Kinematically Induced Excavation by Backhoe Excavator

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ABSTRACT

The paper deals with kinematically controlled excavation process performed by a commonly applied backhoe excavator. It is assumed that all three hydraulic actuators which are driving the arms of the machine may work simultaneously. This creates a unique relationship between - bucket's motion as a rigid body and the actuators action. After discussing kinematic relationship containing constraints arising from limited lenghts of actuators, the static constraints at each point of working space are presented.. They are defined by maximum possible forces in actuators and by the stability of the excavator. In the case of statics, relationship between two components of teeth force and three forces exerted by actuators are not unique. That fact causes a need for constructing a polygon of feasible forces at the dipper's teeth. The last part of the paper is devoted to the hydraulic flow circuit coupled with a processor. The main idea of the system consists in proper distribution of oil volume and assurance of apropriate pressure in all three actuators. Presented solution allows to dig the soil along assumed path.

1. INTRODUCTION

The paper deals with commonly applied backhoe excavators attachment which is composed of three coplanar arms driven by three hydraulic actuators. The idea aims at introducing the process of controlled excavation, reducing at all or to the minimum influence of the machine operator. In the classical man operated excavation only one or two arms are working simultaneously and therefore only one or two actuators are active. This is because of the complexity of the motion when three actuators are active at the same moment. But it doesn't need to be a case in automated or partly automated excavation works.

The automation of the digging process performed by an excavator is certainly one of the most complex tasks in earthmoving works. There are at least three reasons for this complexity. The first one comes from undefined parameter, and stochastic character of the soil. In theoretical considerations the soil is ussually considered as a deterministic medium. The second reason comes from the fact that relationship between two components of the bucket teeth forces and three forces in actuators are not unique. The third reason is caused by three degrees of freedom of the bucket. It means that working zone is composed not only from the set of the possible tip positions but also from the inclination angle of the bucket with respect to the assumed coordinates. The latter information is important for at least two reasons. The first one is that the angle of inclination determines the heaped capacity of the bucket. The second reason is due to the limitation of the penetration in those cases in which the bucket is in contact with the soil by its back instead of its tip.

Due to the mentioned complexity of the discussed problem not much has been done so far in automation of the excavation process. First steps to overcome the mentioned difficulties in its modeling nevertheless were achieved. This was by Huang and Bernold [4] and Vaha and Skibniewski [5]. On the other hand Budny and Bartys [1] gave a concept of a flexible microprocessor system for controll over various building machines. First attempt to construct the model for controlled excavation by the means of the programed hydraulic flow circuit has been done early this year [2]. In case when assumed forces are acting on the dipper teeth some optimization of the attachement arms may be achieved [3].

2. KINEMATIC CONSTRAINTS IN BUCKET MOTION INDUCED BY HYDRAULIC ACTUATORS

The working zone of an excavator is usually defined by a geometrical figure (Fig. 4) containing all points which may be reached by the dipper tip. However, this set of points constitutes only one part of information on the working possibilities of an excavator. It on doesn't mean that if the tip reaches a given point then at this point, excavation may be performed. The additional data should include the angle of the bucket inclination to the assumed coordinate, say horizontal.

Let's be more specific by presenting above remarques in shape of some mathematical relationship. Along with Fig. 1, 2, 3, 4 we denote l_1, $l._2$, $l._3$ to mark distances between hinges of all three arms of the excavator attachement. By α_1, α_2, α_3 we denote the angles between the lines joining mentioned hinges with horizontal x_1. Moreover, by h_1, h_2, h_3 we denote variable lenghts of the hydraulic actuators. Other dimensions are presented at the mentioned four figures. Our aim is to join α_3, the bucket angle, with respect to x_1 line with actuators lenghts.

Simple trigonometric consideration are leading to

$$h_1^2 = a_0^2 + a_1^2 + b_0^2 + b_1^2 + 2(a_0 a_1 + b_0 b_1)\sin\alpha_1 \tag{1}$$

From this relation, substituting h_1 for $h_{1\max}$ and h_{1min} we can find numerically α_{1max} and α_{1min}.

