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A 3D PHYSICS-BASED HYDRAULIC EXCAVATOR SIMULATOR

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ABSTRACT

The actuation of hydraulic excavators is a complex and not 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. The simulator console has a semi-immersive virtual reality interface that emulates the excavator cabin. The operator console imitates most of the controls of the real machine cabin using low-cost standard USB input devices: steering wheel, 2 joystiks with the standard excavator functions and 2 pedals. A tactile screen replicates the digital control panel of the excavator, which lets the operator control different machine settings. A hard shell hemispherical dome of 2 m diameter is used to project the subjective view from the operator's position. The resulting simulator, which can run in a standard PC due to its high computational efficiency, can reproduce almost all the maneuvers performed by real excavators.

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 [1].

The qualification of the excavator operator is not only required to operate the machine properly, but it has also a significant impact in productivity and safety. Bucket loading highly depends on the operator digging style, as demonstrated by Hall [2]; hence, skilled operators can finish the task in less time, with important cost savings, and the same applies to material handling and ground leveling operations. As far as safety is concerned, hydraulic excavators may be involved in two types of accidents. The first one is underground facility damage under excavator loading, in particular pipeline and power or communication cables. For example, it is documented that digging operations cause around 50% of the failures in onshore oil and natural gas transmission pipelines, see e.g. Brooker [3]. The costs derived from supply interruption, facility repair and time delays in the excavation are very high, and these accidents may also involve fire or explosion with severe possible consequences in terms of loss of life, injury, property and environmental damage. Since in most digging operations the excavator bucket is out of sight to the operator, it is difficult to prevent such accidents when the exact position of the underground facility is unknown. However, experienced operators can interpret subtle changes in the excavator movements to immediately detect a collision between the

bucket and an underground facility, and stop the operation before causing severe damage.

A second type of accident is excavator fall or rollover due to loss of stability. Hydraulic excavators, especially those used in civil engineering, usually operate on irregular terrains with poor accessibility. It is a common practice to use the excavator arm as an additional support or impulsion element, as shown in Fig. 1, to avoid obstacles or to maneuver in small working zones. Skilled operators are needed to execute these maneuvers without endangering stability. Falls and rollovers can also happen when lifting heavy loads on uneven terrains, with severe risk for the lives of the operator and nearby personnel.
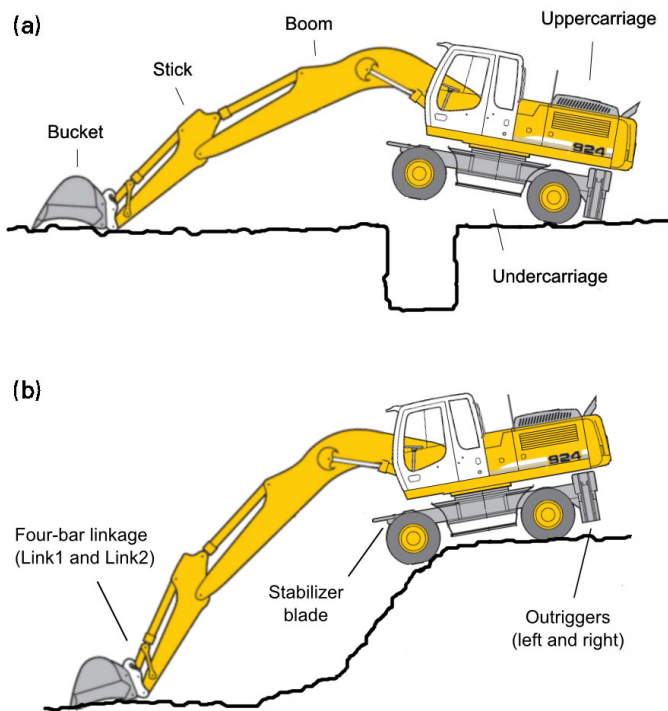

Figure 1. Obstacle avoidance maneuvers using the excavator arm for support or impulsion: (a) traversing a trench; (b) ascending or descending a steep slope.

