A SOIL MODEL FOR A HYDRAULIC SIMULATOR EXCAVATOR BASED ON REAL-TIME MULTIBODY DYNAMICS

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The actuation of hydraulic excavators is a complex and non-intuitive task which requires long and costly training periods, since the qualification of the operator has a significant impact in productivity and safety. Simulation-based training combined with virtual reality, is becoming a competitive alternative to traditional training to reduce costs and risks in the instruction of excavator operators. Several excavator training simulators have been developed, but none of them features a dynamic model of the machine complete enough to simulate all the maneuvers performed in the daily work of real excavators. The authors have applied real-time simulation techniques from multibody system dynamics to develop a full 3D physics-based excavator simulator made up of 14 rigid bodies with 17 degrees of freedom. The simulation engine includes a custom collision detection algorithm and detailed tire force and contact force models. Terrain excavation and bucket loading and unloading are also simulated. The resulting model delivers realistic real-time behavior and can simulate common events in real excavators: slipping on slope terrains, stabilizing the machine with the blade or the outriggers, using the arm for support or impulsion to avoid obstacles, etc. This paper explains several issues related to the development of a simulator of a hydraulic excavator.

Excavation and earth loading are the most common tasks for excavators, and therefore they shall be included in the capabilities of a training simulator. The detailed simulation of bucket filling requires models to predict the material flow, a simplified bucket filling model has been developed for real-time purposes. During the excavation process, the bucket penetrates the removable terrain mesh originating viscous contact forces. A ray-casting method is used to compute the intersection area between the bucket admission and the mesh representing the terrain surface; this area is integrated using the velocity component of the bucket normal to the area, in order to compute the volume and weight of earth loaded by the bucket in each time step. In addition, the algorithm diminishes the z-coordinates of the points from the removable terrain mesh that have entered inside the bucket. The algorithm provides a reasonable estimation of the loaded weight and a realistic visualization of the process. The unloading process is simulated in a similar way: when the front of the bucket surpasses a predefined critical angle, a flow of material is cast from it; the location where this flow contacts the terrain mesh or other object (e.g. a truck) is calculated. If this location does not belong to the terrain mesh, a generic flat mesh is created at that position. The flow of material is used to modify the height field of the mesh, increasing its z-coordinates using a Gaussian distribution to distribute the material randomly around the intersection point.

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ABSTRACT

The actuation of hydraulic excavators is a complex and non-intuitive task which requires long and costly training periods, since the qualification of the operator has a significant impact in productivity and safety. Simulation-based training combined with virtual reality, is becoming a competitive alternative to traditional training to reduce costs and risks in the instruction of excavator operators. Several excavator training simulators have been developed, but none of them features a dynamic model of the machine complete enough to simulate all the maneuvers performed in the daily work of real excavators. The authors have applied real-time simulation techniques from multibody system dynamics to develop a full 3D physics-based excavator simulator made up of 14 rigid bodies with 17 degrees of freedom. The simulation engine includes a custom collision detection algorithm and detailed tire force and contact force models. Terrain excavation and bucket loading and unloading are also simulated. The resulting model delivers realistic real-time behavior and can simulate common events in real excavators: slipping on slope terrains, stabilizing the machine with the blade or the outriggers, using the arm for support or impulsion to avoid obstacles, etc. This paper explains several issues related to the development of a simulator of a hydraulic excavator.

Excavation and earth loading are the most common tasks for excavators, and therefore they shall be included in the capabilities of a training simulator. The detailed simulation of bucket filling requires models to predict the material flow, a simplified bucket filling model has been developed for real-time purposes. During the excavation process, the bucket penetrates the removable terrain mesh originating viscous contact forces. A ray-casting method is used to compute the intersection area between the bucket admission and the mesh representing the terrain surface; this area is integrated using the velocity component of the bucket normal to the area, in order to compute the volume and weight of earth loaded by the bucket in each time step. In addition, the algorithm diminishes the z-coordinates of the points from the removable terrain mesh that have entered inside the bucket. The algorithm provides a reasonable estimation of the loaded weight and a realistic visualization of the process. The unloading process is simulated in a similar way: when the front of the bucket surpasses a predefined critical angle, a flow of material is cast from it; the location where this flow contacts the terrain mesh or other object (e.g. a truck) is calculated. If this location does not belong to the terrain mesh, a generic flat mesh is created at that position. The flow of material is used to modify the height field of the mesh, increasing its z-coordinates using a Gaussian distribution to distribute the material randomly around the intersection point.