Next, passing to the actuator number two with lenght h_2 we find from Fig. 2

$$h_2^2 = a_2^2 + b_2^2 + c_1^2 - 2b_2\left[c_1\cos(\alpha_1 - \alpha_2) + a_2\sin(\alpha_1 - \alpha_2)\right] \tag{2}$$

Again, substituting $h_{2\ max}$ and $h_{1\ min}$ we find number representing the maximum and minimum values of relative rotation of the arm with respect to the boom.

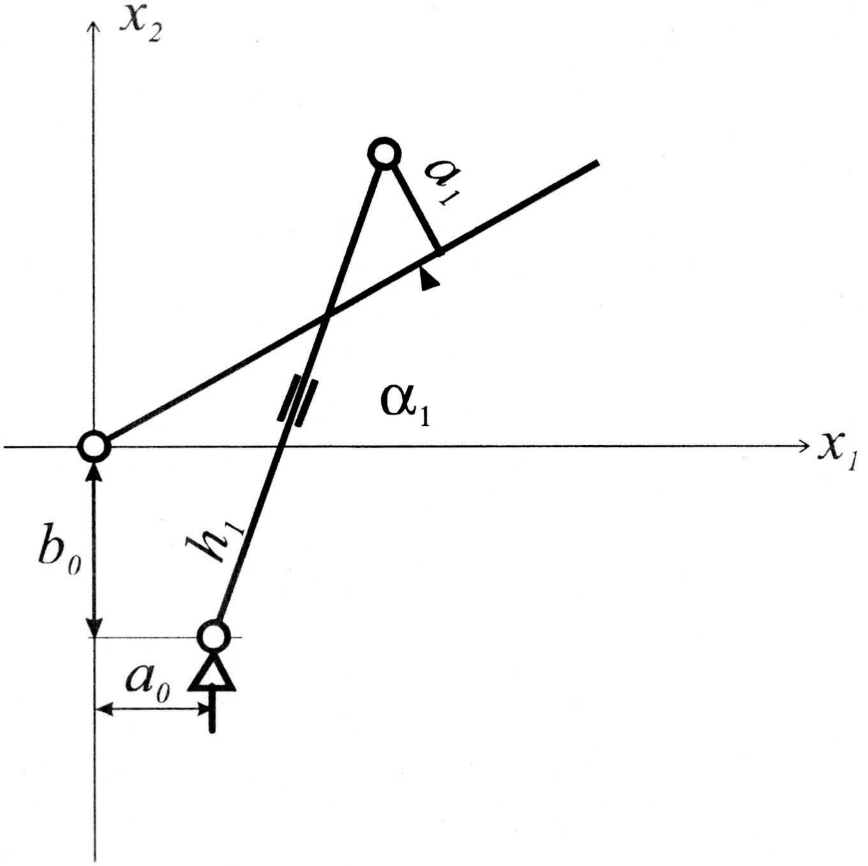

Fig. 1. Relation between h_1 and α_1

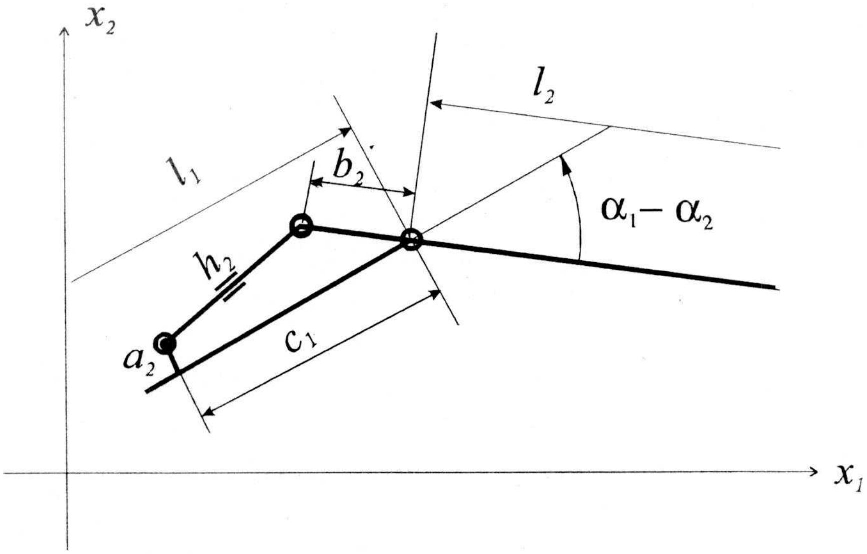

Fig.2. Relation between h_2 and $(\alpha_1 - \alpha_2)$

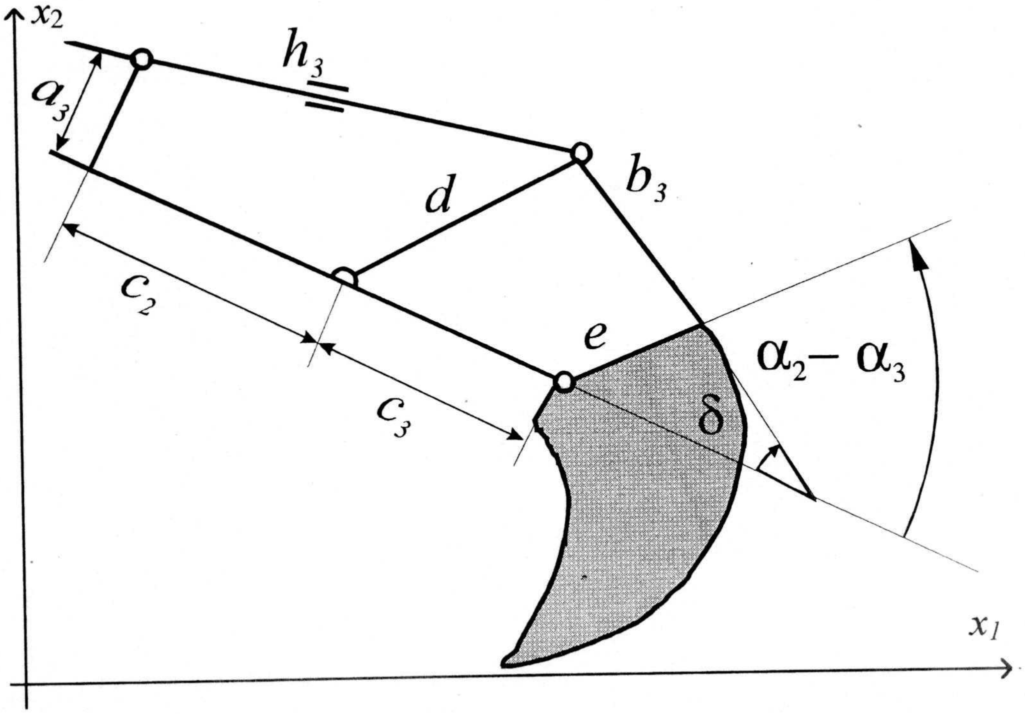

Fig.3. Relation between h_3 and $(\alpha_2 - \alpha_3)$

Finally, examining Fig. 3 we find relationship between the lenght h_3 of the third actuator and the relative rotation α_2 - α_3. However, in this case we need an auxiliary relationship allowing to find variable δ entering into these relations which are