Sales of hydraulic excavators have increased since 2004, and market trends confirm a growing demand for the next years [4], which also means a rising demand for qualified excavator operators. In this scenario, simulation-based training combined with virtual reality is becoming a competitive alternative to traditional training to reduce costs and risks in the operator instruction.

Several excavator simulators for training purposes have been developed. For example, Caterpillar offers training simulators for several types of construction machines [5]. Its hydraulic excavator simulator features several training modules (bucket positioning, loading, trenching, ...) and provides feedback about elapsed time and accuracy in each training exercise; the simulator runs in a PC with a standard monitor, and includes

two control levers as input devices. At the Institute of Robotics Research in Germany (IRF), Freund [6] developed an excavator simulator based on virtual reality technology with close-to-reality presentation of the environment and a physically based simulation; this simulator was aimed at commanding construction machines in real world applications by means of projective virtual reality and telepresence systems. Virtual reality technology was also used by Fukaya [7] to develop an immersive excavator simulator featuring 8 surrounding screens and an operator seat with a motion mechanism, in order to investigate the human factor of the operator and to find safety measures for excavator work. Torres [1,8] developed a haptic interface-based simulator of a semiautomatic hydraulic excavator 2D arm in a virtual environment for training purposes; the goal was the kinesthetic coupling between the operator and the machine, providing information to the operator about the interaction forces between the excavator and the soil.

Research on excavator control and automation has also proposed kinematic and dynamic models for the mechanical behavior of hydraulic excavators. This research focused on designing control systems that can operate the excavator to perform certain tasks (e.g., generate straight-line motions in the bucket) with minimal human intervention, in order to increase productivity in the digging and ground leveling processes. The models developed in this field are also relevant and useful in a training simulator. Kinematic and physics-based dynamic models of the excavator arm, regarded as a planar manipulator with three degrees of freedom, were derived by Zhang [9], Hall [10] and Zweiri [11]. Makkonen [12] combined Matlab/Simulink and the commercial multibody simulation software MSC.Adams to develop a 3D model of the excavator arm with 4 degrees of freedom (DOF) equipped with a 2 DOF accessory at the end of the arm; while this model is significantly more complete than the previous ones, the simulations cannot run in real-time. Some authors included the hydraulic actuator circuit in the dynamic model of the excavator arm, see e.g. Chang [13] and He [14]; this approach takes into account the severe nonlinearities in hydraulic actuators, which are hardly observed in electric motors and make more difficult the design of control systems for automated excavators. Other complex phenomena present during excavator work have been also modeled: for example, Towarek [15] studied the interaction between an excavator with tridimensional motion and a deformable soil foundation, and Coetzee [16] developed 2D discrete and continuum models of excavator bucket filling.

The aforementioned simulators for training purposes feature dynamic models of the excavator simple enough to run in real-time on desktop PCs, but they cannot simulate risky maneuvers like those shown in Figure 1. On the other hand, models originated from control research are limited to 2D arm models or they are too computationally expensive to run in a real-time training simulator. These limitations motivated the development of an excavator simulator with an improved dynamic model

capable to accurately simulate all kind of maneuvers, accidents and dangerous situations, but fast enough to run in real-time in desktop computers. In addition, the simulator provides a low-cost virtual reality immersive environment to the operator, and therefore it is a powerful but affordable training tool for excavator operators.

The remainder of the paper is organized as follows: Section 2 describes the dynamic model of the excavator; Section 3 explains how the excavator interacts with the surrounding environment, e.g. collisions, digging and ground leveling; Section 4 describes the human-machine interfaces implemented in the simulator console and the virtual reality immersive display system; finally, Section 5 provides conclusions and areas for future work.

2 EXCAVATOR MODEL

A training simulator shall feature a dynamic model of the excavator that combines realistic physics-based behavior with high computational efficiency. These two features can only be achieved using real-time simulation techniques originated from multibody system (MBS) dynamics, see e.g. García de Jalón and Bayo [17]. During the last years the authors have developed state-of-the-art MBS dynamic formulations specially designed for real-time simulation of complex mechanical systems, and this experience has been applied to model the dynamics of a hydraulic excavator.