1. INTRODUCTION

Hydraulic excavators are among the most versatile earthmoving equipment: these machines are used in civil engineering, hydraulic engineering, grading and landscaping, pipeline construction and mining. Their primary functions are digging, material handling and ground leveling. To execute these operations, the excavator operator actuates the machine controls (joysticks, pedals and switches) in an organized form to achieve the desired machine motion; the actuation of these controls is a complex and not intuitive task, and therefore it requires long and costly training periods, Torres (2004).

Several excavator simulators for training purposes have been developed. For example, Caterpillar offers training simulators for several types of construction machines, Caterpillar (2008). Freund (2001) and Fukaya (2002), each of them, developed an excavator simulator based on virtual reality technology. Torres (2004 and 2005) developed a haptic interface-based simulator of a semiautomatic hydraulic excavator 2D arm in a virtual environment. To develop a fully operative simulator, there are several difficulties to address and some complex phenomena to take into account that will be explored next.

One of the most difficult parts is the treatment of

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contact forces. As the application to address includes human-in-the-loop, this treatment has to be very careful because the real-time requirements impose firm constraints on the integration time step and, additionally, on the number of iterations if implicit integration is used. In addition to the efficiency considerations, the simulation has to be stable and robust enough along all the range of possible operations of the system, as well as reproduce the behavior of the real system with an acceptable precision. There are a number of methods to solve the impact problem in multibody systems composed of rigid bodies. They can be divided in two families (Lankarani (1990), Flores (2006), Flores (2008)): the discontinuous and the continuous approaches. In applications in which it is expected to occur permanent contacts or at least contacts of a significant duration, continuous methods are needed and there are a number of viscoelastic and viscoplastic models that fit this category (see Flores (2008), Ismail (2008), Butcher (2000)). Moreover, it is worth to mention that, up to these days, there is not a universally accepted model to calculate the friction force between bodies under dry conditions. For the application to tackle, a tangential friction model that includes sticktion at low velocities is indispensable, since the excavator has to work on its legs and blade, for example, on slopes.

Another difficult issue is the excavation process, i.e. the treatment of the soft soil which can be excavated. Studies of soil–tool interaction have been carried out mostly for development of force prediction models using different soils, tools, and operating conditions (speed and depth of operation, tool orientation, etc.). There are different approaches to the solution of the problem, present in the bibliography, Karmakar (2006). The filling of an excavator bucket is a complex granular flow problem. There are some numerical models which try to consider the different mechanisms involved in the filling process. Nevertheless, most of them are not suitable for real-time applications because they were developed for design optimization.

Coetzee (2007), developed 2D discrete and continu um models of excavator bucket filling. Coetzee (2009) developed a numerical model of excavator bucket filling process which accurately predicts the drag force and the volume of material inside the bucket using the discrete element method (DEM) but the precision achieved is at the expense of the computational time, since it uses a large number of particles to simulate the behavior of the material (20,000-30,000 particles).

Several models have been developed based on finite element analysis (Yong (1977), Chi (1990)) but they suffer from the same problems than the DEM models, they are very expensive from the computational point of view.

On the other hand there are also some analytical models which are good for simple geometries and better suited to real-time simulations.

2. EXCAVATOR MULTIBODY MODEL AND DYNAMIC FORMULATION.

A training simulator shall feature a dynamic model of the excavator detailed enough to provide a realistic behavior with high computational efficiency. These two features can only be achieved using multibody system real-time simulation techniques.

2.1 Multibody model.

The modeled machine is a Liebherr A924 Litronic, a medium-size wheeled excavator.

The machine has been modeled with 14 rigid bodies using natural coordinates. The resulting excavator model has 154 coordinates (including 6 distances and 7 angles) and 154 constraints (10 of them are redundant). The excavator model has 17 degrees of freedom (DOF), shown in Table 1: 7 DOF are controlled by the operator, while the remaining 10 DOF are free.

Hydraulic cylinders, responsible for the actuated DOF, have been modeled as kinematic constraints, since the dynamics of the hydraulic circuit has not been considered in this version of the simulator. Velocities and accelerations of these kinematically guided DOFs have been adjusted to match the technical specifications of the real machine (torques and lift capacities), i.e., elementary dynamics has been implemented for each actuator.

