Soil modeling with a DEM Lookup approach

Jonathan Jahnke1,∗, Stefan Steidel1, and Michael Burger1

1 Fraunhofer Institute for Industrial Mathematics ITWM, Fraunhofer Platz 1, 67663 Kaiserslautern

We consider an efficient, data-driven approximation approach for the prediction of soil-tool interaction forces. In a time-consuming offline phase, we perform a set of Discrete Element Method basis simulations. In each simulation, we consider a different tool state, process the acquired data and save it into a data structure, which we call a Lookup Table. In an online phase, when performing arbitrary tool maneuvers, we obtain tool forces and moments from the Lookup Table, based on the current tool state. In other words, we generate a data base of tool maneuver forces and access it efficiently.

1 Introduction

In modern construction equipment design, the accurate representation of the machine itself is crucial, but also its surroundings, more specifically different types of soil and rocks, and the interaction in between require accurate modeling. Measurements provide useful insight when addressing soil-tool forces, however, the construction and design of a specific experimental setup is time-consuming and expensive. A versatile simulation tool, modeling the bulk behavior of granular material, for instance based on the Discrete Element Method (DEM), leads to physically accurate force predictions of unknown scenarios and is much cheaper in handling. A drawback of the DEM as a penalty-based, soft-sphere particle method are the small time-steps in the range of $10^{-4}$ to $10^{-6}$ seconds, required for forward integration leading to huge overall computation times. We try to leverage this issue by accumulating simulation data in a Lookup Table (LUT) and address it in an efficient way. Thus, the reaction forces can be predicted close to real-time, so that the method may be used in combination with a driving simulator in the future.

2 Method Description

2.1 The Discrete Element Method

The Discrete Element Method is a soft-sphere particle model where the particle motion is based upon Newton’s second law. The forces consist of contact and gravitational forces acting on a single particle. Whenever two particles are in contact, a repulsive normal force is activated. Our model is based upon a linear, scale-invariant contact force model. Friction is incorporated via a tangential spring using Coulomb friction. For the simulations, we use our own DEM software package entitled GRAnular Physics Engine (GRAPE). The DEM was first described in [1] and a detailed description of our model and some implementation details can be found in [2, 3].

2.2 The DEM Lookup approach

The DEM Lookup approach consists of two phases. First, in the offline phase, we perform several DEM basis simulations. For a specific simulation scenario, including a parametrized particle sample representing a specific type of soil and a fixed earth-moving tool, a set of relevant tool state parameters are varied within each DEM simulation. Second, within the online phase, we quantify the current tool state with the Lookup parameters. In each time-step, we access the acquired data by a $k$-nearest neighbor search to obtain a meaningful approximation. If $p$ describes the current state vector, we use a weighted mean $F(p) = \sum_{j=1}^{k} w_j \cdot F(p_j)$, where the weights $w_j$ correspond to $1/\delta(p, p_j)$ for some distance measure $\delta$. We use here the standardized euclidean distance function.

Fig. 1: Program structure of the DEM Lookup approach: in the lower half, the classical DEM framework used in the offline phase; in the upper half, the online phase using the Lookup Table.
3 Numerical Example

3.1 Plate in gravel testbed

We consider a blade of 0.2 m width and 0.3 m height moving through a sample of granular material. The horizontal direction of motion will be denoted by \(x\), the vertical upward direction by \(z\). Three parameters are varied, namely the cutting depth \(d\) in \(z\)-direction, the angle around the \(y\)-axis \(\theta\) and the velocity in \(x\)-direction \(v\). When an inclination \(\theta\) comes into play, the depth \(d\) is calculated as the distance between the upper surface of the granular material at the beginning of the experiment and the edge on the lower right of the blade. The parameter choice is motivated by earthmoving equations, see [4], Chapter 3. To generate the Lookup Table in the offline phase, we store mean and variance for each basis simulation. More specifically, we cutoff the first and last 0.5 seconds, when the tool enters or leaves the pile of particles as this may include undesired artefacts in the force and moment time series.

To complement the results already presented in [5], we test our Lookup Table with an online trial simulation, where we alter the velocity and the angle of incidence. For the approximation, we use a weighted mean of the 5 nearest neighbors and generate noise by normally distributed random variables \(X_i \sim N(\mu_F, \sigma_F)\) with mean and variance from the Lookup Table. The force time series seem to agree qualitatively, see Fig. 2. However, the oscillations have a different behavior and require further investigation.

![Fig. 2: Juxtaposition of forces obtained by full DEM simulation (left) and by DEM Lookup with 5-nearest neighbor weighted mean and a stochastic process (right). The considered scenario involves changes in velocity between 0.3 and 0.9 m/s and in the inclination angle \(\theta\) between \(-20\) and \(45\) degrees. The cutting depth of \(0.15\) m remains constant.](image)

3.2 Excavator bucket in gravel testbed

For a more realistic example, we consider the same testbed with an excavation tool. We currently investigate this scenario in an experiment at the soil laboratory of the Technical University of Kaiserslautern, see Fig. 3. That is, we replace the plate by the model of a commercial excavator bucket with a cutting width of 0.305 m. We vary the tool’s cutting depth \(d\) between 0.05 and 0.25 m, while the velocity \(v\) in \(x\)-direction lies between 0 and 1 m/s. Additionally, we change the angle \(\theta\) around the cutting edge in the range of \(-30\) to \(30\) degrees. In this example, we choose a finer meshing of our parameter space, resulting in a total of 125 basis simulations.

![Fig. 3: Visualization of measurement and simulation for \(d = -0.15\) m after dragging the excavator bucket about 2 m through a gravel testbed. Testbed measurement (left) and full DEM simulation (right).](image)

4 Discussion

We describe a fast, data-based approach to assess soil-tool interaction forces with the prospect of applying it in a simulator environment. The approach has been validated in a first example, moving a plate through a gravel testbed. The DEM Lookup approach is currently investigated in a more realistic scenario exchanging the plate by an excavation bucket.

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