Virtual Reality Simulation of Vehicles and Tools Interacting with Deformable Terrain

Daniel Holz, Ali Azimi, Marek Teichmann
CM-Labs Simulations Inc.
http://www.vxsim.com

Abstract

Realistic physics-based simulation of vehicles on soft terrain has increasingly gained importance due to their broad application from operator training to mission planning and design. In this work we combine models from terramechanics and soil mechanics to represent the interaction of vehicles and their tools with a deformable terrain, allowing us to simulate a broad range of vehicles, including earth moving equipment and planetary rovers on soft ground in real time. We consider the impact of both wheel–ground and tool–ground interactions on the vehicle behavior by creating a fully coupled simulation of the dynamics of the vehicle and its environment. Soil exhibits a multitude of different behaviors depending on material properties, soil formations and interactions with the medium, including erosion and compaction. Non-linear stress–strain relationships as well as highly plastic material deformation and flow makes simulation of soil a challenging task. In addition, the demands of real-time simulator environments are rather high concerning both realistic visualization and physical correctness, since for training purposes real life scenarios have to be displayed with sufficient accuracy to prevent negative training. Therefore, in Virtual Reality (VR) training simulators for bulldozers, excavators but also planetary rovers a balance has to be found between interactivity and physical correctness of soil behavior. In this paper, we present one such solution. In simulation studies we show how the vehicle’s behavior (e.g., its trajectory and mobility) is impacted when it is operated over areas already modified by its tool or wheels.

I. INTRODUCTION

Virtual Reality (VR) simulators play a key role in operator training today. In the process of training operators for heavy machinery, e.g., cranes, earth moving excavators or bulldozers, the use of simulators eliminates the risk of damage to the machine or human injuries. The cost of training is very high when it comes to expensive machinery, e.g., in mining and construction. Operators have to spent many hours in the actual machine to perfect and renew their training, occupying valuable equipment, which could otherwise be put to commercial use. Nowadays, modern computers make it possible to produce real-time training simulators with stunning levels of realism both on the visual and the physics side for a reasonable cost. It is probably unrealistic to state that, by means of VR training simulators, the part of operator training which involves working with the actual machine can be completely eliminated in the near future. However, the duration of this part can be drastically reduced. The cost for the real machine exceeds the price of a modern simulator often by several orders of magnitude. Also, simulators provide the means to train unforeseeable situations and work with different and new equipment, both of which is not easily possible in training with the actual equipment. Furthermore, simulators easily allow recording operator efficiency, and can hence be used as a tool to improve it. In addition, the training value of a simulator lies not only in hands-on training in all weather and with no mechanical maintenance costs, but also in a classroom setting where several students benefit from seeing the training of one. Consequently, real-time training simulators are a cost-efficient alternative to traditional training, if the simulator can produce a sufficiently high degree of realism.

Traditional simulators for vehicle driver training on road has been around for a long time. However, training on soft, deformable terrain, and with tools such as blades that affect the terrain itself requires fundamentally new technology and is only starting to be available now. In this work, we address the need of advanced VR training simulators for realistic and fast modelling of vehicles operating on and with soil. Especially when it comes to earth moving operations, or generally, operations on deformable ground, the need for good training is very high. The complex, and constantly changing environments, operators face in, e.g., construction and mining create great challenges during work. In order to prepare operators for these challenges, the quality of training must be very high. A simulator must be able to meet this quality requirement, allowing to simulate complex scenarios with appropriate level of realism and to do so in real-time.
While deformable material has been a field of interest in computer animation for decades, there is a lack of deformable material simulations which meet the real-time requirements of training simulators. Here, we attempt to address this lack, by proposing simulation techniques which can achieve real-time performance while keeping the physical realism high enough for operator training. We model both wheel–ground and tool–ground interactions of a vehicle in a coupled fashion, considering all interaction forces acting on the vehicle at once. We show that the proposed approach is capable of simulating complex emerging behavior in example simulation studies.

The following sections give a brief description of the proposed method followed by a presentation and discussion of simulation results. Finally, we provide an outline of future work and conclude.

