Real-time soil modeling for machine-medium interaction in virtual reality

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ABSTRACT: In the application of the virtual reality technology to earthmoving equipment design, one of the primary difficulties, if not the major difficulty, is the real-time soil model. The soil models are expected to be mechanically correct, to be visually plausible, to provide realistic force feedback to the tool and simulate the behavior of large masses of soil and rock, all in real-time. Such soil models do not exist. In this paper we are reporting on an on-going research project to develop real-time soil models for applications in virtual reality simulations of the earthmoving equipment.

1 INTRODUCTION

Virtually Reality (VR) based methodology has important potential applications in engineering. Among the earliest engineering applications of VR are the advanced VR simulators with realistic force feedback in civilian and military aircraft design and in pilot training. Rapid advances in computer hardware, software and information technology now enable the use of VR environments with realistic force feedback for design and prototyping in a wide range of engineering fields. In the area of vehicle design, VR applications include testing for crashworthiness, ground-vehicle interaction and driver visibility.

An important class of potential applications of VR environments with realistic force feedback is in machine-medium interaction problems. This class of problems includes the machine-medium interaction in heavy earthmoving equipment and off road vehicles. VR environments with realistic force feedback would be a potentially useful tool in the design cycle for new equipments. Early attempts in this field have had limited applications only in examining the issues of driver field of view. The primary difficulty in these early applications has been the realistic and real-time modeling of the medium-tool interaction. The existing real-time models of the medium, such as granular soils, focus on creating visually pleasing graphics in virtual environments. These ad hoc models are not based on sound mechanics principles. Therefore, the models cannot accurately estimate the force feedback exerted by the soil medium on the equipment and the vehicle engine. This lack of realistic force feedback greatly limits the usefulness of such virtual reality models for engineering design, prototyping and trouble-shooting.

Realistic mechanic based models of granular materials have existed for a number of years. Discrete element method has been successfully used to model the flow of granular materials. Particles of granular material have been modeled by simple geometric shapes, such as circular, elliptic or polygonal discs in two-dimensional models and equivalent shapes in three-dimensional models. The models are capable of correctly representing the mechanical behavior of masses of granular materials. However, these models cannot be used in virtual reality environments since they are computational very slow. In a typical computer it may take hours to simulate one minute of a discrete element model with a relatively small number of particles. Virtual Reality environments require real-time responses in simulating the behavior of masses of granular material.

We are proposing a new approach to this problem by using neural networks. The methodology is based on the premise that neural networks can learn to accurately describe the instantaneous motion of the particles in a mass of granular material. The instantaneous motion of the particles depends on a number of factors including proximity to a free surface and the characteristic of the free surface. Neural networks can learn the relationship between these variables and the instantaneous motion of typical particles. The trained neural networks can then form the basis of the real-time soil model.

The proposed real-time soil medium model represents an original use of neural networks to model large movement of soil masses. The ideas and methodology that is being developed for the real-time soil model will be useful for a much wider range of applications such as simulation of slope failures and avalanches, and in other industrial sectors including bulk and powder material handling in agricultural, mining and manufacturing applications.

2 SOIL MODELING FOR EARTHMOVING EQUIPMENT IN A VITUAL ENVIRONMENT

A vast majority of the existing soil models are aimed at describing the deformation of the soil masses. The expected deformations in the typical geotechnical applications are reasonably small. Even in cases where large displacements and large deformations of the soil mass can develop, such as in slope stability problems, only the state at the onset of the instability is of interest. As a consequence, the soil masses in these problems are modeled as continua. The preferred approach in analyzing these problems is to use quasi-static or dynamic nonlinear finite element analysis. These models require the constitutive models of the material behavior in terms of the stresses and strains of the continuum models of the soils. Continuum models of the soil are not capable of describing the large movement of the soil masses that occur in earthmoving operations.

The modeling of the soil response due to earthmoving equipment activity requires capturing the soil response due to large movement of soil particles caused by the earthmoving equipment such as bucket loading and dumping, digging and scraping. The soil masses may undergo significant changes in their geometry, including the formation and modification of the soil piles and the instability and failure of the slope in the existing soil pile. A soil model in this case will have to capture the soil behavior as a discrete assemblage of particles. This is in contrast to modeling approaches that treat the soil as a continuum.

Discrete element models have been developed to describe the large movement of particulate and bulk materials. These models have been used in industrial material handling and mining applications. Discrete element models have also been used in modeling of the large movement of the soil and rock masses. The models simulate the individual particles and the interaction of each particle with particles surrounding and in contact with it.

Considerable progress has been made in the use of the discrete element method to model granular material since its introduction in the early 70's (Cundall, 1971). Models based on discrete element method consider the soil pile as a multi-body system of small particles where the gravity and inter-particle interactions are the main stabilizing and shaping factors of the pile.

