INTELLIGENT DRILLING BY AUTOMATIC CONTROL OF POSITION AND ORIENTATION OF DRILL HEAD OF CRAWLER DRILL MACHINE

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ABSTRACT

A crawler drill is mainly used in the crushed ore industry. This paper is concerned with the automatic control of the drill head of the crawler drill machine. In this study, the crawler drill machine is assumed to be the linkage by considering the actual machine. By using this linkage, two programs were developed. One is a program that determines the position and the orientation of the drill head from the angle of each joint. Another one is a program that determines the angles of each joint to make the drill head move to the desired position and orientation. By use of these programs, numerical simulation to control the drill head was carried out. It was confirmed that these programs work well.

INTRODUCTION

A crawler drill is mainly used in the crushed ore industry or limestone quarry. Usually, crushed ores are produced by the blasting method. In order to use this method, some blasting holes have to be drilled. After these holes are drilled by the crawler drill machine, explosives are poured into the holes. Then, the blasting is conducted. All these works have been already mechanized, but the drilling task is strongly dependent on the skilled hand-operation. But the working environment is not so comfortable for workers because of much dust, machine vibration and long working time. So, the full automation of the drilling task has been receiving considerable attentions. In order to realize the full automation, some studies have already been done for actual automatic drilling, rod exchanging control and explosives charging control [1]. However, there are few works related to the control of position and orientation of the drill head, which is inevitable for the full automation of the crawler drill task. Since it is often said that the blasting efficiency depends on the accuracy of the position and orientation of the drill head, the automatic control of the drill head is a very important problem.

Therefore, the purpose of this paper is to develop the automatic control model of the drill head of the crawler drill machine.

MODELING OF THE CRAWLER DRILL

Figure 1 shows the schematic diagram of the crawler drill machine. The position and the orientation of the drill head are controlled by the boom and the arm mounted the main body. The actual machine has many hydraulic cylinders, but only four hydraulic cylinders are used to determine the position and orientation of the drill head. Therefore, in this study, the crawler drill is assumed to be the linkage with having four degrees of freedom and six links by considering the actual machine. Figure 2 shows the linkage and assignment of the coordinate system. Five coordinate systems are assigned to this linkage according to robotics theory.

