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Simulation Study of a Control Procedure for Automated Loading of Bulk Media

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Abstract **Automation of loading of bulk media, or autoloading by an excavator, implies that an excavator for soft rock or particulate material loads its bucket successfully without the intervention of an operator. The subject has been under investigation for several years now. Nevertheless, the result of research has not yet reached to the level of implementation and commercialization because of two main reasons. The first and major reason is that the process of loading in itself is complicated and difficult to control. This is common to all the excavating machines and the results, when available, can be adapted by any specific machine. The problem to be resolved is "What has to be controlled and how". The second reason is the fact that autoloading is a sub-task of autonomous excavation where many other tasks are involved. Before all of these tasks can be automatically performed perfectly, a successful operation cannot be expected. The fact that not all of the excavating machines function in the same way has made the latter more complicated, since not all the previous pertinent work has been focused on automation of one particular type of excavator. This paper concerns the first category problem and is targeted for finding the solution to the automation of the loading process only. The previous work has led to the appropriate approach (proposal) for the control of the process: At a higher level control the trajectory of the loading/digging/cutting bucket is determined(and adjusted) based on the measurement of the interaction forces; at a lower level, the motion of the bucket is controlled based on the required motion (position and velocity). Before having access to a real system, we have decided to study the results by simulation. This work reports the latest results of implementing this control strategy by simulation.**

Keywords: **Autoloading, Automation of excavation, simulation Front-end loader, Simulation of soil digging**

I INTRODUCTION

In a rotary excavator such as a bucket wheel excavator (BWE) a motor drives the cutting elements, which perform the excavation (a combination of cutting, digging and scooping). The machine is designed for a required power and as long as the resisting power from the medium force is less than the machine power an operation can be continued. The path of the cutting element(s) is a circle. On the contrary, in cyclic excavation machines, such as a loader, backhoe, power shovel, LHD (Load-Haul-Dump) and so on, the path of the blade or bucket (cutting element) is not predetermined and it varies from cycle to cycle. An operator in an interactive way drives the element through a path within the medium, which is often not a smooth curve. In other words, the operator uses his intelligence and senses to correct or adjust the cutting path. He performs as the feedback in a control system inside the operating loop. Automation of cyclic excavating machines implies equipping the machine with the necessary intelligence that can, to an acceptable extent, perform the same control/path correction to the cutting/loading element (Hereafter, we refer to the task as loading, for the sake of simplicity). So far, numerous works have been reported on the subject by various researchers from academia and industry. Yet, neither a significant breakthrough has been reported, nor a machine with such a capability has been introduced to the market. In this sense, the subject is still in its infancy. There are two main reasons. The first is that the process of loading in itself is complicated and difficult to control. The second reason is that autloading (Automated loading), by itself, is not sufficient but is a necessary part of the bigger scenario of autonomous loading. The latter implies a variety of tasks, depending on the type of the excavator. For example, for a front loader (and an LHD in underground mines) a complete operation implies moving from the starting point (any point in the loop) to the loading point without getting stopped/interrupted by obstacles on the way, recognizing the site for loading from, loading the material, moving to the dumping/delivery point, and repeating the whole cycle. As can be seen, within each cycle, in addition to loading the whole set of tasks for deciding the loading point, deciding the unloading point, obstacle detection and avoidance when hauling between the loading and unloading sites, as well as making a decision for the path to follow must be performed with acceptable results. All of these are dynamic and normally change from one cycle to another. (The heap shape and size change, for instance).

The necessary research work, in this sense, covers all the pertinent work to any of the above-mentioned tasks. The subject of this paper is confined to autoloading, only. This necessarily implies the automation of an excavating machine. More precisely, it concerns the development of the necessary intelligence for an excavator to recognize how to control and readjust the motion of its bucket, so that it gets filled. The problem to be addressed is "What has to be controlled and how".

