Physically-Based Interactive Sand Simulation

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Abstract

The interactive simulation of 3D terrains has been approached from several perspectives. Due to the complexity of the system involved, most of the models proposed focus on a visually realistic animation of the scene, rather than on a physically-based accurate simulation of a granular system. Those models lack generality when interacting with the environment; in most cases, no reaction forces are computed, considering only soil deformation. This limitation reduces their usability in applications such as driving simulators. We propose the use of a theoretical discrete model that considers normal forces for 3D real-time simulation of granular systems. We also extend this model to consider horizontal forces, allowing a wider range of interactions. Several numerical tests have been implemented and detailed results have been analyzed which show a good model performance.

Categories and Subject Descriptors (according to ACM CCS): I.3.0 [Computer Graphics]: General

1. Introduction

Dynamics of granular systems is a research field of great interest in soil simulation [SK98]. Within the field of computer graphics (CG) applications, many authors have proposed models for the dynamics of terrain, focusing on a feasible animation of soil under a range of interactions. However, the models proposed are either not based on physical criteria, or their level of interactivity is very low.

In this paper, we propose the use of a discrete theoretical model for the simulation of a sandpile, which can be included in 3D real-time simulations. In addition, we extend this model in order to allow the soil-tool interaction simulation, achieving a higher degree of interactivity between the sandpile and the objects of the virtual environment.

The rest of the paper is organized as follows: section 2 gives an overview of the existing literature in the subject of interactive terrain simulation in CG. Next, Section 3 overviews how to introduce the model chosen in a CG application and explains the soil-tool interaction model. Section 4 describes the tests that have been made to evaluate the model and exposes the simulation results. Finally, Section 5 outlines some concluding remarks and future work.

2. Related Work

Dynamic terrain is usually represented by a height field, which performs a discretization of the system surface, and a dynamic model that accounts for the evolution of the grid points. The first dynamic models for virtual terrain [MKM89] are erosion models, used to obtain a realistic landscape. However, they are aimed to be used in off-line modeling and rendering, and are computationally very expensive. Some more recent models [ON00, BR04] allow desert scenery simulation, including sand accumulation on obstacles. These models, however, give up rigor in favor of computational efficiency and simplicity, and are not capable of interactive simulation.

Chanclou et al. [CLH96] propose a first model for the deformation of terrain. They consider soil as an elasto-plastic sheet that reacts to contact, but they discard the dynamic behavior of granular material by using a simple diffusion model to smooth terrain after contact. Sumner et al. [SOH99] presented a model that considers the interaction between an arbitrary object and a loose soil. In their approach, when a collision happens, a map of the collision area is computed to displace material from the colliding points to its closest non-colliding neighbors. Finally, an erosion process is applied. This model has been extended so that sand can accumulate on moving objects [ON05].

Previous models do not consider any reaction force on the body that is in contact with soil. One of the most relevant contributions dealing with such reaction forces was proposed by Li and Moshell [LM93], who compute the horizontal force on a tool that is pushing a heap of granular material, but their model does not provide vertical or friction forces. In addition, the evolution of points that are separated from each other is coupled by a linear system of equations, which makes it difficult to simulate local features such as impacts efficiently. Benes et al. [BDAB06] propose a very simple scheme to simulate sand manipulation in a haptic environment, considering collisions only against a sphere, but their approach lacks generality.

More recently, Zeng et al. [ZTT*07] propose a more general framework for sand interactive simulation. They compute the velocity of every avalanche, associating momentum to every grid node in order to obtain the response to contacts. Although they base part of their work on that of Li's [LM93], they neither do any validation nor refer to any established model for the sandpile evolution during vertical contacts.

Thus, several authors have addressed the problem of interactive soil simulation with different levels of success. However, in those models, the system was evolved in a non physically-based manner. Moreover, the method used for material displacement during contacts is an heuristic scheme that separates the effect of contacts from the erosion process, leading to additional computations.

