven across the surface in a straight line. The resulting trench is imaged with a LIDAR scanner at 10 points along its length, 5-10 cm apart, with each sampling point yielding a profile comprised of 150-200 unique measurements. The soil profile is then compared to the theoretical profile predicted by Sec. II. See Fig. 1a and the video attachment.

The LIDAR scans of a flat sand surface have a standard deviation of < 1mm, significantly less than the typical feature scale in these experiments. Calibration scans of alignment jigs are used to correct for rotation and offsets of the LIDAR scanner and testbed mounts. Experiments iterate over a representative range of wheel sinkages and slip angles. For each, the average error, \( \delta \), of the trench model is evaluated by finding the average Euclidean distance from each measured point along the soil profile to the theoretical profile, and then determining the average error in bins of fixed width. Each bin is then equally weighted in determining the overall \( \delta \) for the trench, to eliminate weighting errors from nonuniform distribution of sampled points. These scans are also used to evaluate compaction, by comparing the soil volumes before and after trenching.

Thus far, we have completed experiments on a range of slip angles for a fixed wheel with 11-12mm of sinkage. Further testing for other slip ratios, slip angles, and sinkages is ongoing. Preliminary experiments show a good fit, with an average deviation of \( \delta = 1.6 \) mm between the untuned, first-principles model and actual trench shape. Fig. 4 shows profiles measured for five different slip angles along with a first-principles model and actual trench shape. In all but one, the theoretical center of the soil profile (red) closely matches the measured profile (blue). In the case \( \beta = 22.5^\circ \), the agreement isn’t as good, with \( \delta = 2.8 \) mm, but could be improved by refining the symmetry assumption discussed in Sec. II.

The deepest trench dug in preliminary experiments was 22 mm, or 0.46 \( r \). On a rover such as Curiosity, this would amount
Fig. 4: Plots of measured trenches (blue) and theoretical trenches (red) for a fixed wheel ($\omega = 0$) at 11-12 mm sinkage with slip angle varied from $0^\circ$ to $90^\circ$. 

...to a 12 cm deep trench with just a single pass of the wheel[1]. One can easily imagine using multiple passes to remove large quantities of soil, effecting larger scale manipulation of terrain.

REFERENCES


