# Real-time Computer Simulator of Hydraulic Excavator

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**Abstract**

In this paper we present the simulator of crawler excavator which enables interactive simulation with real-time reactions to operator's steering decisions. We introduce a new simple kinematic model of cutting off soil from ground, which gives good results in real-time even on modest off-the-shelf computers. The computational model takes into account working hydraulic elements, making the behavior of the excavator quite realistic. Additionally we present a steering device, very simple but roughly similar to real ones. All the components make plain, but complete simulator.

## 1    Introduction.

Simulators of different kinds are widely applied in machinery and transportation industry to reduce design, prototyping and production costs. We concentrate on the simulator designed to reduce costs and improve operator's training.

In the paper we present a simple, yet complete implementation of a simulator of a hydraulic excavator. The system consists of two parts. The first one is the software which enables real time simulation and visualization. It contains the model of the machine itself, model of the terrain – including elevation shape and ground, model of excavation process, as well as the model of interactions between ground and excavator's track. The second one is the prototype of a steering device, roughly similar to those in real vehicles. A model of the soil, suitable for cutting off, excavation and unloading is a new idea in this scope. The model is simple, yet it gives realistic results which can be calculated and visualized in real time.

The paper is organized as follows. An overview of the research is presented in section 2. Sections 3 and 4 describe general structure of the simulator and the details of the computational model. The steering device is briefly shown in section 5. Results and conclusions close the text.

## 2    Previous work.

Most of excavator simulators developed so far [8, 4, 12, 7] are based on physically correct models in order to achieve sufficient level of realism. Park in his work [8] concentrated mainly on the mathematical model of excavator as well as the soil-bucket interaction, taking under consideration separation, penetration and secondary separation. He also

proposed the architecture of the software system and calculation methodology. DiMaio et al. [4] introduced simulator using joystick with a feedback of the resultant force. In both, mentioned above, models the track-terrain interaction has been omitted. Wakefield et al. in their work [12] proposed a complete simulator, which takes into account mathematical model, track-ground and bucket-soil interactions, enabling simple digging. To achieve higher degree of realism the Authors placed steering devices similarly as in a real cabin with sound effects added. Both Wakefield and DiMaio presented the results graphically, in real time. Visual output, using VRML has been applied in Lipman's et al. graphical simulator [7], however with no physical models.

## 3  Simulator architecture.

Simulator presented here is a computer program, which acquires input control data from the operator's console, performs real-time calculations based on physical models and finally displays the results in the form of 3D visualization of the scene.

Main functional blocks of the simulation system are presented in Fig. 1. They include input interface, simulation engine with physical and graphical models, as well as output interface for visualization.
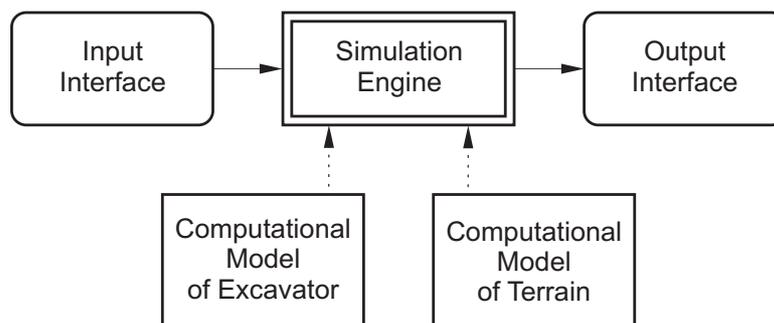


Figure 1: Main blocks in the simulator software.

Input interface is designed as a steering device with two joysticks and foot pedals roughly similar to those in real excavator.

Most important part of the program is the simulation engine used for updating all the states of the simulated objects. Calculations, based on the computational model of the excavator and the terrain, are performed in the main loop repeatedly. Loop's main steps are: calculation of the forces applied to the excavator (based on input signals from the steering device), detection and handling of the collisions, calculation of static contact as well as updates of velocities, coordinates and orientation of the excavator. Calculations of excavation process are performed during detection and handling of the collisions

The last module is responsible for the results visualization. OpenGL library has been applied for this purpose. Graphical models have been prepared using detailed meshes and textures, enabling realistic image of both excavator and the terrain. The model displayed on the screen has been designed on the basis of real product, the LC240 excavator from Terex [10].