Ghaboussi and his co-workers (Ghaboussi, 1992; Ghaboussi and Barbosa; 1990 Barbosa and Ghaboussi 1990) have introduced the use of 3-D discrete elements whereby soil particles can have random sizes and shapes and can be modeled as deformable bodies.

A number of other researchers have also made significant contributions to the discrete element method. For example, Williams and O'Conner, (1995) have made contributions to 3-D discrete elements and the modeling of particles of arbitrary shapes.

The discrete element approach for modeling soil response to earthmoving equipment provides a very good approximation of the particle movement and the forces that are exerted by soil on the earthmoving equipment. The only constitutive models needed in the discrete element method are those describing the frictional properties at the inter-particle contacts. However, a major drawback of the discrete element models in VR applications is the very long computer run times. Reasonably small problems with less than 1000 particles may require run times of anywhere from several hours to several days on a typical computer workstation.

Discrete element soil models accurately simulate the response of the soil mass to earthmoving equipment and, as such, may seem the appropriate choices for the VR applications. Realistic models of soil mass in typical VR applications would require in excess of hundred thousand three-dimensional particles. Computer simulation of such large systems for several minutes of real time would require several days of CPU time on the fastest super-computers, while VR application require real-time simulations.

3 REAL-TIME SOIL MODELS IN CURRENT USE

The focus of the real-time soil modeling to date has been on producing visually plausible movement of soil masses in interaction with machine tools, such as a loader bucket, while minimizing the computational effort to allow for rendering in real-time.

Moshell and his co-workers (Burg and Moshell, 1991; Li and Moshell, 1993) developed a visually plausible kinematics soil model. The soil is discretized as a 2D grid of equally spaced column height values, and the factor of safety is analyzed for each column individually. A two-component soil model is used to simulate soil slippage and soil manipulation. For the slippage model, if a soil configuration is not stable, forces that drive a portion of the soil pile to slide down are computed. Only the surrounding columns that touch a given column are used to determine whether the column is stable. For the soil manipulation models, and interaction between the soil and excavating equipment (bulldozer and scoop loader), the soil always moves upward along the blade and is then placed over a region on top of the moving berm in front of the blade. The algorithms are fast enough to meet the requirements of real-time graphical simulations.

Lehner (1995) developed a similar soil model based on stable final configuration. The bucket has its own 2D array of soil height values constrained by the geometry of the bucket and the soil volumes are moved from one array to another as needed. A simple force feedback is provided from the bucket to the vehicle dynamics model based on the bucket angle and the height of soil in front of the blade. The computational complexity of this approach is linear in the number of height posts, since the algorithm consists of some constant number of passes over the soil array during which comparisons with adjacent values are performed for each array index.

Although they may look visually realistic, current approaches to model real-time soil response have severe limitations that hamper their practical application. The change in particle position is physically unrealistic. During a slope cut, a soil particle at the top of the slope ends up at the bottom of the re-equilibrated soil pile. While in reality a deep-seated slope failure will occur and soil displacements are drastically different. The force feedback into the vehicle dynamics is not based on realistic forces from the soil pile and has not been verified against other measurements of forces.

4 THE PROPOSED REAL-TIME SOIL MODEL

The movements of masses of particulate material in response to manipulations by the earth moving tools, such as buckets of the wheel loaders and blades of the bulldozers, follow very complex rules. Contrary to the existing real-time soil models, these rules are not local and often have global characteristics. Consider the action of the bucket of a wheel loader removing soil from an existing pile. The movement of the bucket into the soil pile will first cause some particles of the soil to move into the bucket. When the bucket lifts out of the soil mass, it immediately creates a very steep slope, which is inherently unstable. This unstable slope causes a large mass of soil to move down until it assumes a stable position and a stable shape. A realistic soil model based on the principles of mechanics has to be able to model these deep-seated movements, as well as the movement of the soil particles into the bucket and their flow out of the bucket. Modeling of these mechanisms is also important for developing a mechanically and visually realistic and plausible configuration of the mass of the granular material, as well as realistic force feedback to the machine tool.

Another example is dumping unto an existing pile of soil. When the dumped material lands on the pile of soil, the particles of soil flow until they reach stable positions. The path that the particles take and the final stable positions they reach depend on the shape of the pile of soil and the location the particles land on. The flow of the dumped particles will be very different if they are dumped on a flat surface than if they are dumped on a pile with steep sides.

The examples described above illustrate how the motion of the soil particles is related in a complex way to the location of the soil particle in the mass and the surface configuration of the soil mass. Starting from a stable soil pile, only the changes in the configuration of the soil pile, including changes in the location of the tool, determine the motion of the particles.