II. METHOD

Here, we present a simulation method which is capable of capturing wheel- and tool-induced terrain deformations in real-time. We model fully articulated vehicles with mounted earth moving tools, such as blades or buckets, using the multi-body dynamics simulation toolkit Vortex\(^1\). A heightfield-based terrain representation is used to simulate the terrain surface under deformation. The proposed approach is versatile enough to be applied to a wide array of earth moving scenarios in construction and mining as well as other applications, e.g., planetary exploration. Examples will be given in Section III. The forces of the wheels and the tool interacting with the terrain surface are computed by means of terramechanics and soil mechanics models, respectively. Both models will be briefly presented in the following sections.

A. Brief description of Vortex

CM-Lab’s Vortex provides a virtual environment for real-time simulation of complex multibody systems. In Vortex, each rigid body is formulated using six degrees of freedom, and these bodies can be connected with several constraint types with varying numbers of linear and/or angular degrees of freedom. The toolkit supports equality as well as inequality constraints, e.g., contacts, which can be holonomic or nonholonomic. Vortex employs the method of Lagrange multipliers together with an implicit integration scheme for stable and fast multi-body simulation [1]. With its optimized core for fast and real-time simulation and its advanced graphical capabilities, Vortex has various applications including operator training, mission planning and design.

Contact constraints are handled by detecting intersections between various different shapes. This includes simple shapes like spheres, boxes, and cylinders as well as more complicated ones such as heightfields and triangle meshes. Friction can also be included in all constraints. In addition, Vortex has a graphical interface in which a user can create a mechanism by placing parts, collision geometries, and constraints, in a user-friendly environment. Furthermore, there are some modules provided in Vortex for particular applications. An example of those is the vehicle simulation module.

B. Wheel–Ground Interaction

In order to model wheel–ground interactions in our dynamics simulator, we generate contact constraints at relevant locations of the wheel, according to collision geometries of the wheel and the ground. Then, the contact constraint equations are formed and parametrized according to a suitable interaction model. This interaction model defines ground reactions (forces and moments) based on kinematic properties which are the wheel pose (position and orientation) and twist (velocity and angular velocity). Also considered are the geometry of the wheel and material properties of wheel and ground.

Two fundamentally different representations for wheel and soft ground interaction have been developed in Vortex. They are (i) semi-empirical terramechanics models, and (ii) a higher-fidelity detailed model based on elasto-plasticity theory, which was recently developed by Azimi et al. [2].

The semi-empirical models are derived from the works of Bekker [3] and Wong [4]. In these models, stress distribution in the wheel–soil contact area is closely dependent to empirical equations relating the average pressure under a rigid plate to its penetration depth into soil. Details for implementing the semi-empirical models in Vortex can be found in [5] and [6]. In [5], a basic implementation of these relations with some modifications required for dynamic operations are explained. In an extended version presented by Azimi et al. [6], vertical terrain compaction

\(^1\)http://www.vxsim.com
Fig. 1. Left: Normal stress distribution under the wheel with the multi-pass effect, in which the second wheel drives in already compacted soil. Right: Equivalent soil reaction effects on the wheel, which result from integration of normal and shear stress distribution in the contact area. The picture shows normal ($F_z$), lateral ($F_l$), and traction ($F_t$) forces and the compaction resistance force ($R_c$).

and hardening effects are considered, which allows for the simulation of the multi-pass effect. In this paper, the stress distribution follow the Bekker model with the repetitive loading model of Wong [4]. Example normal stress distributions are illustrated in Fig. 1.

C. Tool–Ground Interaction

For the interaction of tool and ground, we employ the approach presented by Holz et al. [7]. The authors use a hybrid particle-based and mesh-based soil simulation method originally presented in [8] and extend it by incorporating soil reaction forces acting on soil cutting tools, e.g. a bulldozing blade. The method combines a heightfield-based representation of soil at equilibrium with a particle simulation based on the Discrete Element Method (DEM) to model soil in motion. A detailed contact analysis between tool and heightfield is performed to detect if the tool is, in fact, displacing soil, in which case a corresponding part of the heightfield is replaced by particles as depicted in Fig. 2. No soil displacement is allowed if the tool does not apply sufficient force. The force required to fail the soil is computed through a formulation obtained via the Fundamental Earth Moving Equation (FEE) of Reece [9] and the method of trial wedges presented by McKyes [10]. The FEE formulation requires a set of relevant inputs, among which are certain geometric variables of the tool/terrain overlap. Those are terrain surface inclination angle $\alpha$, tool penetration depth $d$, tool width $w$, and tool/terrain surface angle $\rho$ some of which are shown in Fig. 2. For more details on the FEE formulation and the process of computing the required geometric inputs the reader is referred to [7]. The resultant cutting force is applied to the tool – and therefore to the entire vehicle mechanism – by adding a constraint between tool and terrain to the simulation and parameterizing it with a corresponding maximum force. Note that, as shown in Section III, the DEM particles also add a considerable soil reaction force to the vehicle, due to the creation of contact constraints between tool and particles. The particles represent the surcharge accumulated during any soil cutting operation and play an important role in the overall simulation.