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II. PROCESS ANALYSIS AND PROBLEM STATEMENT

From a control viewpoint, an output variable must be controlled by the measurement of another quantity for monitoring and a feedback to the actuating members (motors/hydraulic cylinders). The process consists of the motion of the bucket relative to the environment. The variables that can be measured from inside a machine are the actuator displacements and the actuator forces (if hydraulic cylinders are used, which is the case in most excavators). Additional sensing devices, such as cameras and microphones, can be added on-board or to the environment. The material loaded in the bucket can be seen by an operator (This is why some have suggested using a camera for the process monitoring). What is required for a successful operation is a proper motion of the bucket while it interacts with the environment. In this interaction, the active forces on the bucket must overcome the resistive forces from the environment. If the resistive force from environment is always inferior to the active forces driving the bucket the problem reduces to motion control of the bucket. Example of this is loading a light dry granular substance without cohesion and adhesion by a strong enough tool. Such a case rarely happens in reality, where soil, fragmented rocks and similar media are to be loaded. The resistance exhibited when trying to cut through and penetrate into such media is stochastic, with a great range of fluctuation. The resistive force, therefore, can be very low or very high, even more than the capacity of the driving forces. As a result, the control problem is very complicated and much more than only the motion control. Figure 1 shows a block diagram for the process model, where $G_1(s)$ represents the bucket and $G_2(s)$ represents the vehicle carrying the bucket.

The previous work concerns various approaches to tackle the problem, which includes:

(a) Modeling the excavator as a robot manipulator and formulating the necessary force and motion relationships.
(b) Analysis and formulation of the force of interaction between a medium and a cutting tool.
(c) Analysis of the force requirement during scooping by a bucket.
(d) The trajectory of the bucket motion for loading by each category of excavator.
(e) Analysis of the shape change for the heap of medium when loading takes place.
(f) Simulation of the geometrical shape of the material as a camera can see.
(g) Experiments with small excavator models or real size machines.

Modeling an excavator as a robot arm allows the use of the advanced methods in robotic control for motion control of an excavator. The list of references exemplifies the previous research. Most of the work corresponds to automation of the function of a front loader or a backhoe. The previous work has led to the three different approaches for the control of the process:

(1) This approach is proposed for a backhoe. The assumption is that the machine must always work at its maximum power. In this respect, the velocity of the bucket is to be monitored. A correction to the motion (path) is to be based on the velocity measurement. Experiments have been carried out for digging a ditch, in which the bucket tip path is almost a straight line [11].

(2) This approach is based on a sort of fuzzy logic principle, containing a tree of action according to a number of – if …, then …- commands. The approach is proposed for a front-loader [12],[13].

(3) This approach is based on two level control of the bucket motion. At a higher level control (with a smaller sampling rate) the trajectory of the bucket is determined (and adjusted) based on the measurement of the interaction forces. At a lower level (with a higher sampling rate), the local motion of the bucket is controlled based on the required motion (position and velocity). This approach requires some knowledge of the interaction forces (based on the material properties, terrain slope, bucket size and so on) to be used for feedback purposes [1],[3].