In reality, there are two primary causes for the motion of the particles in a mass of particulate material. The first primary cause is the direct contact with the tool and the movement of the tool into the soil mass that causes some particles to move. The second primary cause is the creation of a temporary unstable configuration that results in the movement of the mass of the particulate material seeking a stable configuration.

$$\Delta\,\mathbf{u} = f(\mathbf{x}, \mathbf{S}, \mathbf{R})$$

In this equation $\mathbf{u}$ is the incremental displacement of the soil particle, $\mathbf{x}$ is the position of the particle, $\mathbf{S}$ is a vector defining the configuration of the surface, and $\mathbf{R}$ a set of parameters defining the interaction with the tool. It is extremely difficult, if not impossible, to directly describe these complex patterns of movement through mathematical equations. However, it is possible for neural networks to learn the pattern of incremental movement of the particles. Neural networks are ideal tools for learning the highly nonlinear and complex relations, such as in this application. The aim of the research is to develop a package of neural networks to learn the complex relationship between the incremental movement of the particles of soil, the instantaneous configuration of the soil mass and the position of the tool.

$$\Delta\,\mathbf{u} = NN\,(\mathbf{x}, \mathbf{S}, \mathbf{R})$$

The symbol NN represents a multi-layer neural network. This approach is part of the general trend advocated by the first author and his co-workers in applying the biologically inspired computational intelligence tools in engineering problems. He and his co-workers have applied neural networks and genetic algorithm in novel ways to a number of difficult engineering problems including: structural control with neural networks (Bani-Hani and Ghaboussi, 1998; 1999a; 1999b); genetic algorithm in structural shape design (Shrestha and Ghaboussi, 1998; Raich and Ghaboussi 1999); neural networks and genetic algorithms in Non-Destructive Evaluation (Ghaboussi and Banan, 1994; Chou and Ghaboussi, 1997; 1998); determination of neural network constitutive models of materials from the results of structural tests (Ghaboussi, Pecknold, Zhang and HajAli, 1998); and, neural networks in generation of artificial earthquake accelerograms (Ghaboussi and Lin, 1998). Sidarta and Ghaboussi (1998) have successfully used neural network algorithms to capture complex aspect of sand behavior in a non-uniform material test including non-linear stress strain shear behavior. These successful applications of computational intelligence suggest that NN have the potential of capturing the complex relationships in this application.

In the proposed research the relevant virtual space will be discretized by a three dimensional grid. The granularity of this grid will depend on the speed of the computers. With faster computers a finer mesh can be used to discretize the virtual space. We envision at least a two-stage neural network based method. The first series of neural networks will determine the portions of the soil mass that may be unstable and are likely to undergo large motions. The second level of neural networks uses the surface configuration of the relevant portion of the soil mass to determine the direction and the magnitude of the incremental motion for the particles within each block of the grid. A separate set of neural networks will determine the forces acting on the arms of the bucket or the blade.

A comprehensive training data set is needed to train the neural networks to capture the complex relationship among the configuration of the soil mass, the movement of the soil particles, and the forces exerted on the tools. The ideal data set would come from full-scale field experiments involving interaction of the earthmoving equipment with soil. In these experiments it will be necessary to track the trajectory of soil particles throughout the soil mass. While such experiments are feasible, running enough experiments to generate such a data set would be prohibitively costly and time consuming. We intend to use numerical simulations using the discrete element method in conjunction with a limited set of field experiments.

The main advantage of the NN model is that it will realistically capture soil response while at the same time is able to run fast enough in a real-time virtual environment.

5 MODEL CALIBRATION

The discrete element codes developed by Ghaboussi and his co-workers and others based on them have been successful in capturing essential aspects of soil interaction with earthmoving equipment. These codes will be used to perform many simulations of various maneuvers that represent idealized and actual situations of earthmoving equipment interaction with soil as illustrated in Figure 1.

