A HYDRAULIC OPEN LOOP SYSTEM FOR CONTROLLED EXCAVATION ALONG PRESCRIBED PATH

E. Bundy, W. Gutkowski

Institute of Building Mechanization and Rock Mining
Ul.Racjonalizacji 6/8, 02-673 Warszawa Poland
e-mail: eb@imbigs.org.pl;Witold.Gutkowski@ippt.gov.pl

Abstract: In this study, an open loop hydraulic system for controlled excavation is proposed. It is based on a kinematically induced motion of the excavator bucket. The three degrees of freedom of the latter are driven, in a unique way, by three independent hydraulic actuators. All of them are filled with the oil in such a way that, at any instant of time, their lengths define position of the bucket. A system of three force-independent valves is applied. This way the execution of desired trajectory can be performed even in cases of some variations of soil properties.

Keywords: excavation, controlled motion, hydraulic controller, automation, open loop system.

1. INTRODUCTION

Recently, there is an intensive research carrying on in the field of automation and robotics of excavation processes. Two main groups of investigation can be here recognized .The first consisting in the remote controlled of earth moving machines and pure autonomous excavators. These studies are oriented on works in hazardous and non-structured environments, such as nuclear waste and spatial applications [1].

The second group of investigation is concentrated more on limiting the human effort, and limiting the need for very high skill operators. The investigations consist mostly in the automation of a number of repetitive tasks. Here are considered excavations along prescribed paths, digging holes and trenches, as well as drilling and piling. Collecting experimental data coming from the bucket position and the force at its tip, Bernold [2] investigated the possibility of autonomous excavation for different tasks, soil properties and bucket configurations. A simulation study of collecting a scoopful of soil for a bucket, following the given trajectory was discussed by Vähä and Skibniewski [3]. Ha et al. [4] presented the methodology, design and experimental results of force and bucket position control applying electrohydraulic servo systems. Keskinen et al. [5] discussed control of a trajectory of excavator - based sheet – piler system. Their investigations are based on angular and actuator sensing method. Control in above works was mostly proposed as close – loop systems schematically presented in Fig. 1.

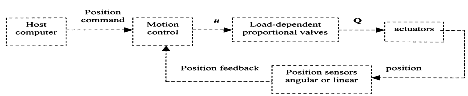

Figure 1. A close loop control with load-dependent proportional valves

In this study, an open loop hydraulic system for excavation, and other works using an excavator, is discussed. It is based on the previous author's works [6,7], consisting in kinematically induced motion of the excavator bucket. The three degrees of the latter are driven, in a unique way, by three independent hydraulic actuators. All of them are filled with the oil in such a way that at any instant of time their lengths define position of the bucket. The presented system allows the bucket to overcome small obstacles occurring in the soil. The motion is limited only by maximum possible forces exerted by actuators and by total power of excavator engine. It means that in cases of larger obstacles, the action of the operator is necessary.

The flow Q_i of the hydraulic oil into i-th actuator is defined in the following way. First, three independent variables describing the bucket motion are assumed. In this case, they are two coordinates of the bucket edge, and orientation of the bucket as a rigid body. Through kinematic relations, the bucket three coordinates are defined by lengths of three actuators. Knowing the velocity of the actuator cylinders and their cross section areas, the flow Q_i is defined. This approach can be also applied to drilling and piling. In this case either a drilling unit or vibratory unit replaces with the bucket. It is assumed that the system can work automatically. However, it is also possible that it may assist the operator in easing his work. The assumption on the automatic controlled excavating is valid only for cases with resultantly small sensitivity of the tool motion in perpendicular directions to its trajectory.

2. KINEMATICS

Consider an excavator with three coplanar rigid links, interconnected by joints in an open chain (Fig. 2). Assumed are joint variables α_1, α_2 and α_3 , relative angles between the links. The configuration of the mechanism is given by a vector $\boldsymbol{\alpha} = [\alpha_1, \alpha_2, \alpha_3]^T$ with constraints $\alpha_i^- \leq \alpha_i \leq \alpha_i^+$. The constraints come from the limited lengths of actuators driving the mechanism. All admissible α_i constitute the configuration space of it. In order to specify the space, a base frame is established at the joint between the boom and the excavator body. The task space fixed with the bucket and origin at its tip, is a space of all bucket positions $\boldsymbol{x}$ and orientations α_o.