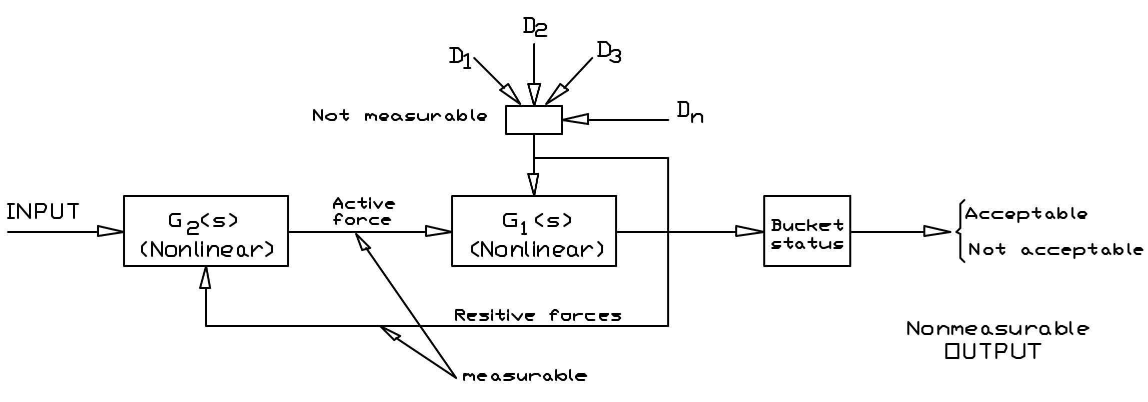


Fig. 1

III. DETAILS OF THE PROPOSED STRATEGY

The work in this paper only concerns the third approach. This proposed method suggests that depending on the machine, its bucket and the material to be excavated, a desired path is decided for the motion of the bucket. From the data corresponding to the properties of the medium, the bucket size and the terrain slope, a maximum value and a minimum value for the total force components during the motion are determined. *During loading, if the measured force at each instant lies between the corresponding maximum and minimum values, then the motion is continued, otherwise the bucket motion path is redefined from the current position of the bucket and based on the current situation. This is the higher level control.*_ This happens at any time during loading if an undesirable condition occurs, such as zero motion (bucket stuck) or fast motion (bucket relatively empty). *The lower level control loop is based on the joint velocity and position feedback for moving the bucket along its desired (determined at the higher level control) path.*

Based on this strategy, in the case the bucket stops moving for instance, the current force input to the bucket is increased in steps to resume the motion. If the exerted force reaches the maximum limit with no result, then the bucket path is redefined. This redefinition of the path depends on the current bucket position with respect to the start and finish points. It is important to note that the points of the path addressed here are ONLY represented by the actuator positions and NOT by the points in a coordinate system attached to the environment. In this respect, keeping a record of the motion (in the controller computer) is necessary (in order to go back a few steps, for instance)

In a similar way, for the case when the bucket moves faster than it should, the force input is decrease in steps until either the motion is regulated or the force reaches the minimum level. This strategy can be programmed and put into a controller computer. All the parameters corresponding to the bucket and the approximate values that crudely define the type of medium can be keyed in for each excavation operation. The effect of the slope can also be taken into account as one of the inputs.

IV EXCAVATOR MODEL

In order to see the practicality and the effect of the proposed control strategy, not having access to a real system, we have decided to study the results by simulation. The simulation is for a loader type excavator and based on the modeling of such a unit as a robot manipulator. All the corresponding work and analysis have been previously done and here we have used the previous results [4], which are not repeated here except for those more which are more fundamental. Figure 2 shows the simple model of a loader assuming that during loading the vehicle has only a planar motion and, thus, there are only three degrees of freedom. The vehicle advance motion is modeled as a prismatic joint. The other two joints are revolute. The joint variables, d_1, ϑ_2 and ϑ_3 are shown in the figure.

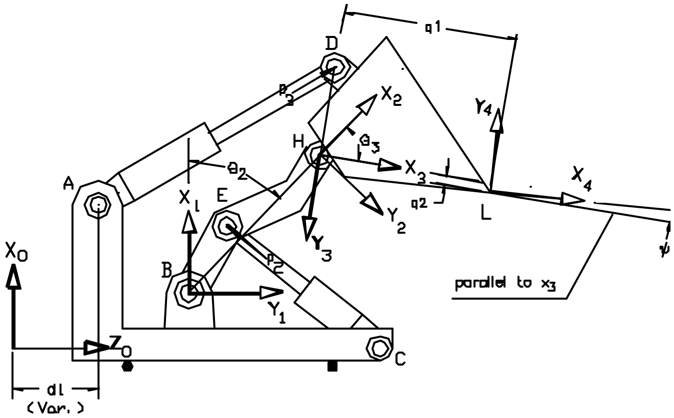


Fig. 2. Definition of coordinates and joint variables

Figure 3 shows the definitions for the dimensions. The bucket tip is the tool point and angle β is the orientation of the bucket. In a loading operation the forward and upward position of L together with the angle β define the loading trajectory with respect to the coordinate system $x_0y_0z_0$, which is attached to the environment (world coordinates). The corresponding values in the joint coordinates are d_1, ϑ_2 and ϑ_3.