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# 4    Computational model.

The realistic model of the excavator takes under consideration its main elements and mechanisms. It also enables correct description of physical processes. The base and the area formed after excavation are described using ordinary terrain model.

## 4.1    The excavator.

From the mechanical point of view, excavator can be considered as an assembly of mechanisms forming a kinematic chain. We can distinguish several parts for different functions: driving mechanisms for operating equipment, mechanism of body rotation, driving gear, etc. Scheme of the general kinematic structure of an excavator is presented in Fig. 2.
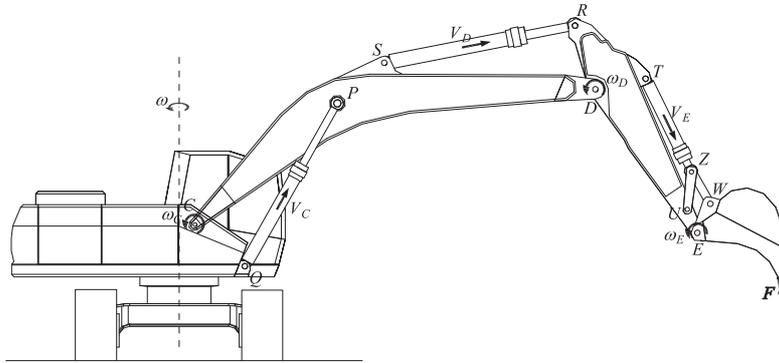


Figure 2: Outline of Kinematic structure of an excavator.

**Driving mechanisms of equipment.**

In the excavator equipment we can point out three main driving mechanisms: boom, arm and bucket. They are 2D mechanisms with one degree of freedom, which means that each of them deserves single drive module. For this purpose hydraulic servo-motors, that convert translatory motion of the piston into rotation, are applied. Values of the flow intensity and the pressure in pipes supplying hydraulic servo-motors, set by the steering elements, influence the linear velocity of the pistons in cylinders.
On the basis of driving mechanisms configurations, one can determine kinematic characteristics, enabling calculation of rotational velocities and mutual positions of the boom, arm an the bucket, depending on their velocities. Details can be found in e.g. [11, 6, 5]. Our model omits dynamic properties of these machanisms.

**Body rotation.**

In most single-bucket excavators, rotation mechanism of the body enables full turning in both directions. It is usually build of hydraulic system consisting of engine, reduction gear and planetary gear.
Our model assumes a mechanism with a pump of varying delivery, controlled with a hydraulic engine of constant absorbing power. This approach is usually applied in medium-size excavators.

Details of the mechanism, together with equations of different rotation phases, can be found in [5].

**Tracking mechanism.**

In order to achieve correct simulation of excavator motion in the terrain, beside gravity and aerodynamic resistance, reactions and active forces of tracks should be taken under consideration. A tracking system forms a closed kinematic chain, where internal forces also exist. Additionally, during motion, driving force is counteracted by resistance force and, in case of moving along slope, also by a gravity component. Total force acting on single track is equal to:

$$P = \frac{M_N}{r_N} - \frac{M_R}{r_R} - \frac{1}{2}\left[mg\sin\psi + R_0\right],\tag{1}$$

where $P$ – active driving force from drive mechanism, $M_N$ – torque from drive mechanism reduced to the axis of the driving wheel, $M_R$ – torque representing internal motion resistance, reduced to the driving wheel axis, $r_N$, $r_R$ – radii of driving and idler wheels, $\psi$ – angle of the slope on which the vehicle moves, $R_0$ – force representing external resistance forces. Due to low velocities of excavators, $R_0$ is calculated as a product of force pressure on the ground multiplied by resistance coefficient of motion.
Expression (1) shows the resultant form of the equation of motion of the track system motion. Velocity of the excavator and its current position can be calculated from this equation.