In order to propose a more accurate approach to the problem, we overview some basic ideas regarding dynamics of sandpiles. A sandpile can be piled up until the surface reaches the *repose angle*. Then, the slope is reduced again by means of surface avalanches. One of the most recognized models that describe this behavior is the so called BCRE [BCRE94], which consists of a set of partial differential equations for the evolution of sandpile surface. Based upon the BCRE model, and other theoretical and experimental results [HWKO97, EA01, PPC04], Pla-Castells et al. [PCGFMD06] propose a discrete model for the evolution of a sandpile that also considers external normal forces. The discrete model is formalized as a rectangular height field, and includes a local rule for the evolution of every node. Preliminary results indicate that this model is adequate for 3D real-time applications.

When a body gets in contact with soil, we are also interested in the horizontal forces that appear, and in the way terrain is displaced. Based on experimental evidence [SK98], when a portion of soil is displaced, it is considered as a solid that slides along a pre-defined interface, causing what is called a *fracture*. Using Mohr-Coulomb theory [SK98] it is possible to determine the forces acting on the tool. We propose the use of the Perumpral's model [NBMR00] to introduce this process in our discrete model.

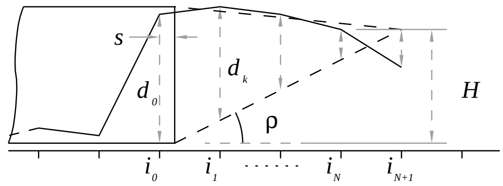

Figure 1: *Superposition of the Perumpral's fracture region (dashed line) and the discrete model proposed in this paper.*

3. Real-Time, Interactive Simulation of a Sand Pile

In order to consider the physical properties of the system dynamics, we propose using use the model in [PCGFMD06]. This model is presented as a cellular automata on a regular grid; the value of each grid node or cell represents the height of the heap on that point. To compute the evolution of the system, the slope and the force applied at every cell are checked. Then, a simple update rule is applied; if a combination of these two values is over a given threshold, some material of the cell is transferred to its neighbors, in the steepest descent direction.

To solve the model efficiently, we use the following implementation scheme; we keep a list of active cells, which include every cell that is in contact with an object and every cell that was updated in the previous step. Then, only the cells that are active are checked and updated, saving an important amount of computation.

3.1. Simulation of Soil-Tool Interaction

Based on this description of the dynamics of a sandpile, we use Perumpral's model [NBMR00] to compute the horizontal force acting on a vertical soil-body interface. The fracture region in this model is the wedge delimited by the tool and a plane inclined a given angle ρ that passes through the lower end of the tool up to the surface (see Figure 1, dashed line). The horizontal force depends on the material density γ, on the wedge's weight W, on the internal friction angle ϕ, and on the external friction angle of soil-tool interface δ, as

$$F = \frac{(W\sin(\phi+\rho)+2F_l\cos\phi)\sin(\delta)}{\sin(\phi+\rho+\delta)} \quad (1)$$

where $F_l = \frac{\gamma}{6}HW(1-\sin\phi)\tan\phi$ is the friction force on the wedge laterals and ρ is taken so that F is minimized. Friction along the interface is also computed and applied. The model is presented for a one-dimensional system. For the 3D general case, we apply this one-dimensional model along both directions of the rectangular grid separately.

For equation (1) to be applied, variables W and H have to be computed from our discrete representation of the system. Thus, let us consider a one-dimensional system, discretized as a succession of M equidistant points, $i = 0,\dots,M$, and the corresponding heights $h_i = h(i)$. We consider that a *vertical* *soil-tool interface* exists at every colliding point i_0 for which i_0+1 is not colliding. We shall denote the vertical fracture depth under point i_0+k as d_k, and N shall be the minimum integer when $h_{N+1}<0$ (see Figure 1). In case $h_0<0$ or $h_1<0$, no interface is considered. The value of W can be obtained by summing the different d_i, and H as $H=d_0-d_N$. The force is applied at a point that is at 1/3 of the height of the interface [SK98].

In order to keep the meaning of d_0, vertical contact forces are not applied on point i_0. Instead, we update i_0 by the surface evolution model, and record the value of s in order to know how much space between i_0 and i_0+1 is occupied. If the object advances in the direction of the free side, the material must be pushed by the body, sliding along the fracture. This causes every cell's height above the fracture to increase accordingly. Otherwise, if the object retires, sand in the interstice between the object and the sandpile must spread in the new gap, reducing the interface node height.

