

Kinematics Analysis of a Mobile 6-DOF Coal Sampling Robot

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Abstract—In order to solve the problem of automatic sampling of coal, this paper introduced the MCYY2000 6-DOF mobile coal sampling robot and analyzed its kinematics. This paper first introduced the mechanical structure of the 6-DOF sampling robot, then the forward kinematics equation of the sampling robot was established by the DH method. Next the interference situation of the sampling robot with coal containers in the sampling process was analyzed, and the judgment whether the interference exists or not was given. Finally the workspace of the sampling robot was analyzed by Monte Carlo method, and taking interference situations into consideration, the distance between the sampling robot and the coal containers should be within 5m was suggested. The work of this paper provides the basis of the follow-up sampling robot inverse kinematics solution and sampling path planning. And the method of studying the kinematic characteristics of coal sampling robot can also be applied to other kinematics analysis of robots.

Keywords—6-DOF coal sampling robot; forward kinematics; DH method; interference detection; workspace analysis

I. INTRODUCTION

Due to the diversification of coal supply, coal quality fluctuation has been increasing[1]. In order to evaluate the economical efficiency of coal combustion, sampling and evaluating coal quality entering the factory has become the most commonly used control measure for all manufacturers[2]. Therefore, the management of coal quality has attracted the attention of all related industries, and the economical efficiency of coal combustion has become the key assessment indicators for coal-fired enterprises. Through obtaining representative coal samples, then testing and analyzing some indicators of the coal, including calorific value, ash content, moisture content, and sulfur content, to determine whether the coal meets the enterprise's coal standards, and determine the price according to the coal quality standards.

The traditional coal sampling machines are divided into three categories: bridge-type train entry coal sampling device, bridge-type car admission coal sampling device and belt sampling device[3]. They are all limited by the fixed occasions and their requirements for sampling locations are very high, so sampling is very inconvenient. As a result, the mobile coal sampler is widely used. It is not limited by the sampling location, and has a wide enough sampling space for flexible sampling. The mobile coal sampler is suitable for the sampling of the cars, the trains and the coal heap of commercial coal yards in coal factory, steel

mills, power plants, ports and other field. With its advantages of small size, high mobility, and wide adaptability, in recent years it shows an important position in the industry of coal mechanized sampling.

This paper presents kinematics analysis of the MCYY2000 mobile coal sampling robot that we developed for enterprise applications. MCYY2000 mobile coal sampling robot has the advantages of convenient movement, easy to use, and various control modes (manual, semi-automatic, and automatic). It can realize full-section sampling, crushing, shrinking, and sample integration, and has the advantages of high sampling efficiency and overcoming the low accuracy, low efficiency, and poor flexibility in manual sampling process. The developed mobile coal sampling robot is composed of a movable truck loaded with a 6-degree-of-freedom hydraulically driven sampling arm. This paper provides a new reference method for automated and intelligent coal sampling under complex conditions, which has certain application value for reducing the labor intensity of sampling and reducing the risk of sampling operations.

II. MECHANICAL DESIGN

A. Working Principle

The three-dimensional model of MCYY2000 mobile coal sampling robot is shown in Figure I. It consists of a movable truck loaded with a 6-DOF hydraulically driven sampling arm. The working principle of this coal sampling robot is as follows: After the coal-carrying vehicle is parked at the designated inspection location, the mobile coal sampler accurately puts the sampling end into the already-set sampling point through adjusting the 6-DOF sampling arm. After the positioning is completed, the sampling end will rotate to sample coal. Then the coal samples are raised through the force of friction caused by rotating hydraulic motor, and the samples finally enter into hoppers for storage. Next the hopper door is opened when samples are transported to the sample preparation system, and finally the samples are crushed, shrunk and sent to the coal samples analytical equipment. This sampling process is completed and the next sampling process is preparing.