$$\begin{aligned} h_3^2 &= a_3^2 + b_3^2 + c_2^2 + c_3^2 + e^2 + 2c_2c_3 + 2e\cos(d_2 - d_3)(c_2 + c_3 - b_3\cos\delta) + \\ &+ 2e\sin(\alpha_2 - \alpha_3)(b_3\sin\delta - a_3) - 2b_3(c_2 + c_3)\cos\delta + 2a_3 b\sin\delta \end{aligned} \tag{3}$$

$$d^2 = b_3^2 + c_3^2 + e^2 + 2b_3 e\cos(\alpha_3 - \delta) + 2c_3(e\cos\alpha_3 - b_3\cos\delta) \tag{4}$$

In order to get numerical values of $\alpha_{3\,max}$ and $\alpha_{3\,min}$ at each point reached by digging tip we divide numerically α_1 in a finite number of the values between $\alpha_{1\,min}$ and $\alpha_{1\,max}$. Then, for each of these values, we can find uniquely α_2 and α_3 (the tip position is fixed) checking if constraints imposed on relative rotation the α_1 - α_2 and α_2 - α_3 are not violated. On Fig. 4 α_{3max} *and* $\alpha_{3\,min}$ are given at two points of the feasible tip position. That problem may be also solved half analitycally as an optimum problem in which objective function is α_3 (max. or min.) under constraints defined by the limit values of α_1; α_1 - α_2; α_2 - α_3 in terms of extreme values of h_1; h_2; h_3 .