2.1 Multibody model

The modeled machine is a Liebherr A924 Litronic, a medium-size wheeled excavator. It has been modeled with 14 rigid bodies and 13 revolute joints, shown in Figure 2. 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. Hydraulic cylinders have been modeled as kinematic constraints, since the dynamics of the hydraulic circuit has not been considered in this version of the simulator.

Kinematics of the multibody system has been modeled with natural coordinates [17]: this technique uses a set of dependent coordinates (points, vectors, angles and distances) related by constraints to characterize the motion of each body. 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. At this moment, the actuated DOF are kinematically guided because the dynamics of the hydraulic actuator circuit has not been modeled yet; therefore, the operator controls the position of actuated DOF without any delay or inertial effects. Velocities and accelerations of these kinematically guided DOFs have been adjusted to match the technical specifications of the real machine (torques and lift capacities). The motion of the non-actuated DOF is determined by the forces applied to the model:

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 [18].
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 3.

2.2 Dynamic formulation

The equations of motion of the whole multibody system are given by the well-known index-3 augmented Lagrangian formulation; as integration scheme, the implicit single-step trapezoidal rule has been adopted, and cleaned velocities and accelerations are obtained by means of mass-damping-stiffness orthogonal projections. This method, described in detail in [19], has proved to be a robust and efficient global formulation to achieve real-time simulation of the excavator with time-steps of 5 ms.
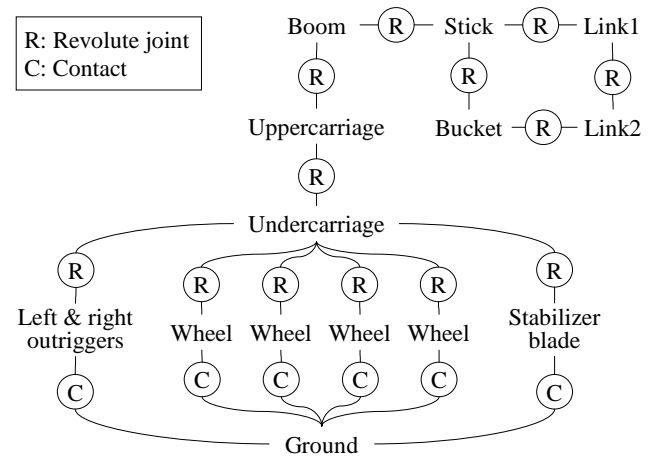

Figure 2. Topology diagram of the excavator representing rigid bodies and kinematic joints.

Table 1. Degrees of freedom in the excavator model

Motion	No.
Actuated degrees of freedom	
Boom, stick and bucket hydraulic cylinders	3
Uppercarriage rotation	1
Steering	1
Stabilizer blade	1
Outriggers	1
TOTAL	7
Non-actuated degrees of freedom	
Undercarriage free motion	6
Wheel rotation	4
TOTAL	10
TOTAL	17

3 INTERACTION WITH THE ENVIRONMENT

The excavator is placed in a working environment (Figure 3) 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, which generate contact forces; and (b) terrain excavation and loading with the bucket.

Some scene objects are fixed (e.g. buildings, terrain) while others are movable (e.g. fences). 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.

3.1 Collision detection

General collision libraries aim to detect arbitrary collisions between two meshes. This procedure is very exact but time-consuming. In order to achieve the real-time constraints imposed by the simulator, a custom collision detection algorithm between a mesh and primitive objects was implemented. In this way, terrain and scene objects are represented by a triangle mesh, but the geometry of the excavator parts is replaced by a set of points, spheres and boxes placed in key regions of the geometry, in order to detect the most common contact conditions in a fast way.

The algorithm uses an octree based hierarchical decomposition of the entire scene mesh [20]. 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 excavator geometry. The depth of the tree has been empirically optimized for speed.