The forward kinematics for our problem is then determining the mapping

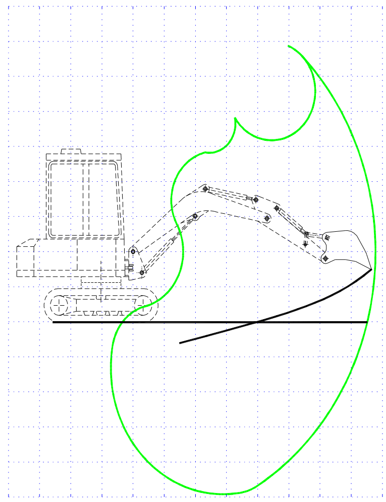

Figure 2 The excavator under considerations

$$\mathbf{X} = [\, x(\alpha_i),\ z(\alpha_i),\ \alpha_o]^T \quad \mathbf{(1)}$$

In the form

$$x = l_1 \cos(\alpha_1) + l_2 \cos(\alpha_1 + \alpha_2) + l_3 \cos(\alpha_1 + \alpha_2 + \alpha_3) \quad \mathbf{(2)}$$

$$z = l_1 \cdot \sin(\alpha_1) + l_2 \sin(\alpha_1 + \alpha_2) + l_3 \sin(\alpha_1 + \alpha_2 + \alpha_3)$$

$$\frac{dz}{dx} = -\operatorname{ctg}(\alpha_1 + \alpha_2 + \alpha_3 + \delta)$$

(3)

(4)

where l_1, l_2, and l_3 are lengths of the boom, the arm, and the bucket respectively. It is assumed that the orientation of the bucket is given with respect to the tip trajectory, according to the relation (4), in which δ is a constant depending on the bucket shape

3.TRAJECTORY PLANNING

The first step in the present considerations is trajectory planning of the excavator bucket or of a tool for piling or drilling. Let assume a repetitive curve along which the digging has to be executed. This may be digging of a trench or drilling along a straight line. The trajectory planning consists in checking if assumed trajectory can be physically realized. In the other words, if the bucket travelling along assumed trajectory is holding in the admissible working space. The latter consists not only of the bucket tip position, but also of bucket orientation, which is defined together with the trajectory line (Fig. 2). The admissible working space is of course linked to the excavator position in the discussed problem. The latter is defined by just mentioned coordinate system attached to the excavator body.

4.TRAJECTORY GENERATION

The trajectory is calculated in the host computer. Then the flow Q_i command is converted through PLC into the signal voltage needed to actuate the load-independent proportional valve transferring the oil flow to actuators. It is assumed that motion is slow enough to neglect the inertia terms, and to treat the motion as kinematically induced. Additionally it is postulated that the total power needed to operate the mechanism doesn't reach at any instant of time its maximum value. Under above conditions, the load-independent proportional valves are assumed to assure the desired bucket motion. The whole process is then defined by the following system of equations. First, the variables α_i are calculated applying the inverse kinematics.

$$\alpha_i = \alpha_i(x, z, \alpha_o) \qquad \mathbf{(5)}$$

Next, joint space elements α_i are related to actuator lengths h_i. In the case of considered excavator, after inspecting Fig. 3,4,5 these relations can be found as follows.
Let's start with h_1, the length of the first actuator. In Fig. 3 all dimensions needed to define $h_1=h_1(\alpha_1)$ are given. With simple trigonometrical relations we find:

$$h_1^2 = r_1^2 - s_1^2 \cdot \sin\alpha_1 - t_1^2 \cdot \cos\alpha_1 \qquad (6)$$

where:

$$r_1^2 = a_0^2 + a_1^2 + b_0^2 + b_1^2$$
$$s_1^2 = a_0 a_1 + b_0 b_1$$
$$t_1^2 = a_0 b_1 + a_1 b_0$$

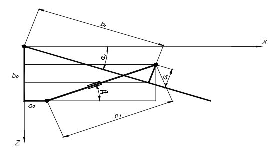

Figure3. Dimension joined with the first actuator

In the same way we find the length $h_2 = h_2(\alpha_2)$ (Fig. 4) of the second actuator. The length depends only on α_2.

$$h_2^2 = r_2^2 - s_2^2 \cdot \sin(\alpha_2 + \delta_0) - t_2^2 \cdot \cos(\alpha_3 + \delta_0)$$

$$\mathbf{(7)}$$

where:

$$r_2^2 = a_2^2 + b_2^2 + c_2^2$$
$$s_2^2 = 2a_2 b_2$$
$$t_2^2 = 2b_2 c_2$$

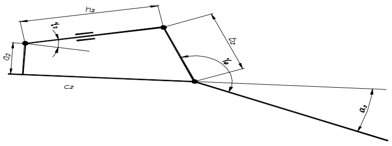

Figure 4. Dimension with the second actuator

The h_3 with respect to α_3 relation is more complex than the previous ones. In this case it is convenient to introduce an additional variable β shown in Fig.5. First, the pentagon BCDEF is considered. From trigonometric relations we get

$$h_3^2 = r_3^2 - s_3^2 \sin\beta + t_3^2 \cos\beta \qquad \textbf{(8)}$$

where

$$r_3^2 = a_3^2 + c_3^2 + d^2 + g^2 - 2a_3 g$$
$$s_3^2 = 2d(a_3 - g)$$
$$t_3^2 = 2c_3 d$$