We decided to formulate the soil cutting force based on the Fundamental Earth Moving Equation motivated by the fact that (i) it is a 2D model which makes it easy to apply and (ii) that it has a reasonable range of operations appropriate for simulation of several soil cutting tools. As mentioned by Shen et al. [11], this equation is approximately valid for tools which have a sufficiently high width-to-depth ratio. This allows us to use the FEE formulation for wide tools, such as bulldozer blades and wheel loader buckets. Narrow tools, by contrast, not only induce horizontal and vertical soil movement, but also movement to the sides, in direction of the tool width. In this case, the FEE is not valid anymore. Consequently, any tool with side walls can be simulated by the FEE reasonably well since the side walls restrict sideward motion of the soil. This justifies application of our model also to buckets of earth moving excavators and backhoes [12].
D. Visualization

In this work, we apply the techniques presented by Holz et al. [8] for visualization of soil. The utilized techniques provide a sufficient degree of realism for VR training simulator environments, and, due to their low time consumption, give priority to the computationally more demanding parts of the overall simulation. The reader is referred to the corresponding work for details. While Holz et al. display all particles as directly moving on top of the soil surface – the heightfield – we decided to distinguish between particles on the surface and free-falling particles. We detect the latter and visualize them individually as shown in Fig. 3. This allows for the simulation of scenarios in which material is moved between different locations, e.g., from a pile onto a truck bed. We visualize the free-falling particles using a mesh-based representation of a clump of soil (see Fig. 3). By employing GPU-accelerated geometry instancing\(^2\), we can keep the visualization time consumption at reasonable levels even when displaying a high number of meshes. For each particle, one of several different mesh prototypes is chosen. This creates diversity in rendering and a more realistic look.

In order to maintain sufficiently high frame rates, we have to keep the number of particles in our DEM simulation reasonably low. Since we have to still model the full amount of soil, each particle has a correspondingly larger size. This creates a significant discrepancy between the look of the simulated soil and real life soil, such as sand, which has a homogeneous appearance. To address this issue we could employ implicit surface reconstruction techniques to create this homogeneous look. Unfortunately, those techniques are computationally very demanding, and require a large number of particles for good visual results. Instead, we add an additional set of particles to the simulation, which we display as point sprites. Those so-called secondary particles are simulated with a simple euler integration scheme, only affected by gravity and a linear velocity prescribed at particle birth. The secondary particles are emitted at a configurable rate by the (primary) DEM particles. A similar approach was suggested by Alduán et al. [13] who integrate the secondary particles in a velocity field generated by the primary particles.

Also dust plays an important role in training. Large and dense dust clouds created while handling certain types of granular media in construction and mining, can at times completely obscure the operator’s view. Modelling dust, therefore, greatly increases the realism of a training simulator. Here, we propose an event-based dust creation mechanism. At certain events, e.g., the detection of an impact force when dropping soil, dust sprites are generated and integrated by a secondary particle system. An example of this effect is shown in Fig. 3 where an excavator bucket causes dust generation during digging.

\(^2\)http://www.opengl.org
III. RESULTS AND DISCUSSION

In Fig. 3, we show screenshots of various simulated vehicles in Vortex dealing with deformable terrain, ranging from a light small-size fully articulated rover (Sojourner) to an excavator and a bulldozer model. In Fig. 4 we show another rover – Neptec’s Juno Rover – on which we mounted an additional bulldozing blade (long or short).

Fig. 3. Screenshots from various terrain deformation simulations employing the proposed method. The center pictures show both the mesh-based particle display and the proposed dust sprite generation technique. Dust is created during digging with an earth moving excavator, consequently greatly improving visual realism.