4. Simulation Results

In order to analyze the model proposed, we have implemented two tests that shall be referred as T1 and T2. T1 corresponds to a cube with unit edges falling on a flat ground, and T2 corresponds to the same cube pushing material horizontally. To use an easily reproduced scenario, we have used the physics library Open Dynamics Engine (ODE) v0.8, compiled with gcc v4.2.2 (libc6 v2.6.1), on a dedicated Intel PIV-HT, 3.4GHz with GNU/Linux system. As in related works [ON05, ZTT*07], collision detection is based on ray casting. However, and unlike previous proposals, we have applied no optimization in collision detection, using the standard ODE collision facilities. The reason for doing so is to consider a neutral scenario, in order to evaluate how the sandpile model may affect an application performance.

We have measured the average CPU time per simulation step using different grid densities. Also, using Valgrind [NS07], we have estimated the percentage of CPU usage of the three main parts of the simulation loop during test T2: sandpile evolution (SPE), collision detection (CD) and horizontal displacement (HD). For each grid density, 30 repetitions have been made, and confidence intervals have been obtained assuming normal distribution for the mean. The parameters of the model have shown no significant influence on the time obtained; this is reasonable as the cost only depends on the number of active nodes.

The results of the tests are shown in Table 1. Columns are labeled as follows. N is the number of subdivisions per unit length (the grid density). T1 and T2 are the average CPU times (in ms.) of one step for each test. Confidence intervals are below 0.001ms for T1 and below 0.01ms for T2, and are not shown in the table. Also for test T2, columns four to six correspond to the CPU time percentages of the aforementioned parts of the simulation, labeled SPE, CD, and HD, respectively.

N	T1	T2	SPE	CD	HD
20	0.02	0.21	18%	38%	44%
30	0.03	0.45	19%	35%	46%
40	0.06	0.73	22%	33%	45%
50	0.09	1.21	27%	31%	42%
60	0.13	1.93	40%	29%	31%

Table 1: *Results of the numerical tests.*

According to the results, the dynamic model that we propose has a very low computational cost. In those situations when horizontal displacement is not involved (Test T1) the average time for simulation loop makes it possible the simulation of a granular system in applications with very little spare CPU time. The main limitation of the model is the fact that the cost grows with the square of the grid density. However, in the range between 20 and 60 grid points, which we consider enough for applications such as driving simulators, results are excellent. Although we have not yet performed comparison tests with previous models, it is remarkable that in our model no analysis of the collision patch needs to be made. Instead, it is the dynamic model itself that decides how the material must be spread, saving additional computations. In Test T2, horizontal displacement involves a larger amount of cells, mainly due to the fracture region, leading to higher average values. However, it is noticeable that collision detection takes over 30% of the resources in our tests. Thus, we expect that the times can be reduced with an adequate optimization. Anyhow, even without optimization, the results indicate that for the range between 20 and 50 subdivisions, the model can be used at an update frequency of 100Hz, which should be enough, at least for stability issues.

The model has been successfully integrated into a production bulldozer simulator, showing that it can be used in a highly demanding environment without optimization. Rendering of sand is done by a mesh, implemented with triangle strips. We use texture sliding in order to make the visual effect of sand flow during avalanches [ZTT*07]. Figure 2 shows an image of the model interacting with the bulldozer model.

5. Conclusions

The field of terrain simulation has made considerable headway in the last years, from models of terrain deformation to models that account for more complex interaction, some including reaction forces. However, the current proposals do not take into account physical correctness. In this work we have proposed the use of a physically-based model which can be integrated in real-time computer graphic applications. The model allows a high degree of interactivity, considering the evolution of the system under an external action, and the corresponding reaction, including friction forces. Although other authors have previously claimed similar results, we

Figure 2: *A telescopic manipulator, acting as a bulldozer, pushes sand horizontally. Wheel trails, can also be observed.*

have used a validated dynamic model, getting more realistic results. Moreover, we have provided a detailed description of a model for soil-tool interaction, which is crucial for interactive simulation of terrain. Another remarkable feature is that, in our approach, the evolution of the granular system is computed within the main physics loop. With this approach, no modification is made outside the main loop, making it easier to implement multi-threaded applications.