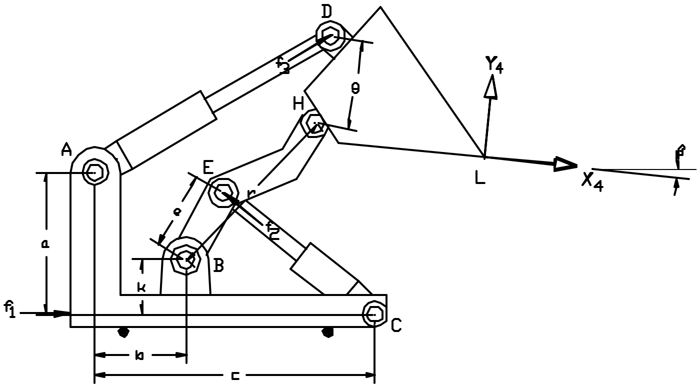


Fig. 3. Definition of various dimensions

In order to transfer from the environment coordinates ($x_0y_0z_0$) to the actuator coordinates, first the joint coordinates must be found. The relationships between the joint coordinates and the $x_0y_0z_0$ are as follows:

$$L_{ver} = q_1 \cos J_{23} - q_2 \sin J_{23} + r \cos J_2 + k$$

$$L_{hor} = q_1 \sin J_{23} + q_2 \cos J_{23} + r \sin J_2 + b + d_1$$

$$b = \frac{p}{2} - (J_2 + J_3 + y) \qquad (1)$$

where ϑ_{23} denotes $\vartheta_2+\vartheta_3$. In addition to the above (position) relationships, the following Jacobian matrix defines the force relationships between the joint force/torques and the three force components in the $x_0y_0z_0$ (medium resistance at the bucket tip or the active cutting forces at the tip) in the form of

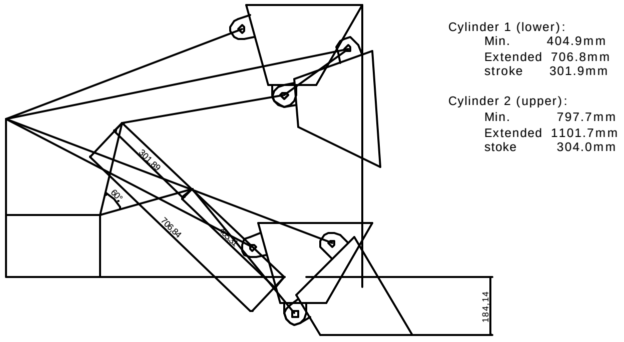
$$t = \begin{bmatrix} vehicle\ push \\ torque\ 2 \\ torque\ 3 \end{bmatrix} = J^T \begin{bmatrix} vertical\ force \\ horizontal\ force \\ torque \end{bmatrix} \qquad (2)$$

where

$$J = \begin{bmatrix} 0 & -(q_1 \cos J_{23} + q_2 \sin J_{23} + r \cos J_2) & -(q_1 \sin J_{23} + q_2 \cos J_{23}) \\ 0 & -1 & -1 \\ 1 & q_1 \cos J_{23} - q_2 \sin J_{23} + r \cos J_2 & q_1 \cos J_{23} - q_2 \sin J_{23} \end{bmatrix} \qquad (3)$$

Moreover, from the joint coordinates another transformation to actuator coordinates is relating the corresponding values (displacement and forces) in the actuators. These are not shown here because of space.