3.2 Contact Model

Once contact has been detected between the machine and the environment, contact forces shall be applied to the colliding bodies. The normal component of the contact forces is a regularized model with a combination of nonlinear spring and damper elements; this kind of models relates the energy dissipation to the impact velocity and the theoretical coefficient of restitution. Both the Lankarani-Nikravesh [21] and the Hunt-Crossley [22] models have been implemented in the simulator, obtaining similar results. The tangential-friction component of the contact force has a nonlinear Coulomb friction with sticking and sliding states. To model the frictional effects at low speed, characterized by the sticktion state and the decreasing friction with increasing velocity, a model with elastic bristles was implemented; the smooth transition between stick and slip friction states was achieved by introducing the state function proposed by Gonthier [23].

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 or the outriggers, using the arm for support or impulsion (Figure 4), moving objects with the bucket, etc.

Figure 3. Virtual excavator in its working environment.

Figure 4. Using the arm for descending a steep slope.

3.3 Terrain excavation and earthmoving operations

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 complex models to predict the material flow, see e.g. Coetzee [16]; this kind of models are too complex to run in real-time, and therefore a simplified bucket filling model has been developed.

The proposed method uses the above-mentioned collision detection method to spot intersections between the bucket (represented by a simplified polyhedron) and special areas of the terrain mesh marked as "removable". During the excavation process, the bucket penetrates the removable terrain mesh without originating 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. Despite the algorithm does not guarantee that the loaded earth volume is identical to the removed volume, it provides a reasonable estimation of the loaded weight and a realistic visualization of the process. In the future, a model for the reaction force in the bucket due to material flow during excavation will be included.

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.

4 HUMAN-MACHINE INTERFACES

The operator console has a semi-immersive virtual reality interface that emulates the excavator cabin, see Figure 5. 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.

4.1 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.

4.2 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 5) and a configurable external view (like in Figures 3 and 4). The instructor console also shows real-time information about events happened during the simulation (collisions, loss of stability, etc.).

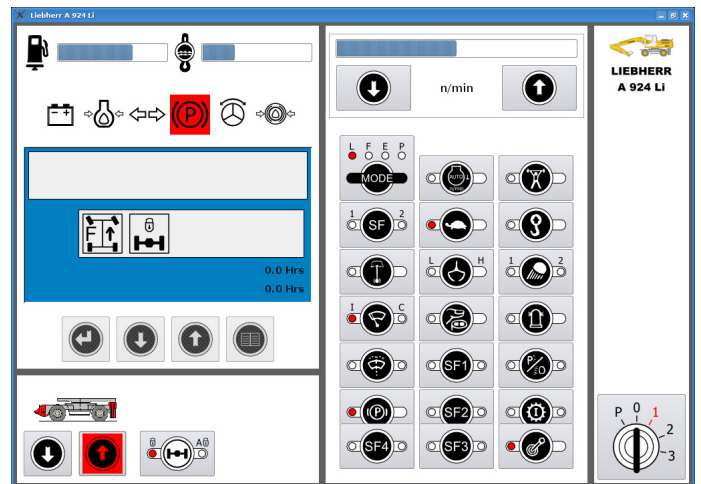**Figure 5.** Operator console of the simulator.

Figure 6. Digital control panel in the tactile screen.

5 CONCLUSIONS AND FUTURE WORK

Real-time simulation techniques from multibody system dynamics allowed the development of a realistic but computationally efficient 3D physics-based 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.

The project has finished the software development stage, and now is starting the human evaluation stage: the simulator will be tested by experienced operators, and their findings will be used to adjust the mathematical model of the excavator (contact forces and other data not supplied by the manufacturer) to increase the realism of the simulator.

In addition, further work must be carried out to:

a) Include the dynamic equations of the hydraulic circuit in the multibody dynamic formulation used for the real-time integration of the equations of motion of the mechanism.
b) Use rheological models to estimate the reaction forces in the bucket due to material flow during excavation.
c) Simulate the collision with underground deformable facilities in removable terrain areas during excavation.
d) Mount the operator console on a motion platform to transmit the cabin motion to the operator.

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