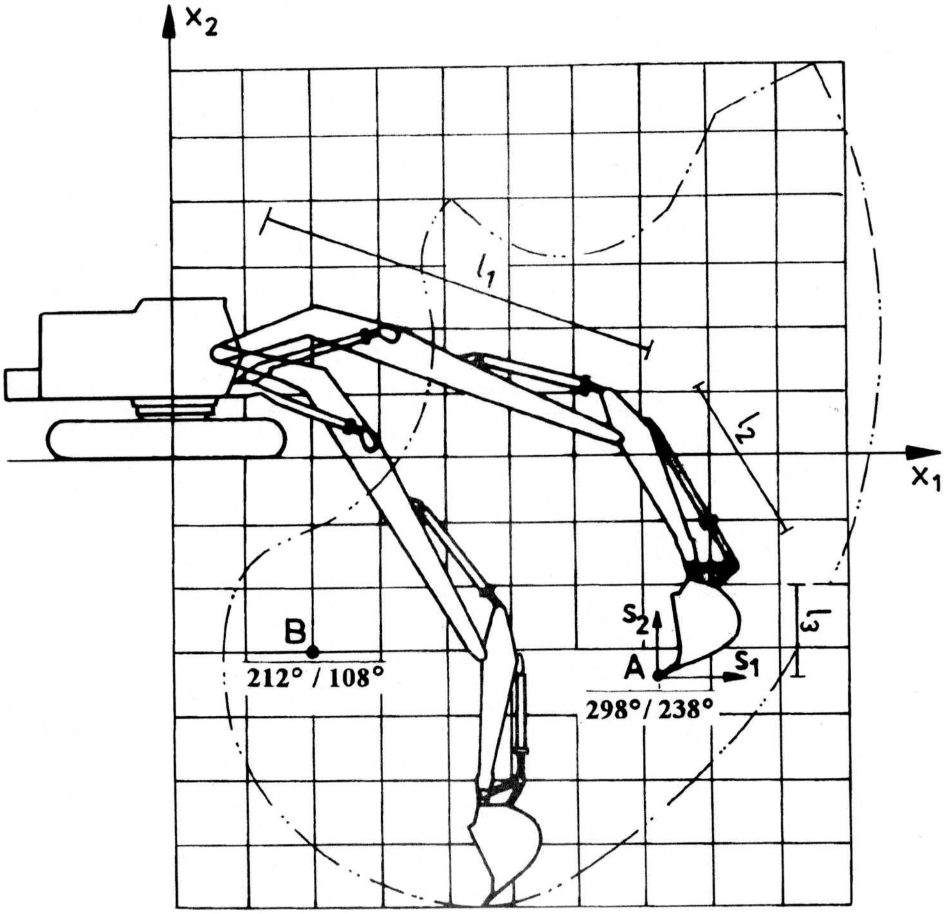

Fig.4.Working zone of the dipper

3. POLYGON OF FEASIBLE TEETH FORCES

The forces exerted by the actuators are limited by the maximum pressure in their cylinders. It is therefore clear that total digging force at the dipper teeth is also limited. Howeve, it must be pointed out that the relationship between actuator force and force at the dipper teeth is not unique. Let's examine this statement by taking sum of the moments acting on the dipper and its arm with respect to the joint linking dipper arm with boom. Denoting by: S_1 and S_2 components of the teeth force along directions x_1 and x_2 (Fig. 5); r_1 and r_2 distances of the arm - boom joint from the bucket tip along the same axes; R_{2max} the maximum force exerted by the arm actuator, a_2 the distance and R_2 the force from the mentioned joint, we can write the following equilibrium condition