## 4.2   Terrain

One of the most important and most difficult problems in creating the excavator simulator is modeling the soil excavation process. It is pretty complicated, partly because the bucket cutting edge can move along an arbitrary path and excavations often are carried out in non homogeneous material. Thus the forces acting on the bucket are difficult to evaluate. They depend mainly on the type of soil, weight of the excavated material as well as the velocity and position of the bucket against the soil. The shape of the bucket itself is also important. The type of the soil depends on many components: its humidity, internal structure, porosity, as well as hardness. Usually these values vary in the course the whole excavation process.

**Existing models.**

Problem of the determination of cutting resistance in earthmoving processes has been investigated from the 30' of XX century. However scientific approach mainly has been developed in 50' and later, along with significant progress in machinery construction. Simultanously many models of earthmoving process appeared at that time. They were mainly empirical models (e.g. A. N. Zelenin, V. I. Balovnev, I. P. Kerov – in 80' and A. Hemami, S. Goulet, M. Aubertin – in 90') based on experiments, as well as analytical (e.g. J. V. Perumpral, R. D. Grisso, C. S. Desai; E. McKyes – in 80'), where total resistance was represented by friction forces needed to overcome the cohesion and the weight of the soil. Other models are based on finite elements models as well as damped mass-spring systems. Survey on the different models can be found in [2, 3, 9].

**Kinematic-geometrical model.**

The model of digging developed in the paper can be described as kinematic-geometrical. It is simplified, mainly because it does not apply forces in cutting off process. Despite its simplicity it enables realistic simulation of the excavation.

During the excavation process the wedge shaped edge of the bucket separates the excavated material form undisturbed soil. Its tip moves along cutting edge path, in the direction of velocity $V_F$. Outer surface of the blade and the tangent of blade path form angle $\varphi$ (Fig. 3). In order to keep cutting process correct, condition

$$\varphi \geq 0 \tag{2}$$

should be fulfilled, otherwise if $\varphi < 0$ the bucket would be indented into ground soil. This effect seriously decreases the efficiency of the entire process and can even stop it in
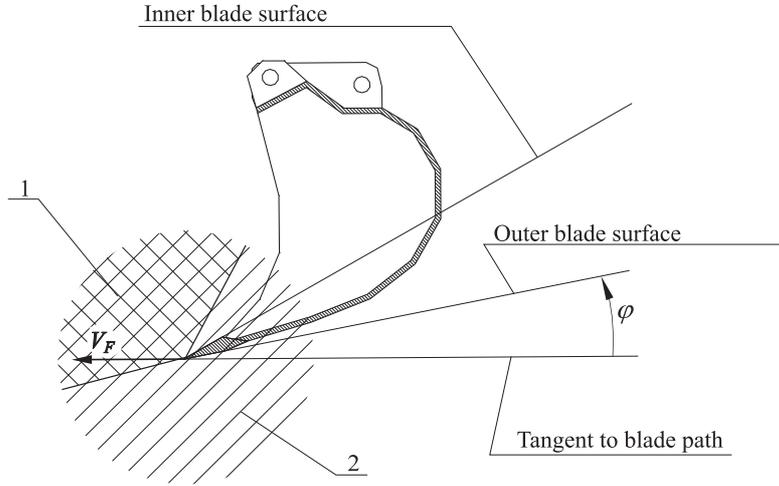


Figure 3: Interaction of bucket blade and undisturbed ground soil.

certain cases. Velocity of cutting edge, $V_F$, depends on angular velocities of currently driven elements. In excavators there are usually several driving mechanisms applied simultaneously, due to multiple hydraulic circuits, so total velocity of the cutting edge can be calculated from the equation:

$$V_F = \omega_C l_{CF} + \omega_D l_{DF} + \omega_E l_{EF}, \tag{3}$$

where $\omega_C$, $\omega_D$, $\omega_E$ – angular velocities for, respectively, boom, arm and bucket, $l_{CF}$, $l_{DF}$, $l_{EF}$ – velocity radius-vectors.

