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Interactive earthmoving simulation in real-time

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Abstract

Virtual Reality simulators of heavy machinery are often used for training purposes. However, the complexity of terrain as a dynamical system makes the simulation of earthmoving machinery an specially challenging problem. In this paper, the architecture of an excavator simulator is described, together with the different models used to describe the behavior of the systems involved. Special attention is paid to soil dynamics and to the interaction models, including soil-wheel interaction and soil-tool interaction. The different models used are physically-based, in order to guarantee a realistic simulation and an appropriate force feedback.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Animation, Virtual Reality. I.3.8 [Computer Graphics]: Applications—.

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1. Introduction

In the last decades, interactive simulation based on Virtual Reality techniques has become a powerful tool for training purposes in activities which involve high risks and costs. The use of a simulator prevents from exposing the trainee to the risks of manipulating the real machine in it usual working environment. In addition it provides with the possibility of working in the desired conditions, without having to wait for these condition to happen (e.g. arbitrary weather conditions can be reproduced at any time).

Within this context, the simulation of earthmoving machinery presents a challenging problem; in this case, not only the mechanical system that comprises the machine (excavator, bulldozer, etc.) has to be simulated. In addition, a realistic simulation of soil has to be achieved, including the interaction with the machinery considered. In the revised bibliography, some authors refer to soil simulation models [GFVH98, FBVS07], though without providing any technical details about such models or their implementation. Other authors present mathematical models for bucket filling with different degrees of complexity [FEP05, KM05], but without addressing neither the forces that appear nor the evolution of soil surface.

In this paper, an small size excavator simulation system is presented. The main contribution of this work is to show the application of the physically-based model of terrain presented in [PCGFMD08] within a production environment, and the presentation of a simple tyre-soil interaction model.

The rest of the paper is organized as follows: in what remains of Section 1 an overview of the simulation system is presented. Section 2 presents the model of the bulldozer and the way the different elements of the system are integrated together. Next, Section 3 overviews the models used for terrain simulation, including the soil-tool interaction model. Section 4 describes the tests that have been implemented to evaluate the model and exposes the simulation results. Finally, Section 5 outlines some concluding remarks and the future work to be done.

1.1. Simulator Architecture

A vehicle simulator aimed to training tasks is a complex system composed of several modules which allow to reproduce the behavior of the environment, to acquire the user's actions and to visually represent the simulated environment. The simulator considered in this work is composed of the following elements:

- Physical model of the machine and the environment.
- Input/Output devices and controls to acquire user actions.
- Visualization system, which provides a graphical representation of the environment.
- 6-Degree of Freedom (DOF) mobile platform, to provide the user with inertial stimuli.

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During the simulation, the input devices, which reproduce the control panel of the simulated machinery, capture the user actions. These input data are used by the dynamic models in order to determine the evolution of the machinery and of the environment. The state of the simulated environment, which represents a typical construction site, is reproduced by means of a 3D graphics application, implemented using the OpenSceneGraph programming library. Within this environment a lightweight excavator is simulated. In the next sections, the models for the excavator and for the terrain and the interaction procedures are described.

Figura 1: *A view of the virtual environment and the simulated machine.*

2. The Excavator Model

The system simulated is a lightweight excavator which is employed to transport and handle small amounts of granular materials, such as gravel sand, cement, etc. The dynamic model used in the presented simulator consists of three main components: the mechanical model of the vehicle, the power subsystem and the tyres, which provide the model with soil-machine interaction.

2.1. Mechanical Model

The excavator is decomposed in several bodies. All of them are considered as homogeneous rigid bodies, with no flexibility. The bodies considered are:

Main body. The vehicle body is considered as a single rigid solid that comprises the mass of the vehicle chassis, the cabin, the engine and the hydraulic and electrical systems. The mass of this solid is 1900Kg, and the machine has an overall length of $3.3m$.

Arm. The arm connects the chassis of the machine with its attachments. It is considered as a rigid beam of 450Kg and has a rotation of 95^o, driven by a hydraulic piston.

The Loader. It is an attachment used for the load of bulk material, situated at the end of the arm. It has a weight of 300Kg and dimensions $0,86 \times 2,3 \times 0,95$m.

2.2. Engine and Hydraulic System

The excavator is driven by a diesel engine that generates a power of 60cv at 2800 rpm. The engine has been modelled using a typical diesel power curve [Won01]; the input of the model is the value of the throttle pedal while the output is a torque which is introduced into the traction model. The machine has a maximum speed of 11 km/h, forward and backward, at maximum power.

The hydraulic system of the excavator consists of a pump, driven by the diesel engine, and two hydraulic pistons for lifting the arm and for controlling the inclination of the loader. A description of the dynamic model used for the simulation of the hydraulic pumps and the pistons can be found in [BBL*99].

2.3. Vehicle Tyres

In order to simplfy the model and to avoid possible numerical instabilities, the wheels of the vehicle have not been considered as solids in the multibody system. Instead, they have been considered as massless discs which are attached to the main body of the excavator, and their actual mass and mass matrix added to the excavator mass matrix.

The forces that act on the tyres are applied directly on the chassis body at the soil-tyre contact point, which is determined by ray casting. The simulated vehicle has no suspension other than the pneumatic pressure of tyres. Thus, a damped spring model is used in order to determine vertical forces. Section 3.2 gives a detailed description of the model that determines the interaction between the vehicle tyres and the ground.

3. Interactive Soil Model

In order to obtain a realistic simulation of the environment and the simulated machinery it is necessary to use physically-based models of the different subsystems involved. However, the problem of soil dynamics and its interaction with an object is a complex one.