Fig. 4. Bulldozing simulation with Juno rover. Left: Usage of a short blade. The wheels do not enter the trench left by the blade and the rover can continue driving. Center: Usage of a long blade. Rover drives into the trench left by the blade and gets immobilized. Right: Side view of the simulation with long blade. The rover is stuck and the wheels’ slip are close to 100%.

Fig. 5. (a) Blade force, (b) the resulting average slip ratio of all wheels, and (c) Blade force. Cases 1 and 2 correspond to blade width of 0.9m and 1.65m. In both cases, the initial blade depth (d) is 0.038m, and initial tool-soil angle (ρ) is 72°.

When a long blade is used to cut a trench, the front wheel drives over an already scraped surface. This causes the rover to progressively tilt forward, which in turn increases the blade depth and tool–soil angle. As a result, the soil cutting force increases and may cause the vehicle to get stuck if the operator does not lift the blade. We are able to capture this behavior with our method. Screenshots of the corresponding simulation runs are shown in Fig. 4 and simulation results comparing the rover behavior with the two blade sizes are shown in Fig. 5.

http://www.neptec.com/
In the second simulation study, the rover drives straight towards a mound of soil with 20cm height and a diameter of 2m. In a first run the bulldozing blade is up, not touching the ground throughout the simulation. In the second run and the third run, the bulldozing blade is lowered and contacts the mound when the rover approaches it. In the second run, the rover is equipped with the short blade while in the third run the longer blade is used causing strong soil deformations once the rover reaches the mound. Fig. 6 illustrates this case study by showing rover trajectory and position in all three runs, while Fig. 7 shows the comparison between rover trajectories on the horizontal $x-y$ plane for all three runs and the soil reaction forces for the second and third runs. As can be clearly seen, the rover trajectory deviates from the original straight path when bulldozing forces are involved, acting only on one side of the blade. Also the average wheel slip ratio increases and the progress of the rover is slowed. Furthermore, we see that, as expected, the soil forces rise and fall steadily while the rover passes over the mound.

Fig. 6. Final position of Juno rover after driving over a mound of soil without soil/blade contact (left), with a short blade (center) and a long blade (right) respectively. All runs result in different rover trajectories due to different soil reaction forces added to the vehicle.

Fig. 7. (a) Rover trajectories while driving toward and over a mound of soil (blue circles) with a height of 20cm: triangles corresponds to a simulation run with high blade position (no blade contact with soil), while squares and circles to runs with low blade positions causing soil deformation (blade is longer in the case of circles). The markers, representing the center of the rover, are placed every 2 seconds of the simulation and their color corresponds to the average wheel slip ratio ranging from a minimum of 0.05 (light color) to a maximum of 0.49 (dark color). Triangle and square markers are slightly offset in $y$ direction for clarity. (b) and (c) Soil reaction forces from FEE and DEM (particles) for the long blade (trajectory with circles) and short blade (trajectory with squares).

IV. CONCLUSION AND FUTURE WORK

In this work we presented a method for real-time simulation of terrain deformations, versatile enough to be employed for Virtual Reality training simulators. A combination of terramechanics and soil mechanics models captures the effects of both wheel–ground and tool–ground interactions. Soil reaction forces acting on wheels and mounted tools are directly coupled with the vehicle through the run-time creation and parametrization of constraints in the Vortex simulation framework. This allows our method to capture emerging behavior and to provide a level of fidelity sufficient for its application in Virtual Reality training simulators. We apply efficient visualization techniques and augment visual realism by incorporating low-cost secondary particles, realizing the effect of dust. The flexibility of the physics model allows deployment in various applications ranging from construction and mining to planetary exploration.
The usage of a heightfield-based surface representation has many advantages. A heightfield can be employed very efficiently for collision detection and visualization. Being formed by a regular grid, it is easy to deform and it can trivially be used to approximate soil volume. However, the heightfield representation has one main flaw. It is unable to represent steep slopes with satisfying accuracy due to its fixed resolution. Using hierarchical heightfields would mitigate this issue. Still, soil overhangs, often found in open pit mines, or caves and tunnels, relevant in underground mining simulation, can not be represented with a heightfield at all. We are currently extending our soil simulation method to a full 3D data structure, which is able to capture all mentioned surface arrangements. So far we have achieved promising results.

REFERENCES