Calculated velocity is called *effective* if its direction is in accordance with natural direction of the bucket. In Fig. 3 numbers 1 and 2 denote respectively the regions of velocities being in accordance and in reverse with bucket direction.

**The algorithm.**

In our model the terrain surface is represented by a grid of triangles. Coordinates of every vertex are determined by a height-field map. It enables to perform simulation in virtual terrain which has been based on a real one. 3D terrain space is represented by a set of indivisible elements – small cubes. Their state is determined during the

model initialization in the following way: if the cube is under the grid denoting terrain's surface, is marked as 'ground'; otherwise it remains empty.

Basic assumptions of the model are the conditions which have to be fulfilled to enable cutting.

1. Cutting edge should be beneath the terrain surface. Checking up this condition is performed during detection of collision between surface and the bucket. If any point of the cutting edge is beneath the surface – the condition is fulfilled.

2. Terrain element marked as 'ground' is placed in the neighborhood of the cutting edge. The condition is checked for elements which are not marked as empty. It is fulfilled if the distance of the element center from the blade edge is smaller than element's edge length (cube size).

3. Direction of the velocity vector of the blade edge is consistent with its natural direction. It's worth mentioning that this condition is not fulfilled if rotational velocity of the body is not equal to zero.

The above conditions are checked up many times during the run of the simulation algorithm. Its main steps are as follows. After surface-bucket collision detection is performed, condition (1) is checked and if it is not fulfilled, the algorithm terminates. Otherwise, for all terrain elements marked as 'ground' in the neighborhood of the bucket, conditions (2) and (3) are checked. In case of positive result in both cases, and if the terrain element is inside the bucket, and if the bucket is not fully loaded – the element under consideration is marked as 'empty' and added to the bucket. The algorithm terminates after all elements have been checked.

In order to improve realism of the model, a simple model of ground soil resistance is introduced – in the course of cutting process all velocities of driving elements are proportionally reduced.

**Model of ground slippage.**

As it was mentioned, the terrain is described by a grid of indivisible small cubes. The simulation of slippage is performed using a few simple rules which change the state of single elements.

During the cutting process the bucket is filled with terrain elements (cubes) and subsequently, due to motion of excavator equipment, the elements are transported and eventually unloaded. At the initial phase of unloading, the elements fall freely in gravity field, according to the equations of motion. When the falling element hits another one marked as 'ground', the algorithm starts a loop in which element's state is modified in the following way. If the state of any of the four neighbors placed under the currently slipping element (the one that has just fallen) is empty – it becomes marked as 'ground' and the current one is emptied. By neighbors of certain element we understand the elements which share common face with it and are on the same height level. If the algorithm cannot find empty place beneath, the current element is blocked and will not be considered in future.

Very similar model can be used to investigate the behavior of the soil elements in the bucket. The difference is in two more states added. The first one denotes that the element touches the bucket wall, while the second means free space over the element

- so it can be dumped from the bucket. The next modification in the algorithm is that equations of motion are not applied, only the states of neighbor elements can be exchanged (i.e. current element is moved into empty place). Elements close to the bucket wall don't move, while elements with free space above them, are removed and added to the ground.

# 5  Steering device.

Integral part of the simulator is the steering device, which allows to operate the excavator in a manner similar to that in real vehicle. The device has been designed as an USB computer input, built of off-the-shelf elements and materials only, thus reducing the costs to very low level. The main purpose is, of course, steering the excavator, but it can be also applied to steer other simulated models, such as cranes, tanks or even airplanes.