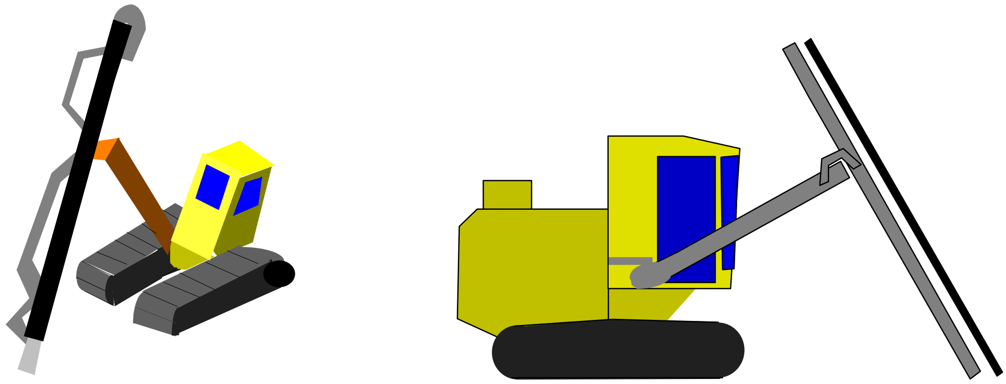


Fig. 1 Schematic diagram of the crawler drill machine

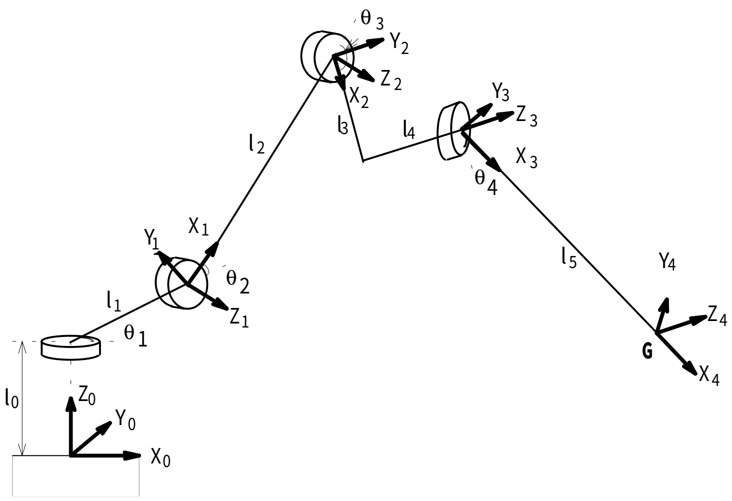


Fig.2 Linkage and assignment of the coordinate system

KINEMATIC CONTROL MODEL

Each link is defined by the fixed base coodinate system. The link frame i is related to the link frame i-1 by the transformation matrix ${}^{i-1}_{i}A$ which can be written as an 4×4 homogeneous matrix, and is expressed by

$$
{}^{i-1}_{i}A = \begin{pmatrix} \cos\theta_i & -\sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (1)
$$

Table 1 Link parameter of manipulator of crawler drill

i	d_i	θ_i	a_i	α_i
1	l_0	θ_1	l_1	$\pi/2$
2	0	θ_2	l_2	0
3	0	$-\theta_3$	l_3	$-\pi/2$
4	l_4	θ_4	l_5	0

According to this equation, the drill head position and orientation with respect to the fixed base coodinate frame X_0-Y_0-Z_0 can be described by the following matrix with considering the link parameter shown in Table 1:

$$ {}^{0}_{4}A = {}^{0}_{1}A\,{}^{1}_{2}A\,{}^{2}_{3}A\,{}^{3}_{4}A $$

$$ = \begin{bmatrix} c_1c_{23}c_4 + s_1s_4 & -c_1s_{23}c_4 - s_1c_4 & -c_1s_{23} & l_5(c_1c_{23}c_4 - s_1s_4) - c_1(l_4s_{23} + l_3c_{23} + l_2c_2 + l_1) \\ s_1c_{23}c_4 + c_1s_4 & -s_1s_{23}c_4 + c_1c_4 & -s_1s_{23} & l_5(s_1c_{23}c_4 + c_1s_4) - s_1(l_4s_{23} + l_3c_{23} + l_2c_2 + l_1) \\ s_{23}c_4 & -s_{23}s_4 & c_{23} & l_5s_{23}c_4 + l_4c_{23} + l_3s_{23} + l_2s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ = \begin{bmatrix} N_x & O_x & A_x & P_x \\ N_y & O_y & A_y & P_y \\ N_z & O_z & A_z & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

where c_1 and s_1 represent $\cos\theta_i$ and $\sin\theta_i$, respectively, and c_{23} and s_{23} represent $\cos(\theta_2-\theta_3)$ and $\sin(\theta_2-\theta_3)$, respectively

It is noticed that five dimentional quantities are needed to represent the position and orientation of the drill head.They are the three dimentional position (x, y, z) and the horizontal inclination angle α and the vertical inclination angle β. They are given from Eq.(2) as follows:.

$$ x = P_x = l_5(c_1c_{23}c_4 - s_1s_4) - c_1(l_4s_{23} + l_3c_{23} + l_2c_2 + l_1) $$
$$ y = P_y = l_5(s_1c_{23}c_4 + c_1s_4) - s_1(l_4s_{23} + l_3c_{23} + l_2c_2 + l_1) $$
$$ z = P_z = l_5s_{23}c_4 + l_4c_{23} + l_3s_{23} + l_2s_2 + l_0 \tag{3} $$
$$ \alpha = \frac{N_y}{N_x} = \frac{s_1c_{23}c_4 + c_1s_4}{c_1c_{23}c_4 + s_1s_4} $$
$$ \beta = \frac{N_z}{N_x} = \frac{s_{23}c_4}{c_1c_{23}c_4 + s_1s_4} $$