In the context of computer animation, main concern is to obtain a realistic behavior of deformable soil. In these cases, physical accuracy is not an issue and the behavior of the objects in the scene is usually prescribed. For this reason, no physical interaction is considered. Instead, evolution models are proposed for the deformation of loose soil under a contact [SOH99, ON05, ZTT*07].

When simulating earthmoving machinery, however, the physical interaction between soil and the used tool is of great concern, specially if the application is aimed to operator training. Seeking for a better physical description of the system, some authors have based their work on theoretical models [LM93, Are05, PCGFMD08].

3.1. Dynamic Model of Terrain

The dynamic model of terrain used in the simulator is the cellular automata presented in Pla-Castells et al. [PCGFMD06]. In this model, geometrical representation of terrain is made by means of a height field on a regular grid. Taking this structure as a basis, a local rule computes the evolution of soil according to some classical models of terramechanics. The model simulates the evolution of soil as a granular system, simulating avalanches and critical slope, and also deals with different types of interaction and soil manipulation.

Before the simulation starts, the grid is read from a file that stores the desired initial terrain state. During the simulation, collisions between the objects of the scene and the grid are detected. The discretization of some classical soil fracture models makes it possible to simulate the evolution of soil when in contact with the excavator parts and to compute the interaction forces that appear during these contacts.

Figura 2: *The interaction between terrain and other objects is simulated by a model based on terramechanics models.*

The different dynamic models need to be integrated together so that an interactive simulation can be run involving the considered subsystems. Both the multibody system model and the terrain model are run on a separate thread, at a rate of five hundred times per second, in order to guarantee numerical stability. When the graphic system finishes the render of a frame, the dynamic models are requested for the new state of the environment, which is used to create the new frame.

3.2. Simulation of Soil-Tyre Interaction

The computation of the interaction between the tyre and the soil is a high complexity problem, due to the number of factors that influence their behavior. However, there are relatively simple models that performs sufficiently precise simulations.

The more established model for the dynamics of tyres on rigid soil is Pacejka's *magic formula* [Pac96]. This model is used in our work for the interaction with the areas with paved ground. However, when simulation an off-road vehicle the main problem is the interaction between the tyre and lose ground. Several models can be found in the context of all-terrain vehicles design [Won01]. These models are based mainly on the combination of the model of pressure-sinkage of Bekker [Bek69] and the calculation of the friction between the ground and the tyre.

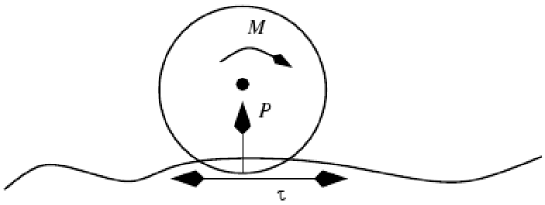

Figura 3: *Forces involved in the model of traction on soft ground.*

Let us consider a wheel of radius R. According to the state of the engine and the user input data, a torque M is applied to the wheel axis. As a result of this torque, it appears a traction force F_t on the contact surface between soil and the tyre. However, depending on the properties of the terrain material, the effective traction will be lower than F_t.

To compute the effective traction force, first the pressure in the contact region between soil and tyre, p, is computed. From this pressure, then the maximum shearing force, , that soil can resist on the interface tyre-ground is obtained from the friction angle of the soil-tyre contact. The value of for different soil properties can be found in [Won01].

Then, the effective traction force that is applied on the contact patch, F_e, is computed. If traction force is lower than the shear force , then $F_e = F_t$ is applied on the tyre and on the ground according to the corresponding models. If traction force is higher than shear force, , then only this value is applied, $F_e =$, causing the ground to slip below the tyre.

4. Simulation Results

In order to determine the performance of the system and the influence of the terrain model on it, the environment has been simulated using several grid densities for the terrain simulation, referred in number of cells per meter. The considered interactive terrain is a square region of 8m×8m, which has been decomposed in $N \times N$ square cells. All tests have been run on an Intel PIV-HT, 3.4GHz, with a graphics processor nVidia 8600GT with 512Mb RAM, under Windows XP.

N	cells/m	Verts.	Faces	Rest	Moving
40	5	3280	3200	60	36
50	6.25	5100	5000	54	31.6
60	8	7320	7200	48	28
70	9	9940	9800	47.6	24.6
80	10	12960	12800	44.8	20.2

Tabla 1: *Results for different values of N. Cell density is indicated in the second column. The third and fourth columns show the number of vertexes and faces of the soil model. Fifth and sixth columns show the frame rates obtained with the excavator at rest and while terrain was manipulated.*

Table 1 shows the frame rates that have been observed during simulations for different cell densities. The results are shown for different values of the number of cells, N. For every N, it is shown the worst frame rate that was obtained during terrain manipulation and also the frame rate that is obtained when the excavator is stopped. The environment has 80000 vertexes and 110000 faces, while the vehicle has 17000 vertexes and 29000 faces.

It can be observed that the frame rate remains over 20 fps during all the simulation, even for grid densities of 10 cells/m, obtaining good quality interactive rates. These results show that the selected methodology for the simulation of the ground and the simulation of the soil-machine interaction are adequate for virtual reality applications, even when a complex environment is considered.

5. Conclusions

In this paper a simulation system to simulate a small excavator has been presented. The system uses a physically-based model for the simulation of machine-soil interaction. Thanks to the efficiency of the model a realistic excavator simulation can be obtained at interactive frame rates.

As future work we intend to develop a multi-resolution adaptive scheme that allows for larger pieces of interactive soil. In this scheme, special attention need to be paid to memory consumption. Also, the tyre soil interaction model can be improved, by considering more complex terramechanics models. The application presented here is a prototype for the development of a simulator for heavier excavators which is being developed. In the near future more complex simulation environments and machine models will be considered.

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