## 5.1  Arrangement of steering elements.

Requirements for basic steering elements in crawler excavators and their arrangement in the cabin has been defined according to Polish standard PN-ISO 10968:2000 [1]. General outline is presented in Fig. 4.
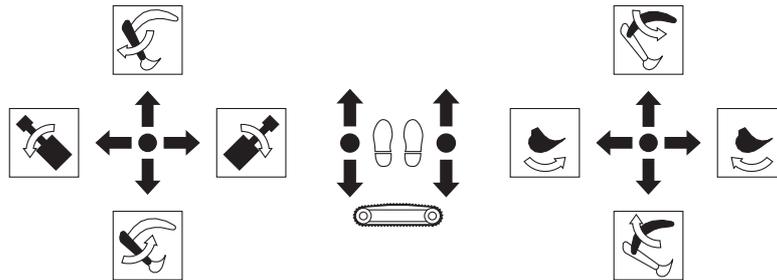


Figure 4: Arrangement of steering elements according to standard PN-ISO 10968:2000.

According to the standards, one of the suggested ways of steering is usage of multi-functional devices (joysticks). Control of velocity and direction is usually achieved by means of two foot pedals. Our control device fulfills the standard.
In real excavators, there are many more buttons, triggers and levers. Such elements obviously depend on specific model, and are less general. Nevertheless we added four buttons and two general purpose triggers.

## 5.2  Implementation details.

From the construction point of view we can divide the project into two parts: electronic and mechanical. Simplified scheme of the system is presented in Fig. 5.
Electronic part consists of microprocessor (PIC18F4550 from Microchip) which is responsible for acquiring input signal from steering devices, analog to digital conversion and communication with computer. Mechanical part contains two mechanisms, each of which is used to convert rotation of foot pedal into translation of the potentiometer slider.
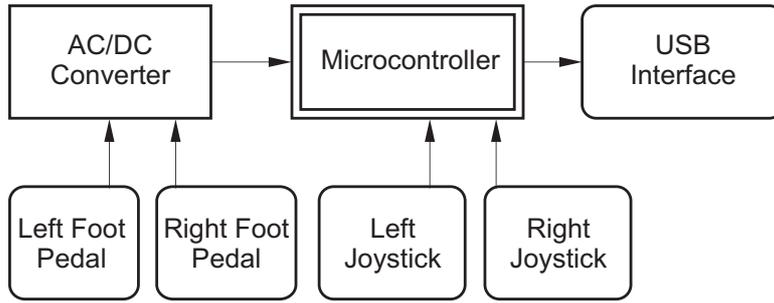Communication with computer is obtained by means of USB connection.

Figure 5: Simplified scheme of the steering device.

# 6 Results.

Images in Fig. 6 present sample snapshots from the simulator. They show general view and two phases of the work cycle: excavation (cutting) and unloading.



Figure 6: Sample images from the simulator screen. From top: general view, excavation, unloading.

Implementation and testing of the simulator was done using rather modest computer with AMD Athlon 2100+, 1GB RAM, NVIDIA GeForce 6600LE, running under Fedora Linux.

Generally it appeared sufficient, especially when the application was running in two separate threads (one for visualization and one for physical simulation). In this case for both screen resolutions: $1280 \times 1024$ and $1024 \times 768$ we can obtain smooth animation (from 30 frames per second (fps) up to 60 fps) using integration step slightly greater then 0.003 sec. This time-step appears to be sufficient to get stable solution in real-time.

# 7 Conclusions and future work.

In the paper we presented a simple yet realistic simulator of hydraulic crawler excavator, running in real time on cheap off-the shelf hardware.

The steering device is flexible and can be used with different vehicles. In case of excavator its behavior is similar to that from real machine and can be used for training purposes. However there are several limitations and simplifications in both model and steering device. The model does not take into account forces applied during excavation process. Also due to the collision algorithm assumed, there is no possibility for the excavator to ride into excavated hole. These two drawbacks should be eliminated first. Additionally, in real excavators, the velocities of specified equipment depend on the number of currently running driving gears, what was not assumed in the model.

What more, currently used joysticks do not allow to measure the angle of deflection, so accessories of the excavator can move with constant velocity only.

The simulator is fairly simple, but we think that after not so many modifications it could be applied as a tool for training. As far as we know it is not currently present in Polish training centers.

## Acknowledgments

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