Also, an in depth analysis of the performance has been provided, together with the necessary details to reproduce and compare the tests. The results of the performed tests show that the model is suitable for real-time applications. They also give valuable information about which modules should deserve more optimization effort. In this context, in future research, we intend to implement an optimized version of the collision detection and to introduce multiscale decompositions of the grid, reducing the number of active cells and, thus, improving the overall performance of the system.

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References

[BCRE94] BOUCHAUD J. P., CATES M. E., RAVI-PRAKASH J., EDWARDS S. F.: A model for the dynamics of sandpile surfaces. *Journal de Physique I France 4* (1994), 1383–1410.

[BDAB06] BENES B., DORJGOTOV E., ARNS L., BERTOLINE G.: Granular material interactive manipulation: Touching sand with haptic feedback. In *WSCG'2006* (2006).

[BR04] BENES B., ROA T.: Simulating desert scenery. In *Winter School of Computer Graphics SHORT Communication Papers Proceedings* (2004), pp. 17–22.

[CLH96] CHANCLOU B., LUCIANI A., HABIBI A.: Physical models of loose soils dynamically marked by a moving object. In *Computer Animation, CA'96* (1996), pp. 27–35.

[EA01] EARL E., ALEXANDROU A.: Deformation process below a plate sinkage test on sandy loam soil: experimental approach. *Journal of terramechanics 38* (2001), 153–162.

[HWKO97] HIROMA T., WANJII S., KATAOKA T., OTA Y.: Stress analysis using FEM on stress distribution under a wheel considering friction with adhesion between a wheel and soil. *Journal of terramechanics 34*, 4 (1997), 225–33.

[LM93] LI X., MOSHELL J. M.: Modeling soil: Realtime dynamic models for soil slippage and manipulation. In *SIGGRAPH'93* (1993), pp. 361–368.

[MKM89] MUSGRAVE F. K., KOLB C. E., MACE R. S.: The syntesis and rendering of eroded fractal terrains. In *SIGGRAPH'89* (1989), pp. 41–50.

[NBMR00] NOUGUIER C., BOHATIER C., MOREAU J. J., RADJAI F.: Force fluctuations in a pushed granular material. *Granular matter 2*, 4 (2000), 171–178.

[NS07] NETHERCOTE N., SEWARD J.: Valgrind: A framework for heavyweight dynamic binary instrumentation. In *ACM SIGPLAN 2007 Conference on Programming Language Design and Implementation* (2007).

[ON00] ONOUE K., NISHITA T.: A method for modeling and rendering dunes with wind-ripples. *Pacific Graphics* (2000), 427–428.

[ON05] ONOUE K., NISHITA T.: An interactive deformation system for granular material. *Computer Graphics Forum 24*, 1 (2005), 51–60.

[PCGFMD06] PLA-CASTELLS M., GARCIA-FERNANDEZ I., MARTÍNEZ-DURÁ R. J.: Interactive terrain simulation and force distribution models in sand piles. In *Cellular Automata. Lecture Notes on Computer Science* (2006), vol. 4173, pp. 392–401.

[PPC04] PARK S., POPOV A. A., COLE D. J.: Influence of soil deformation of off-road heavy vehicle suspension vibration. *Journal of Terramechanics 41* (2004), 41–68.

[SK98] SHEN J., KUSHWAHA R. L.: *Soil-Machine Interactions*. Marcel Dekker, New York, 1998.

[SOH99] SUMNER R. W., O'BRIEN J. F., HODGINS J. K.: Animating sand, mud and snow. *Computer Graphic Forum 18* (1999).

[ZTT*07] ZENG Y.-L., TAN C. I., TAI W.-K., YANG M.-T., CHIANG C.-C., CHANG C.-C.: A momentum-based deformation system for granular material. *Computer Animation and Virtual Worlds* (2007).