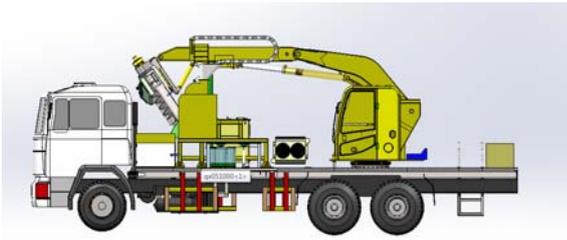


FIGURE I. 3D MODEL OF MOBILE COAL SAMPLING ROBOT

B. The Design of Sampling Robot

The designed sampling arm of the mobile coal sampling robot is a 6-degree-of-freedom manipulators consisting of a rotatable supporting arm, a big arm, a lower arm, 2 telescopic arms, a sampling end, and many hydraulic cylinders. The layout structure is shown in Figure II.

The supporting arm is bolted with the slewing bearing on the base of truck. The pinion gear on the base of supporting arm meshes with the outer teeth of the slewing bearing, and the pinion gear is connected with the hydraulic slewing motor. The hydraulic motor provides power to drive the entire sampling robot accomplish 300° rotation. A rotary encoder driven by a pinion gear is also mounted on the other end, which has the ability to transmit rotary angle signals to the control system. The big arm, the lower arm and the telescopic arms are driven by their respective hydraulic cylinders to achieve pitching or telescoping; The sampling end is the core mechanism of the coal sampling robot. It is fixed in the telescopic arm at the end of sampling robot and moves along guide rail through the moving pulley block and the chain to make a linear reciprocating motion. Due to the 6-DOF sampling robot, the sampling end can move down at different angles to sample. The sampling end adopts a spiral structure, which is a screw transmission mechanism that the hydraulic motor provides power to drive the rotation of the screw mandrel. Its main function is to drill and transport the coal sample. When the spiral mandrel rotates, the alloy drill at the end of the spiral mandrel breaks the relatively larger coal samples while drilling the coal samples. The force of friction between coal samples and the spiral blade will send the coal samples to the top of the sampling end, and 1/4 coal samples will be stored in the small storage silo, the rest will overflow back to the coal cart.

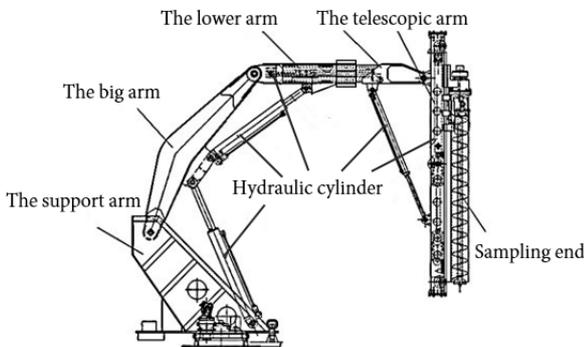


FIGURE II. LAYOUT OF COAL SAMPLING ROBOT.

III. FORWARD KINEMATICS

The establishment of a robot forward kinematics model is the basis for analysing the kinematics of a robot. When the robot's structural dimensions and movement parameters (rotational joint rotation angle and displacement of the moving joint) are known, in order to analyze the end position and attitude of the robot, it is necessary to use a forward kinematics solution. Therefore, in order to analyze the kinematics of the sampling robot during the sampling process, we need to establish the forward kinematics model of the sampling robot.

A. Coordinate System of Sampling Robot

Analyzing the structure of the sampling robot, we can see that the sampling robot is similar to the industrial robot in mechanical structure, which consists of a series of connecting rods through the rotating joint and the moving joint. The relative rotation of the rotating joint and the relative movement of the moving joint make the sampling end to reach the desired position and attitude. The kinematic model of the sampling arm can be established by the DH method[4].

According to the DH method, a coordinate system can be established. The sampling arm consists of four rotating joints and two moving joints. In order to determine the position and attitude of each arm, it is necessary to establish seven coordinate systems that are fixed to each arm. The established sampling arm coordinate systems are shown in Figure III.