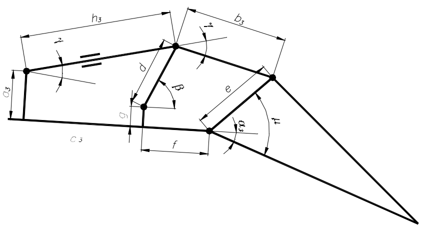

Figure 5. Dimensions joined with the third actuator

Next, inspecting the pentagon DEFGH, we get relation between β and α_3 in the form

$$b_3^2 = r_4^2 + 2d(g\sin\beta - f\cos\beta) + 2e(f - d\cos\beta)\sin\alpha_3 + - 2e(g + d\sin\beta)\cos\alpha_3 \qquad \textbf{(9)}$$

where

$$r_4^2 = d^2 + e^2 + f^2 + g^2$$

After finding β as a function of h_3 from (8), and substituting it into (9) we can find the sought relation of h_3 with respect to α_3. Reassuming, all together, for a given x_A we have eight unknowns, namely: z_A; h_1; h_2; h_3; α_1, α_2; α_3 and β. They can be solved from eight equations from (2) to (5) with (7) to (9).

5. THE HYDRAULIC OIL FLOW INTO ACTUATORS.

We have just found the actuator lengths as functions of the bucket motion. Having this we can determine the required amount of the hydraulic oil, which has to be pumped in particular actuators. This should assure the right tool motion.

Let denote:

$$Q_i = \frac{dh_i}{dt} A_i = \dot{h}_i A_i \qquad i = 1, 2, 3 \qquad \textbf{(10)}$$

The volume of the oil per unit time entering into cylinder of *i-th* actuator. A_i start for the cross section is of the cylinder. Taking time derivative of α_i (i = 1,2,3) in the form $\dot{\alpha}_i = \frac{d\alpha_i}{dt}$, and bearing in the mind notations assumed in the previous chapter, we find:

$$Q_1 = \frac{t_1^2 \sin\alpha_1 \quad s_1^2 \cos\alpha_1}{2h_1} \dot{\alpha}_1 A_1 \qquad \textbf{(11)}$$

$$Q_2 = \frac{t_2^2 \sin({}_o + \alpha_2) + s_2^2 \cos({}_o + \alpha_2)}{2h_2} \dot{\alpha}_2 A_2 \qquad \textbf{(12)}$$

$$Q_3 = \frac{t_3^2 \sin\beta + s_3^2 \cos\beta}{2h_3} \dot{\beta} A_3 \qquad \textbf{(13)}$$

with β and α_3 related by time derivative of (9):

$$[2d(g\cos\beta + f\sin\beta) + 2ed\sin\beta\sin\alpha_3 \quad 2ed\cos\beta\cos\alpha_3]\dot{\beta} =$$
$$= [2e(d\cos\beta \quad f)\cos\alpha_3 + 2e(g + d\sin\beta)\sin\alpha_3]\dot{\alpha}_3$$

The total process of supplying the oil in the actuators, in accordance with the assumed trajectory generation, is presented in Fig. 6

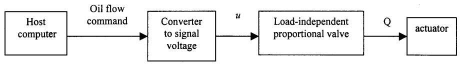

Fig. 6 An open loop control for a fully actuated, load-independent valve

Figure 6 An open loop control for a fully actuated, load independed valve

6. A NUMERICAL EXAMPLE

Consider the motion of a mini- excavator bucket along a straight line given by the relation:

$$z = 0.5x + 1[\mathrm{m}]$$

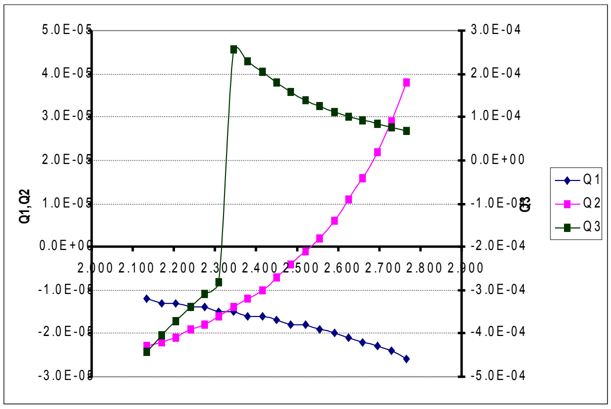

Fig.7. Flows Q_1, Q_2, Q_3 with respect to x

and a constraint imposed on x in the form

$$2.1[\mathrm{m}] \leq x \leq 2.8\ [\mathrm{m}]$$

The straight line imposes constant value of $\alpha_o = \alpha_1 + \alpha_2 + \alpha_3$. With an assumption that $\delta = 0$ we get $ctg(\alpha_o) = -0.5$.

Substituting the value of α_o into (2) and (3), we arive to two equations with two unknowns α_1 and α_2. Numerical calculations are performed for a mini-excavator with the following parameters specified in Fig.3, 4, 5.

$l_1 = 2.2$ m;

$l_2 = 1.1$

$a_o = 0.120$ [m] $b_o = 0.300$ [m] $c_1 = 0.941$ [m]

$a_1 = 0.300$ [m] $b_1 = 1.120$ [m] $c_2 = 1.037$ [m]

$a_2 = 0.658$ [m] $b_2 = 0.300$ [m] $c_3 = 0.175$ [m]

$a_3 = 0.269$ [m] $b_3 = 0.190$ [m]

$d = 0.260$ [m] $A_1 = 0.00503$ [m^2]

$e = 0.199$ [m] $A_2 = 0.00503$ [m^2]

$f = 0.175$ [m] $A_3 = 0.00330$ [m^2]
$g = 0.200$ [m] $h_o = 1.100$ [m]
The solution of the inverse kinematics for α_i is carried out at twenty equidistant points i between for between 2.1 – 2.8 [m], from the following equations

$$\begin{aligned} x_i &= l_1 \cos\alpha_{1i} + l_2 \cos(\alpha_{1i} + \alpha_{2i}) + l_3 \cos\alpha_o \\ x_i + 1 &= l_1 \sin\alpha_{1i} + l_2 \sin(\alpha_{1i} + \alpha_{2i}) + l_3 \sin\alpha_o \\ \alpha_o &= \alpha_{1i} + \alpha_{2i} + \alpha_{3i} \end{aligned} \qquad \mathbf{(14)}$$

Now, obtained values of x_i we substitute into equations (11), (12) and (13) expressing flows Q_i. In Fig.7 a diagram relating these flows to x_i is presented.

7. CONCLUSIONS

It has been shown that there is a possibility to apply a robust, open loop controlled system for excavation , and other excavator-based works. The idea consists in introducing three independent hydraulic valves for each of three actuators. This makes possible to control three degrees of motion of the bucket in a unique way. The applied load-independent valves allow to control the motion along prescribed trajectory in a soil with some variations of its properties. The trajectory is generated from the host computer to a PSC, changing the command to a voltage system which in turn drives the valves .

REFERENCES

[1] Barrientos A.., Luengo O., Mora A.. “Teleoperaded backhoe excavator with haptic control” Proceedings of 16th Int. Symp. Automation and Robotics in Construction, pp.491- 496

[2] Bernold L. I., “Motion and path control for robotic excavation”, J. Aero. Engr. ASCE, vol. 6, No 1, pp 1-18, 1993

[3] Vaha P.K., Skibniewski M.J., Cognitive force control of excavators, J. Aero. Engug. ASCE vol.6, No 2, 1993

[4] Ha Q.P., Nguyen O.H., Rye D.C., and Durrant-Whyte H.F., “Force and position control for electrohydraulic systems of a robotic excavator”, Proceedings of 16th Int. Symp. Automation and Robotics in Construction.pp. 483-389, 1999

[5] Keskinen E., Launis S., Cotsafis M., Raunisto Y., “Trajectory Control Performance Analysis of Excavator – Based Sheet – Piles System”, Proceedings of 16th Int. Symp. on Automation and Robotics in Construction, pp535 – 540, 1999

[6] Budny E., and Gutkowski W., Kinematically induced excavation by backhoe excavator, 13th ISARC, Proceedings, 1996, pp 673-680

[7] Gutkowski W., Chłosta M., Sensitivity of the Bucket Motion in Controlled Excavation, ANC 8th Int. Topical Meeting on Robotics and Remote Systems, April 25-29, 1999, Pittsburgh