Elements crucial for stability like the front stabilizer blade and the left and right lateral outriggers (rear retractable legs) have been included in the model.

The motion of the non-actuated DOF is governed by the dynamic equations of the system subjected to the constraints and external forces. The considered external forces are the following:

a) Weight of the machine parts and the bucket load.

b) Tire contact forces, which consist of linear spring and damper elements for the normal forces, and the magic formula tire model for the tangential forces, Pacejka (1993).

c) Tire torques applied with the accelerator and brake pedals.

d) Contact forces originated from the collision of the excavator with the terrain or the surrounding objects; the contact model will be described in Section 4.

e) When soft soil is excavated, forces coming from the excavation process (see Section 5).

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Motion	No.
Actuated Degrees of freedom	
Boom, stick and bucket hydraulic cylinders	3
Uppercarriage rotation	1
Steering	1
Stabilizer blade	1
Outriggers	1
Non-actuated degrees of freedom	
Undercarriage free motion	6
Wheel rotation	4
TOTAL	17

Table 1. DEGREES OF FREEDOM IN THE EXCAVATOR MODEL.

2.2 Multibody formulation.

The multibody formulation chosen for this work is an index-3 augmented Lagrangian with projections of velocities and accelerations onto the constraints manifolds. As integration scheme, the implicit single-step trapezoidal rule has been adopted. The mentioned formulation was extensively described in Cuadrado (2001 and 2004).

3. THE EXCAVATOR SIMULATOR.

3.1 Interaction with the environment.

The excavator is placed in a working environment (in Figure 1 standing on its legs and blade), where the operator can perform different training exercises: maneuvering, digging, material handling, etc. The excavator interacts with the environment in two ways: a) collisions with the scene objects and the terrain (see Figure 2 and Figure 4), which generate contact forces; and b) terrain excavation and loading with the bucket (Figure 3).

Some scene objects are fixed (e.g. buildings, terrain) while others are movable (e.g. fences) as can be seen in Figure 4. In order to compute the dynamics of movable objects, they are introduced in/removed from the simulation only when the excavator approaches to/moves away from them; this technique makes possible to simulate in real-time working environments with a large number of movable objects.

The selected contact model delivers very realistic behavior and is able to simulate common events in the daily work of real excavators: slipping on slope terrains, stabilizing the machine with the blade and the outriggers (Figure 1 and Figure 4), using the arm for support or impulsion (Figure 2), moving objects with the bucket or blade (Figure 4), etc. or even other dangerous events not so common in the daily work, like rolling the excavator over (Figure 5), etc.

Figure 1. VIRTUAL EXCAVATOR IN ITS WORKING ENVIRONMENT.

Figure 2. USING THE ARM TO DESCEND A STEEP SLOPE.

Figure 3. TERRAIN EXCAVATION.

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Figure 4. INTERACTING WITH MOVABLE OBJECTS.

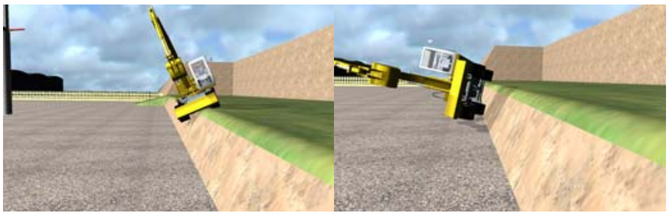

Figure 5. EXCAVATOR ROLLOVER.

3.2 Human-Machine interface.

The operator console has a semi-immersive virtual reality interface that emulates the excavator cabin (see Figure 6). A hard shell hemispherical dome of 2130 mm diameter from Immersive Display UK Ltd. is used to project the subjective view from the operator's position. It features an Epson EMP-765C projector and an Omnifocus lens that provides a 180° horizontal x 135° vertical view angle with XGA resolution (1024 x 768) at 72Hz. The OpenSceneGraph software library is used to render the virtual scene; the distortion correction for the hemispherical screen is achieved by a cube-mapping algorithm.

In addition, the SDL-Mixer library is used to generate sound for the excavator engine, buzzers and collisions.