A small loader with the dimensions as shown in table 1 has been conceptually designed. The bucket is 0.4m wide and has a capacity of about 26 litres. The empty bucket has a mass of 4 kg and the density of the mediumto be loaded is taken to be 2.5 ton/m^3. Figure 4 illustrates the maximum and minimum reach of the bucket from loading position to dumping position.



Fig, 4. Conceptual design of the loading gear, upper and lower extreme positions

The loading trajectory in the medium (world) coordinates for the motion of the bucket from a starting point to a full position is defined by the values given in table 2. The intermediate points are obtained by linearly dividing each interval. The nominal resistance of the soil at these given points (on the trajectory) are calculated. These are based on the five force components as modelled in [4], summarized. The nominal force is the possible average force. The real force lies between a minimum and a maximum envelope [4]. Table 3 illustrates the results of the total force at each point in the form of its horizontal, vertical components and the torque.

TABLE 2

Geometric dimensions of the loader (see figure 3)

a (m)	b (m)	c (m)	e (m)	g (m)	k (m)	ε (°)
0.5	0.3	0.88	0.3	0.25	0.2	20

TABLE 2

Definition of nominal loading trajectory

Hor. (m)	Ver. (m)	Orient.(?)
0	0	0
0.6	0	0
0.88	0.07	6
1.2	0.14	12
1.18	0.21	18
1.28	0.28	24
1.38	0.35	30
1.46	0.42	36
1.53	0.49	42
1.59	0.56	48
1.64	0.63	54
1.67	0.7	60

TABLE 3

Force values at defined loading path points

Hor. (N)	Ver. (N)	Torque(N.M)
220	40	12
332.8	89.4	24.5
142.8	152.25	38
544.9	310.45	53
635.5	459.5	67
258.2	433.55	83.5
348	589.55	101
744.25	1010.25	122
446.2	951.05	142
313.95	968.85	159.5
136.4	884	177
57	842.26	187

V SOIL MODELING AND SIMULATION SENARIOS

We are considering the excavation of soil as the most common case. The excavation force on the bucket tip has a stochastic nature and varies randomly and continuously. The values in table 3 are only the estimated values of the forces of resistance of the substance at the finite points on the desired trajectory. It is assumed that between each two defined points the values of each force/torque component change linearly.

The actual force values are randomly fluctuating around these nominal values. Depending on the nature of the mixture of a specified soil, this fluctuation can be at a higher or lower percentage. One should consider a number of scenarios with different percentage of variation. Also, in reality, more often there might be boulders within the soil whose effects must be brought into consideration. As a result, as a priority we should first make a model of the soil force bringing into effect the existence of smaller or larger pieces of boulders and at lower or higher frequency of occurrence. Also, we should make a model of the changes that occurs in the soil resistance when the bucket does not follow the desired path, which is the usual case (The desired path is for the tip of the bucket in a two dimensional motion).

Figure 5 shows a two dimensional mesh of the points around part of the desired path for the bucket front edge. As the bucket moves the three values of the horizontal force, vertical force and torque change based on the actual values of these entities on the trajectory and the relative deviation (That is, horizontal and vertical distances from the desired points.

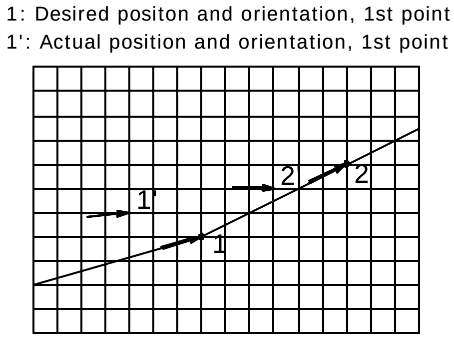


Fig. 5. Deviation from desired points (for force adjustment)

The more realistic values of the horizontal force, vertical force and the torque at the edge of the bucket based on the values in table 3 and with 10% fluctuation (5% up or down) are shown in figures 6 to 8, respectively. These are the forces that the bucket has to overcome in order to follow its desired loading trajectory.