$$S_1 r_1 + S_2 r_2 \leq R_{2\max} a_2 \tag{5}$$

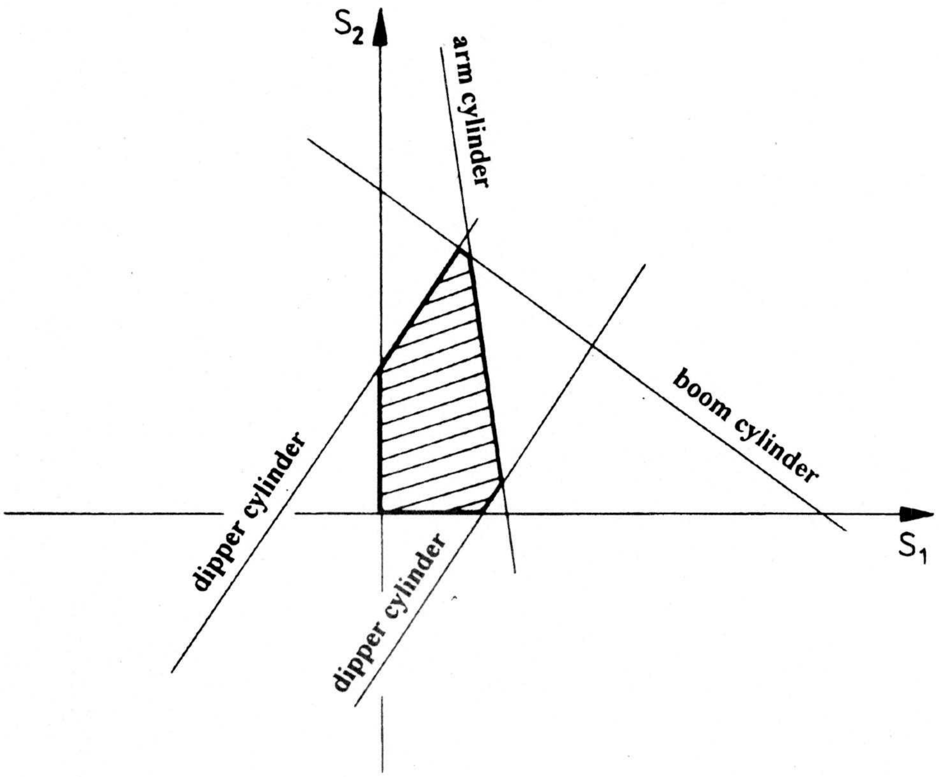

Fig.5. Polygon of the feasible teeth forces

Equality condition gives an equation of straight line in S_1, S_2 coordinate system (Fig.5). It means that there is an infinite number of the tip forces which can equilibrate fixed actuator force R_2.

Writing similar relations for moments with respect to two other joints connecting machine body with the boom and the arm with the bucket we get a set of straight lines in S_1 and S_2 coordinate system (Fig. 5). These lines are defining a field of feasible digging forces at a given point of the excavator working zone. The knowledge of the field in the form of a polygon, which may be seen as „flow polygon", is a part of data needed for controlled excavation by the means of kinematic induced operation.

There is still the fourth condition limiting digging force. It is related to the stability of the whole excavator as a rigid body. In this case the sum of the moments should be taken with respect to the supporting edge at which tipping of the machine can take place. In our example of „flow polygon" Fig. 5, the line limiting S_1 and S_2 in the case of stability is out of the range of the figure.

4. MECHATRONIC SYSTEM FOR CONTROLLED KINEMATIC INDUCEMENT

Proper digging consists in driving the clipper as a rigid body of three degrees of freedom along given trajectory. This may be done in a unique way by the means of three independent actuators. It must be repeated here that there is no unique relationship between teeth force components and actuator forces. This is therefore the main reason for which controlled excavation must be performed by kinematic inducement. The controlled process is a combined application of a machine hydraulic system with a microprocessor. The hydraulic system allows to split given fixed volume of oil between three pumps supplying particular actuators. On the other hand the microprocessors are programmed for a given excavation path along an algorithm presented below.