INVERSE KINEMATIC CONTROL MODEL

In order to make the drill head move to the desired position and orientation automatically, the angles of each joint have to be determined. The matrix ${}^{0}_{3}A$ and ${}^{0}_{4}A$ are expressed as follows:

$${}^{0}_{3}A = \begin{bmatrix} n_{x3} & o_{x3} & a_{x3} & p_{x3} \\ n_{y3} & o_{y3} & a_{y3} & p_{y3} \\ n_{z3} & o_{z3} & a_{z3} & p_{z3} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} & {}^{0}_{3}R & & {}^{0}_{3}P \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$${}^{0}_{4}A = \begin{bmatrix} N_x & O_x & A_x & P_x \\ N_y & O_y & A_y & P_y \\ N_z & O_z & A_z & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} & {}^{0}_{4}R & & {}^{0}_{4}P \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

From above equations, $(p_{x3},p_{y3},p_{z3})^T$ is expressed by Eq.(6).

$$\begin{pmatrix} p_{x3} \\ p_{y3} \\ p_{z3} \end{pmatrix} = \begin{pmatrix} P_x - l_4 A_x - l_5 N_x \\ P_y - l_4 A_y - l_5 N_y \\ P_z - l_4 A_z - l_5 N_z \end{pmatrix} \tag{6}$$

As p_{y3}/p_{x3} gives tan θ_1, θ_1 is obatined as follows:

$$\theta_1 = \tan^{-1} \frac{P_y - l_4 A_y - l_5 N_y}{P_x - l_4 A_x - l_5 N_x} \tag{7}$$

$${}^{3}_{4}R = {}^{0}_{3}R^{-1} \cdot {}^{0}_{4}R$$

$$\begin{bmatrix} c_4 & -s_4 & 0 \\ s_4 & c_4 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_1 c_{23} & s_1 c_{23} & s_{23} \\ -s_1 & c_1 & 0 \\ -c_1 s_{23} & -s_1 s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} N_x & O_x & A_x \\ N_y & O_y & A_y \\ N_z & O_z & A_z \end{bmatrix} = \begin{bmatrix} f(N) & f(O) & f(A) \\ g(N) & g(O) & g(A) \\ h(N) & h(O) & h(A) \end{bmatrix} \tag{8}$$

From (1,3) component of Eq.(8), the next equation is obtained.

$$0 = -c_1 s_{23} N_x - s_1 s_{23} N_y + c_{23} N_y \tag{9}$$

Thetrefore, θ_{23} is given by Eq.(10).

$$\theta_{23} (= \theta_2 - \theta_3) = \tan^{-1} \left(\frac{N_z}{c_1 N_x + s_1 N_y} \right) \tag{10}$$

From p_{x3} and p_{z3}, θ_3 is given by Eq.(11).

$$p_{x3} = l_3 c_1 c_{23} + l_2 c_1 c_2 + l_1 c_1$$

$$p_{z3} = l_3 s_{23} + l_2 s_2$$

$$\theta_2 = \tan^{-1} \left(\frac{p_{z3} - l_3 s_{23}}{p_{x3} - l_4 A_z - l_5 N_z} \right) \tag{11}$$

Then θ_3 is expressed as follows:

$$\theta_3 = \theta_2 - \theta_{23} \tag{12}$$

From cos θ_4 and sin θ_4, θ_4 is given by Eq.(12).

$$c_4 = c_1 c_{23} N_x + s_1 c_{23} N_y + s_{23} N_z$$

$$s_4 = -s_1 N_x + c_1 N_y$$

$$\theta_4 = \tan^{-1}\left(\frac{-s_1 N_x + c_1 N_y}{c_1 c_{23} N_x + s_1 c_{23} N_y + s_{23} N_z} \right) \tag{13}$$

TRAJECTORY OF DRILL HEAD

In order to make the drill head move to the desired position, the trajectory of the drill head movement is necessary. In this study, this trajectory is assumed to be linear from the initial position to the desired position. At the start and the end of the movement, the velocity of the drill head should be zero. Therefore, the trajectory of the drill head is given by following equations based on the above assumption.

$$\begin{aligned}
x(t) &= x(0) + \frac{3}{T^2}(P_x - x(0))t^2 - \frac{2}{T^3}(P_x - x(0))t^3 \\
y(t) &= \frac{(x(t) - x(0))(P_y - y(0))}{P_x - x(0)} + y(0) \\
z(t) &= \frac{(x(t) - x(0))(P_z - z(0))}{P_x - x(0)} + z(0) \\
\alpha(t) &= \alpha(0) + \frac{(x(t) - x(0))}{P_x - x(0)}(\alpha_f - \alpha(0)) \\
\beta(t) &= \beta(0) + \frac{(x(t) - x(0))}{P_x - x(0)}(\beta_f - \beta(0))
\end{aligned} \tag{14}$$

Here, T is the movement time, α_f and β_f are desired horizontal and vertical inclination angles, respectively.