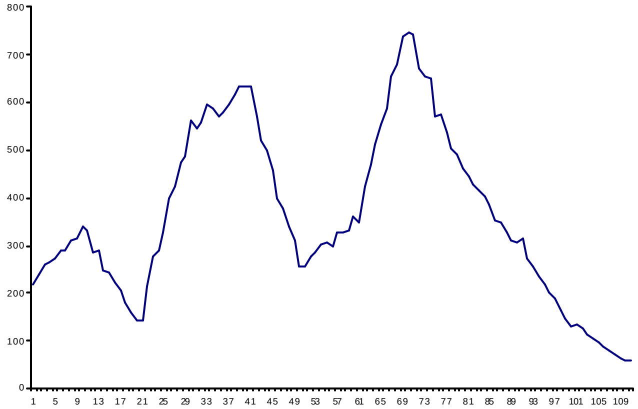


Fig. 6. Horizontal force component (N) along the loading path

At each instant of time, the bucket has to be controlled such that it overcomes the resisting force/torque combination. The control is carried out by adjusting the three actuators in the machine, the prismatic (vehicle advance) and the forces in the two cylinders.

VI RESULTS

The result of this work up to now has been primarily the development of the software for simulation of the soil and its behaviour and carrying out the lower level control (That is, following a smooth curve, without force fluctuation and without any boulders inside the uniform soil). This by itself has proved to be quite challenging for a reasonable and reliable tool that can be used for the complete control strategy.

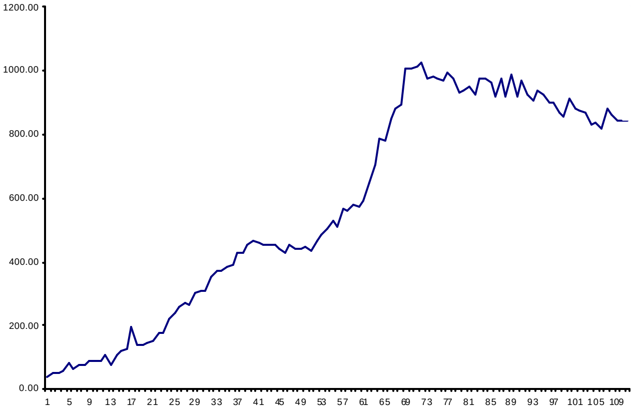


Fig.7. Vertical force component (N) along the loading path

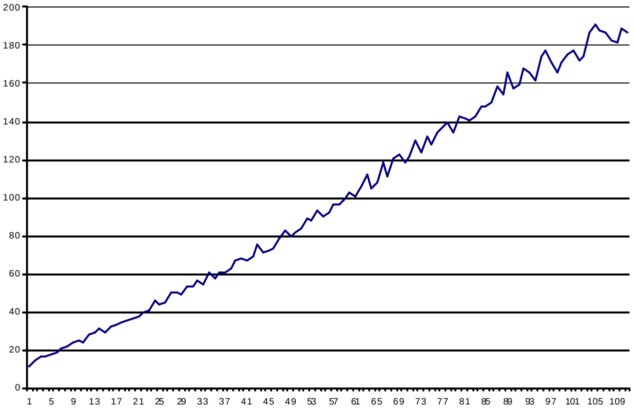


Fig.8. Torque component (Nm) along the loading path

VII SUMMARY

This work is a part of the simulation of a strategy for the control of the loading process in a loader type excavator. The strategy, if proved to be successful, is not confined to only this class of excavators. The strategy proposes the adjustment of the motion trajectory of the bucket (at higher level control) by force feedback That is, the redefinition of the partial trajectory based on measurement of the necessary forces and comparing with the most possible higher and lower levels of force at each instant. The lower level control is based on the position feedback at a higher frequency.

Implementation of the complete control strategy takes more time than expected and could not be performed by this date. The software developed is, nevertheless, capable of performing the lower level control. The formulation and simulation of the soil behaviour and interaction with the bucket by itself has been a success.

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