Let's denote by x_i $(i = 1,2)$ position of dipper tip. With previous assumptions as to notations the tip position is given by

$$\begin{aligned} x_1 &= l_1 \cos\alpha_1 + l_2 \cos\alpha_2 + l_3 \cos\alpha_3 \\ x_2 &= l_1 \sin\alpha_1 + l_2 \sin\alpha_2 + l_3 \sin\alpha_3 \end{aligned} \qquad (6)$$

Besides that lenghts of the actuating cylinders h_1, h_2, h_3 with respect to α_1, α_2, α_3 are given in (1) (2) (3).

Assuming a parameter t, the being the time we can find he relations between components of the dipper tip velocity dx_i/dt and the velocity of the pistons with respect to their cylinders dh_j/dt. The latter velocities multiplied by piston areas A_k give the volume of the oil per unit of parameter (time) to be pumped into cylinders. The relations mentioned above may be found by taking derivatives of x_1 and x_2 with respect to t as total derivatives expressed by α_j and h_k $(j,k = 1, 2, 3)$

$$\frac{dx_1}{dt} = \sum_{k=1}^{3} \frac{\partial x_1}{\partial \alpha_k} \frac{d\alpha_k}{dt}; \qquad \frac{dx_2}{dt} = \sum_{j=1}^{3} \frac{\partial x_2}{\partial \alpha_k} \frac{d\alpha_k}{dt} \qquad (7)$$

and by taking total derivatives of $d\alpha_k/dt$

$$\frac{d\alpha_k}{dt} = \sum_{j=1}^{3} \frac{\partial \alpha_k}{\partial h_j} \frac{dh_j}{dt} \qquad (8)$$

Based on above relations an algorithm to be programmed in the controling processor unit may be presented as follows:

STEP 1 Assume $x_1(t)$; $x_2(t)$; $\alpha_3(t)$; $\alpha_3(t)$ (α_3 must be given if proper position of the dipper with respect to the excavation path has to be assured)

STEP 2. Find dx_1/dt ; dx_2/dt; $d\alpha_3/dt$

STEP 3 From (7) find $\partial x_1/\partial\alpha_k$; $\partial x_2/\partial\alpha_k$

STEP 4 From (1); (2); (3) find $\dfrac{\partial \alpha_j}{\partial h_k}$ $for\ j,k = 1,2\ 3,$

STEP 5 Substitute $\partial\alpha_j/\partial h_k$ into (8) and find $d\alpha_k/dt$

STEP 6 From (8) find $dh_k/dt = v_k$ velocities of three pistons with respect to their cylinders.

STEP 7 Taking sum $\sum_{k=1}^{3} A_k\ v_k = V(t)$ we find total volume of the oil to be pumped per unit of time in all three actuators.

STEP 8 Scale obtained $V(t)$ with the capacity of the hydraulic system of the excavator.

In the case of purely numerical data of x_1 x_2 α_3 the above algorithm may be performed by applying finite differences.

However, it must be taken into account, that excavated soil having random properties may have some inclusions like small rocks requiring larger forces to overcome their resistance. From previous chapter we saw that for a given set of three actuator forces there is infinite number of teeth force components. It is only important to keep the teeth force within the polygon. The additional role of the processor is then to control the pressure of the oil in the actuators. The pressure control is assured as follows:

Every change in teeth forces is registered by actuators and/or by their pumps due to the change of the engine speed. In the case of the decreasing engine speed the permissible pressure of all three actuator pomps is increased. This must be done in such a way which would note violate the given relation of v_1; v_2; v_3 which is defining the motion of the dipper.

5. CONCLUSIONS

It is shown, that by controlling output of three hydraulic actuator pumps, it is possible to guide excavator's dipper in two-dimensionall working space in a unique way. This requires knowledge of all kinetic and force constraints which are discussed in the paper. Among former one position of the dipper as a body with three degrees of freedom is considered. Force constraints are presented by a „flow polygon" indicating the permissible forces to be exerted on the soil by dipper's teeth. The presented algorithm allows to program the processor for an arbitrary excavation path with given constraints.

6. REFERENCES

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