3.2.1 Input controls. The operator console of the simulator emulates most of the controls in the real machine cabin using low-cost standard USB input devices: a steering wheel, 2 joystiks with the standard excavator functions (arm motion and uppercarriage rotation) and 2 pedals (accelerator and brake).

In addition, a 15" LG L1510BF tactile screen (Figure 6) replicates the digital control panel of the excavator, which lets the operator control different machine settings (engine revolutions, drive speed, etc.) and shows warnings and errors. Some controls that exist as hardware switches in the actual excavator, like the ones to position the stabilizer blade and outriggers, have been also included in the tactile screen as software switches, since they cannot be easily reproduced with standard off-the-shelf hardware.

3.2.2 Monitoring. In addition to the operator console, the training simulator includes an instructor console: from this console, the instructor can control a networked group of operator consoles in a classroom to launch exercises, monitor the progress of the learners and evaluate them in a qualitative manner. The instructor console monitor features two cameras for the virtual simulator scene: a subjective view from the operator's point of view (like in Figure 6) and a configurable external view (like in Figures 1, 2 and 3). The instructor console also shows real-time information about events happened during the simulation (collisions, loss of stability, etc.).

Figure 6. OPERATOR CONSOLE.

4. DESCRIPTION OF THE CONTACT MODEL.

The contact forces approach proposed for this work comprises two different models: the normal force model and the tangential force model. The two models are presented separately in subsequent sections. The tangential model is an original contribution from the authors, Dopico (2009), while the normal model is completely taken from previous works.

In the human-in-the-loop application tackled in this paper the multibody model studied is divided in primitive objects (in the majority of the cases spheres) for contact detection purposes, and interact with CAD environments composed of triangular meshes. Under these circumstances, all the contacts can be approximated as contacts between primitives and plane surface bodies.

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4.1 Normal force model.

In order to choose the normal force model, some tests were done with several continuous viscoelastic models. Finally, the normal force model chosen for this work was the Hunt-Crossley model, Hunt 1975. The model is suited to collisions between massive solids for which the assumption of quasi static contact holds and it can be supposed that the deformation is limited to a small region of the colliding bodies while the remainder of them is assumed to be rigid. The expression for the normal force, after some calculations, has the following form,

$$\mathbf{F}_{rad} = k_{rad}\left(1 + \frac{3(1-\varepsilon)}{2}\frac{\dot{\delta}}{\dot{\delta}_0}\right)\mathbf{n}_{fl} \qquad (1)$$

Where k_{rad} is the equivalent stiffness of the contact and depends on the shape and material properties of the colliding bodies, δ is the indentation and δ_0 is indentation when the contact is detected, ε is the coefficient of restitution, and $\mathbf{n}_{fl}$ is the direction of the force, i.e., the normal vector to the contact region.

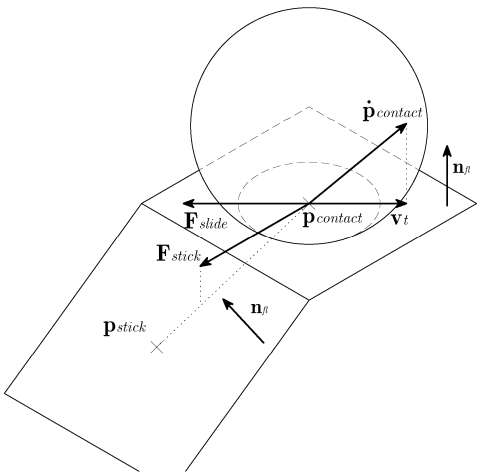

Figure 7. TANGENTIAL CONTACT BETWEEN SPHERE AND PLANE.

4.2 Tangential force model.

The tangential force model developed for the friction force is based on Coulomb's law including sticktion. Moreover a viscous term is added to the dry friction force. The model is extensively described in Dopico (2009) but a brief summary is given here.

The general form of this force is the following,

$$\mathbf{F}_{roz} = \kappa\mathbf{F}_{stick} + (1-\kappa)\mathbf{F}_{slide} - \mu_{visc}\mathbf{v}_t \qquad (2)$$

In the previous expression, the first two terms constitute the dry friction, while the third term accounts for the viscous friction. For the smooth transition between sticking and slipping the dry friction force is divided in two components coupled by a smooth function.