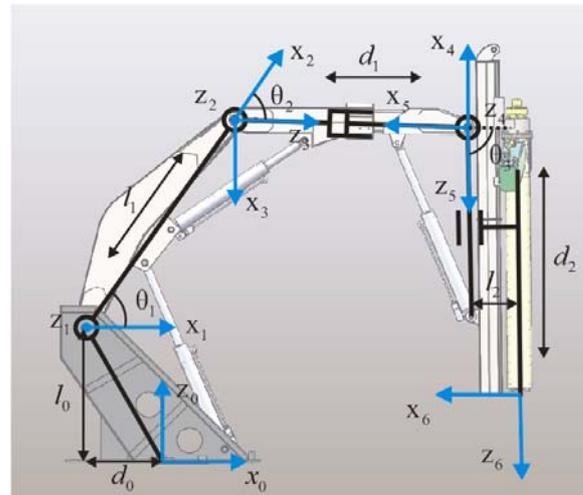


FIGURE III. KINEMATIC STRUCTURE WITH COORDINATE ASSIGNMENT OF SAMPLING ROBOT

Among them: the $z_1, z_2,$ and z_4 axis are pointing outward along the normal direction of the paper surface; All coordinate systems are right-handed coordinate system, and the Y-axis direction can be determined by the right-hand rule; θ_0 is the angle in horizontal surface between the support arm and the base of the robot; θ_1 is the angle between the support arm and the big arm; θ_2 is the angle between the big arm and the lower arm; θ_3 is the angle between the first telescopic arm and the last telescopic arm(near the sampling end); l_0 is the vertical distance between the big arm rotating joint and the center of the slewing

bearing on the base; l_1 is the length of the big arm; l_2 is the base tangent length between the axis of sampling end and the axis of the last telescopic arm; d_0 is the horizontal distance between the big arm rotating joint and the center of the slewing bearing on the base; d_1 is the arm length of the first telescopic arm (variable). d_2 is the length of the last telescopic arm (variable). The specific size parameters are in Table I.

TABLE I. SIZE PARAMETERS OF SAMPLING ROBOT

parameter	value
d_0	1.4m
l_0	0.75m
l_1	2.884m
l_2	0.47m

B. Forward Kinematics Model

In order to study the influence of the motion of each joint on the position and attitude of the sampling end, a homogeneous coordinate system transformation method is used to solve the description of the position and attitude transformation of the sampling robot. The transformation relationship between $i-1$ and i coordinate systems can be achieved by the translation and rotation of coordinate systems. According to the DH method, the coordinate system transformation between the $i-1$ coordinate system and the i coordinate system can be represented by the following transformation matrix when the DH parameter is known.

$$T_{i-1,i} = \begin{bmatrix} \cos \theta_i & -\sin \theta_i \cos \alpha_i & \sin \theta_i \sin \alpha_i & l_i \cos \theta_i \\ \sin \theta_i & \cos \theta_i \cos \alpha_i & -\cos \theta_i \sin \alpha_i & l_i \sin \theta_i \\ 0 & \sin \alpha_i & \cos \alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

According to the meaning of each DH parameter, the structural dimensions of the sampling robot can be analyzed to obtain the parameters of the connecting rod, as shown in the Table II.

TABLE II. D-H PARAMETERS OF SAMPLING ROBOT

I	D-H Parameters				
	θ_i	d_i	l_i	α_i	variable range
1	θ_0	1.4m	-0.75m	90°	0-300°
2	θ_1	0m	2.884m	0°	22.5-88°
3	$-(90^\circ + \theta_2)$	0m	0m	-90°	20-90°
4	180°	d_1	0m	-90°	2.7-3.3m
5	$180^\circ - \theta_3$	0m	0m	-90°	45-120°
6	0°	d_2	0.47m	0°	3.4-5.5m