SIMULATION RESULTS

By using the model developed here, a numerical simulation was carried out. Table 2 shows the link dimension and initial joint angles. Figure 3 shows the initial position of the linkage. This is the position when the crawler drill moves.

Table 2 Link dimension and initial joint angles

Length of Link [mm]	Initial Angle of Joint [degree]
l_0= 500, l_1= 500 l_2= 2000, l_3= 300 l_4= 100, l_5= 1500	θ_1=0, θ_2=30 θ_3=30, θ_4=0

Figures 4 and 5 show the simulated results of the movement of the drill head. In these figures, the desired positions of the drill head and inclination angles are (x,y,z)=(265,125,0), (α, β)=(45,-60) and (x,y,z)=(270,-10,0), (α, β)=(5,-60) , respectively. Although the trajectory of the movement of drill head is given by a linear function, the simulated result of the trajectory of drill head is a little distorted from the linear line. It can be considered that this is due to the calculation error in the computer. However, it is found that the drill head is well controlled and it moves smoothly to the desired position.

Figures 6 and 7 shows the change of the joint angle. The change of the joint angle, θ_1, θ_2 and θ_4 is small. On the other hand, the change of θ_3 is very large.

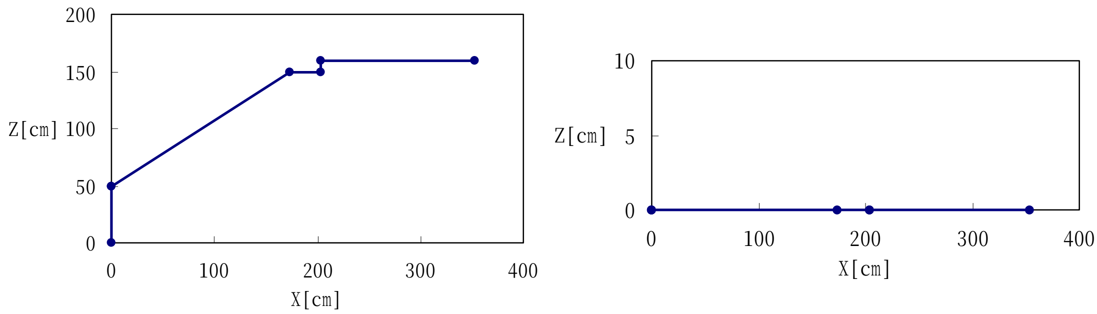


Fig. 3 Initial position of the linkage

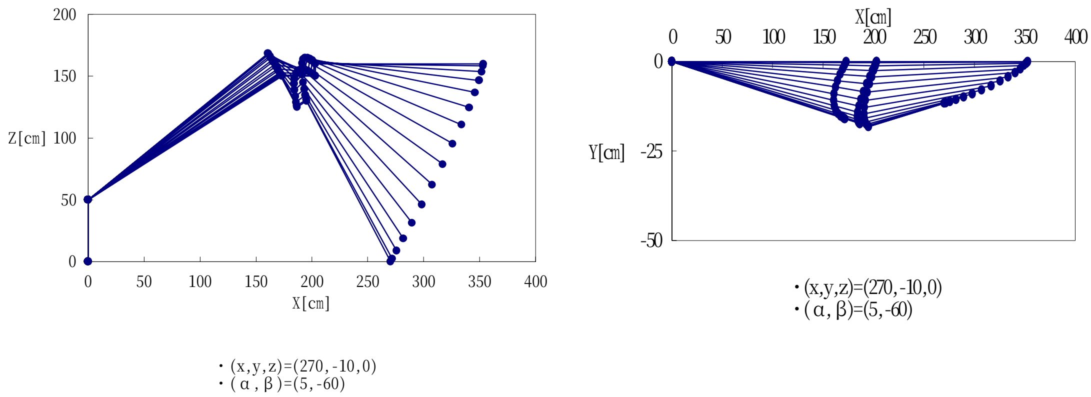


Fig.4 Simulated results of the movement of the drill head

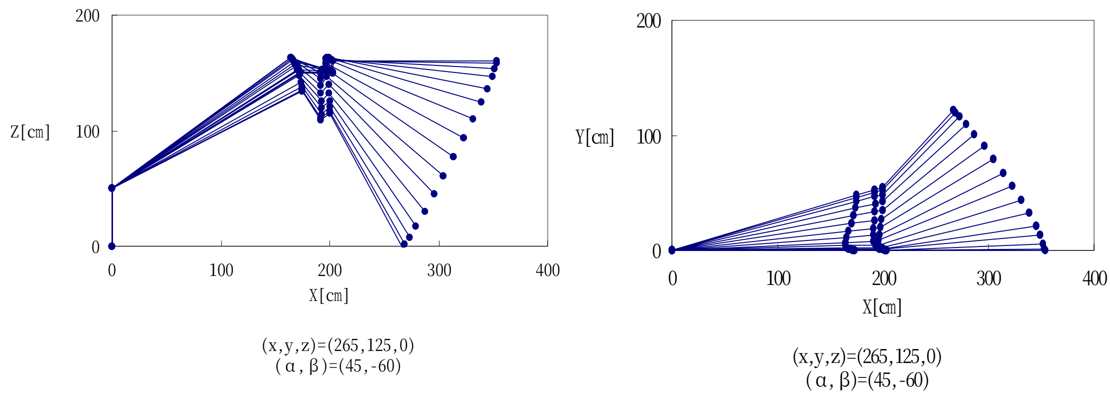
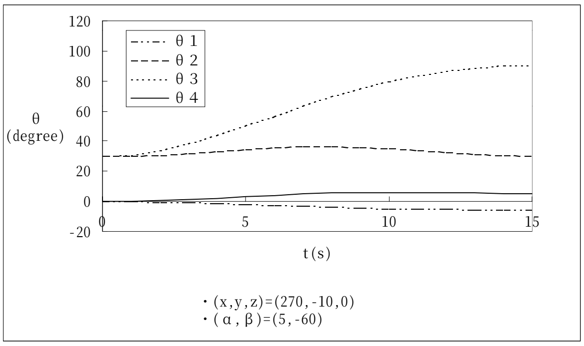


Fig. 5 Simulated results of the movement of the drill head



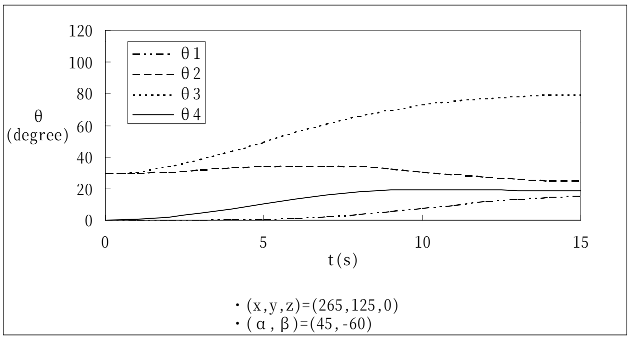


Fig. 6 Change of the joint angle

Fig. 7 Change of the joint angle

CONCLUSIONS

The control model to make the drill head move to the desired position was developed in this study. The actual machine was modeled by a simple linkage with four degrees of freedom. By using this model, the numerical simulation was carried out. It was confirmed that the developed model works well. This program will be used to realize the full automation of crawler drill tasks.

ACKNOWLEDGEMENT

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REFERENCE

[1]K.Miyake et al. : “Development of Automatic Technology of Drilling, Loading and Hauling Operation for Crushed Stone Industry”, J. of the Mining and Materials Processing Institute of Japan, Vol.112, No.8, pp.571-580, 1996.