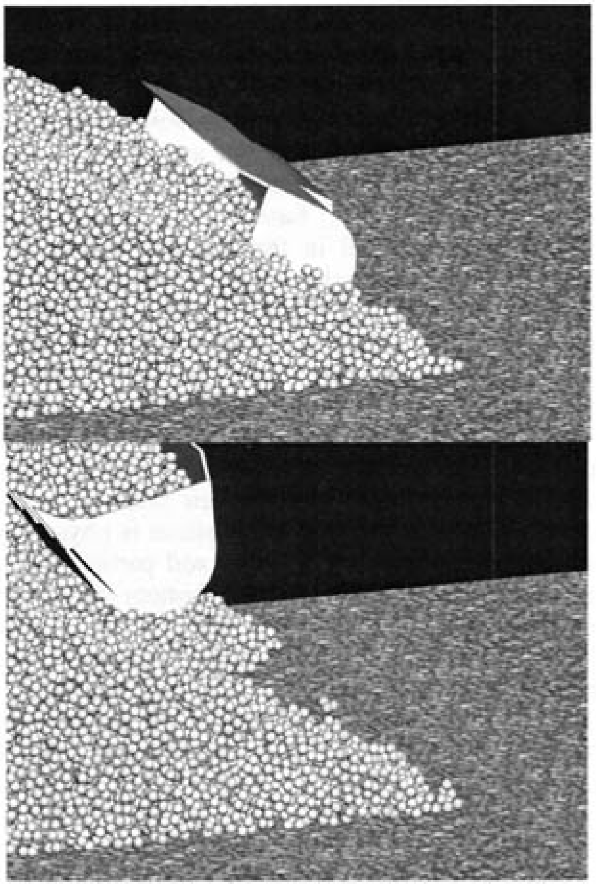

Figure 1 Discrete element simulation of soil manipulation by an earthmoving machine bucket. Courtesy Caterpillar, Inc.

In these simulations, the movements of delineated zones of the soil mass are tracked as well as the forces exerted on the earthmoving equipment. Using available supercomputing facilities at NCSA (National Center for Super Computing Applications), it will be possible to perform hundreds of such simulations for parametric studies of the influence of soil type, and earthmoving equipment configuration. The data sets will then be used to train the neural network soil models. The training of the NN model will be done on the non-real time scale using NCSA's supercomputing facilities. However, the resulting NN model, once trained, will run in real-time.

We plan to run a limited number of field tests. In these tests, the earthmoving equipment will be instrumented to measure forces exerted on the hydraulics of the equipment. Optical targets will be placed on the surface of the soil pile. The movement of these targets will be tracked in response to earthmoving equipment manipulation by taking series of pictures and using them to compute the optical targets' positions as a function of time. The data set produced from this limited number of field experiments will be used to further train the NN model.

6 VIRTUAL REALITY ENVIRONMENT FOR EARTHMOVING EQUIPMENT

Research on the development of virtual reality simulators for earthmoving equipment has been conducted for both civilian and military applications. The US Army Waterways Experiment Station (http://www.wes.army.mil/) has invested significant resources in pursuing such development. Moshell and Li (1990) have worked on the development of such a virtual environment.

A virtual reality environment for vehicle simulation has been developed at the University of Iowa. The Iowa Driving Simulator Center (http://www.ccad.uiowa.edu/research/ids/) is an advanced simulator for vehicles that can be used for safety as well as vehicle prototyping studies.

Lipman and Reed (2000), http://cic.nist.gov/vrml/, use VRML to simulate activities at a construction site. The simulation includes earthmoving equipment and soil manipulation. However, the authors state that soil manipulation is not based on physical principles and is limited to producing visual renderings of these activities.

Caterpillar, Inc. has been actively involved in VR research with NCSA at the University of Illinois at Urbana-Champaign over the past 10 years (Zentmyer, 1993; Zentmyer et. al., 1994; Kindratenko and Kirsch, 1998). One of the major results of this work is the Virtual Prototyping System (VPS, http://www.ncsa.uiuc.edu/VEG/DVR/) that implements operator-in-the-loop scenario and enables engineers to test new machine designs prior to building physical models. The system can evaluate several aspects of earthmoving equipment design such as cabin visibility, cabin controls usability, and reachability for maintenance. It also enables engineers located at geographically remote sites to collaborate on new product designs while sharing the same virtual model and communicating via integrated video and audio transmissions.

The new vehicle-soil simulation system will be implemented as a set of independent modules – each responsible for a particular task. The following are the core modules to be implemented first: graphics render, vehicle dynamics, and the NN-based real-time soil model. Additional modules, such as vehicle sound system and distributed virtual reality, can be introduced later. Vehicle and soil dynamics modules will be running independently from the render and will access the simulation state both to obtain the initial conditions for the next simulation step and to transfer the results of the simulation to the rendering module.

Real-time soil model will be implemented as an independent module that will be interfaced with the rest of the simulation system via the simulation state structure. The basic idea is to represent the entire virtual soil space as a 3D array of cells stored in the simulation state shared structure. Each cell can be occupied by the soil and the size of the cells will define the spatial granularity of the soil model. This 3D array will be updated in real-time via the developed soil model and at each simulation time step it will represent current spatial soil configuration. In order for the soil pile geometry to be visible to the user, the 3D array will be scanned by the renderer and a smooth texture-based geometry will be created over the cells occupied by the soil

A significant limitation of the existing soil models is the absence of a realistic real-time force feedback to the vehicle dynamics. Such feedback is needed in order to model vehicle response as it digs, dozes a pile of soil, or drives over soil. Therefore, the soil model will compute the soil force feedback in real-time as the vehicle interacts with the virtual soil. This feedback will then be used for a number of applications including vehicle engine response to the soil load on the bucket and digging arm, and wheels-soil interaction.

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