In Eq.(2), $\boldsymbol{\mu}_{visc}$ is the viscous damping coefficient, $\mathbf{F}_{stick}$ and $\mathbf{F}_{slide}$ are the components of the sticktion and slipping forces, κ is a smooth function of the tangential velocity, $\mathbf{v}_t$, which is defined in terms of the central point of the contact region, $\mathbf{p}_{contact}$, and the normal vector at the contact, $\mathbf{n}_{fl}$, as follows.

$$\mathbf{v}_t = \dot{\mathbf{p}}_{contact} - \left(\mathbf{n}_{fl}^{\mathrm{T}}\dot{\mathbf{p}}_{contact}\right)\mathbf{n}_{fl} \qquad (3)$$

The mentioned function, κ, has to match the following conditions,

$$\kappa = \begin{cases} 0; & |\mathbf{v}_t| >> v_{stick} \\ 1; & |\mathbf{v}_t| = 0 \end{cases} \qquad (4)$$

where v_{stick} is a parameter of the model accounting for the velocity of the stick-slip transition. A good choice for the transition function, κ, was given in Gonthier (2004) and has the following form.

$$\kappa = \mathrm{e}^{-\left(\mathbf{v}_t^{\mathrm{T}}\mathbf{v}_t\right)/v_{stick}^2} \qquad (5)$$

Eq. (2) showed that the total force is composed of three contributions: the sliding dry friction force at high velocities, the sticktion force of the bristles at low velocities and the viscous friction force. The sliding dry friction force $\mathbf{F}_{slide}$ is the well known Coulomb's expression, but the sticktion force $\mathbf{F}_{stick}$ is rather involved and it is not going to be described here. For further details, see Dopico (2009).

4.2 Contacts detection technique and computational aspects.

The methods developed in this work are designed for applications in which contact plays an important role and moreover the multibody model or models have to interact with complex CAD environments. This is the case of the simulators of certain kind of machinery and vehicles.

To deal with the kind of applications mentioned, the technique used here is to approximate the environments and the multibody models by primitive objects: the complex CAD environments by meshes of triangular faces and the geometry of the multibody systems by spheres of different sizes (in the majority of the cases) and in some cases by boxes (when the geometry cannot be approximated by spheres in a satisfactory way). Each face of the CAD environments has its own normal vector and its own

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properties of stiffness and friction and each sphere is characterized also depending on the material properties and curvature of the multibody model.

At each time step, the contact conditions have to be detected in a fast way. This involves checking all the spheres against all the faces and their edges. These are a lot of calculations per time step when the environments are realistic. In order to speed up this process the algorithm uses an octree based hierarchical decomposition of the entire scene mesh Foley (1993). The bounds of the polygon soup are calculated through an Axis Aligned Bounding Box (AABB) to generate a tree-based hierarchical structure that is used to quickly reject the polygons not involved in potential collisions, in order to reduce the number of polygons tested against contact with the primitive objects that represent the models geometry. The depth of the tree has to be empirically optimized for speed.

In addition, also in order to save computational time, all the calculations necessary for computing the detections are reduced to the minimum. In this sense many calculations are precomputed like: all the equations of the planes of the meshes, certain constant expressions used to decide if a point belonging to a plane is as well contained in the triangle of the face, the equations of the semi-infinite straight lines of the edges, and so on.

All the mentioned techniques are not enough for real-time purposes. For this work, an implicit integrator is used with the aim of improving the stability of the integration and consequently the algorithm is iterative, what means that if all the calculations related to the contact detection were carried out in each iteration, the cost of the detection would rise in an uncontrollable manner as the number of iterations grows. The consequences of this rise could be disastrous, because when the integration is more difficult the number of iterations grows and consequently both the computational cost of the dynamics and contact detection would grow as well. This is completely unacceptable. To avoid the testing of the whole tree of faces in each iteration, the faces susceptible of collision are selected after the prediction stage of the integrator and kept during the whole time step, this means once per time step instead once per iteration, what helps to maintain the computational cost per time step more constant. Depending on the number of primitives present in the multibody model, the parallelization of the contact detection must be considered also.

5. THE EXCAVATION PROCESS.

The soft soil is modeled as a terrain mesh. During the excavation process, the bucket penetrates the terrain mesh. A ray-casting method is used to compute the intersection area between the bucket admission and the mesh representing the terrain surface; this area is integrated using the velocity component of the bucket normal to the area, in order to compute the volume and weight of earth loaded by the bucket in each time step.

In addition, the algorithm diminishes the z-coordinates of the points from the removable terrain mesh that have entered inside the bucket. The algorithm provides a reasonable estimation of the loaded weight and a realistic visualization of the process.

The unloading process is simulated in a similar way: when the front of the bucket surpasses a predefined critical angle, a flow of material is cast from it; the dropping process of the material is simulated, the exact instant and the location where this flow contacts the terrain mesh or other object (e.g. a truck) is calculated. If this location does not belong to the terrain mesh, a generic flat mesh is created at that position. The flow of material is used to modify the height field of the mesh, increasing its z-coordinates using a Gaussian distribution to distribute the material randomly around the intersection point.

The filling of the excavator bucket is a complex granular flow problem. The majority of the numerical models that try to consider the different mechanisms involved in the filling process, are not suitable for real-time applications because they were developed for design optimization, and they are too heavy for real-time purposes. On the other hand there are also some analytical models which are good for simple geometries and better suited to real-time simulations. This is the option chosen here.

In order to calculate the bucket digging force, different types of soil failure mechanisms have to be considered (Karmakar (2006)): rigid-brittle type of failure and flow failure. In brittle failure, blocks of soil are periodically separated from the soil mass, and the force on the tool is of periodic nature in brittle failure. Speed does not affect the shear strength under the conditions of brittle soil failure.

In this work, the brittle type of failure will be neglected; being possible, thus, to develop a simplified force model in terms of a given bucket depth and the soil volume flow towards the bucket. The simplified expression to calculate the digging force is the following,

$$\mathbf{F}_{dig} = -\mu_{dig}\left(\sigma_1 + \sigma_2 V_b^m\right) d_b^n \mathbf{v}_t - \mu_{cp} d_b^n \mathbf{v}_n \qquad (6)$$

Where $\mathbf{F}_{dig}$ is the digging force, V_b is the volume of material inside the bucket, d_b is the bucket depth and σ_1, σ_2, μ_{dig}, μ_{cp}, m and n are parameters of the model; $\mathbf{v}_d$ is the velocity of the bucket's teeth, $\mathbf{v}_t$ is the projection of $\mathbf{v}_d$ onto the excavation direction and $\mathbf{v}_n = \mathbf{v}_d - \mathbf{v}_t$ (see Figure 8).

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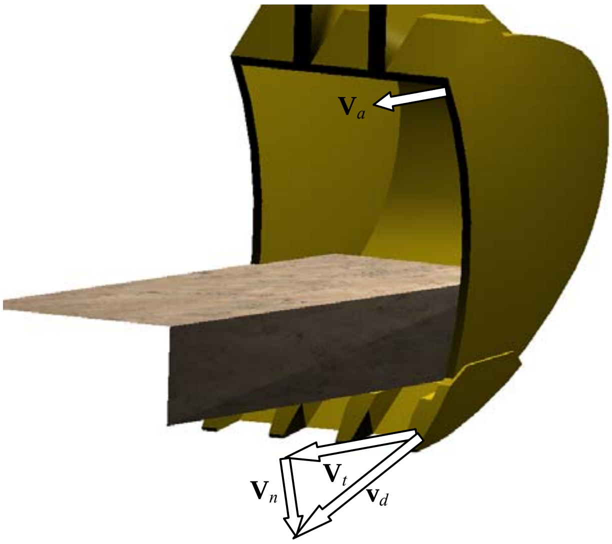

Figure 8. EXCAVATION PROCESS.

The weight of the soil inside the bucket is directly calculated from the volume V_b:

$$\mathbf{P}_{soil} = \rho V_b \mathbf{g} \quad (7)$$

The calculation of V_b is not straightforward because the soil volume flow is different in each plane of the bucket. The volume flow is calculated in several parallel planes of the bucket. The integration of the total volume flow gives the volume V_b.

6. CONCLUSIONS.

- Real-time simulation techniques from multibody system dynamics allowed the development of a realistic but computationally efficient 3D model of a complex machine like a hydraulic excavator. The resulting simulator, which runs in a standard PC, can reproduce almost all the maneuvers performed by real excavators.
- An integral solution to address contacts between the machine and a complex CAD 3D environment was described.
- A solution to simulate the excavation process, including bucket loading and unloading was proposed.

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