Substituting the size parameters in Table I and DH parameters in Table II into (1), you can get the transformation matrix of each adjacent coordinate system. $T_{0,1}$ and $T_{1,2}$ are as follows, and the rest are also available.

$$T_{0,1} = \begin{bmatrix} \cos \theta_0 & 0 & \sin \theta_0 & -l_0 \cos \theta_0 \\ \sin \theta_0 & 0 & -\cos \theta_0 & -l_0 \sin \theta_0 \\ 0 & 1 & 0 & d_0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{1,2} = \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 & 0 & l_1 \cos \theta_1 \\ \sin \theta_1 & \cos \theta_1 & 0 & l_1 \sin \theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Thus the transformation matrix from the base coordinate system to the sampling end coordinate system is as follows:

$$T_{0,6} = T_{0,1}T_{1,2}T_{2,3}T_{3,4}T_{4,5}T_{5,6}$$

Then the kinematic equation of the sampling robot can be expressed as:

$$S_6 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = T_{0,6} \quad (2)$$

Among them: $u = (p_x, p_y, p_z)^T$ is the coordinate of the end point of the sampling end in the base coordinate system $O_0 - x_0 y_0 z_0$; n, o, a sequentially represents the pose of the sampling end coordinate system $O_6 - x_6 y_6 z_6$ with respect to the base coordinate system $O_0 - x_0 y_0 z_0$.

IV. INTERFERENCE DETECTION

The coal is placed in the train containers. The 6-axis sampling robot must prevent collision with the walls of the containers during the sampling process. Therefore, it is necessary to analyze the interference between the arm of the sampling robot and the walls of the containers during the sampling process. Considering the actual working conditions, the sampling end of the sampling robot is the part that the most likely interferes with the containers. Therefore, the interference situation between them is analyzed as follows.

1) When the interference does not exist, the points on the sampling end axis below the dashed line (in Figure IV) should be on the same side as the boundary of the train container's wall, as shown in the Figure IV. Among them, QP is the axis of the sampling end, T the highest point of the containers.

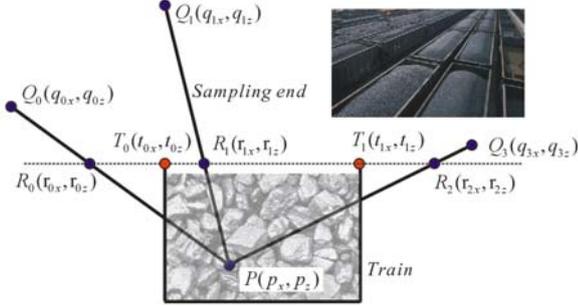


FIGURE IV. SCHEMATIC DIAGRAM OF INTERFERENCE SITUATION

Since $Q(q_x, q_z)$ and $P(p_x, p_z)$ can be obtained from (2) of the sampling robot, the linear equation of QP is:

$$\left(\frac{q_z - p_z}{q_x - p_x}\right)x - y + p_z - \left(\frac{q_z - p_z}{q_x - p_x}\right)p_x = 0 \quad (3)$$

$T(t_x, t_y)$ is known and substituted into (3), The coordinates of $R(r_x, r_y)$ are:

$$\begin{cases} r_x = p_x + \left(\frac{q_x - p_x}{q_z - p_z}\right)(t_z - p_z) \\ r_z = t_z \end{cases}$$

It can be seen that when the sampling end interferes with the train container's wall:

$$(p_x - t_{0x})(r_x - t_{0x}) < 0 \quad \text{or} \quad (p_x - t_x)(r_x - t_{1x}) < 0$$

2) When interference does not exist, the distance from T to the straight line QP should be greater than the diameter D of the sampling end, which can be obtained from (3). when the sampling end interferes with the wall of the train container:

$$D < \left| \frac{At_{0x} + Bt_{0z} + C}{\sqrt{A^2 + B^2}} \right| \quad \text{or} \quad D < \left| \frac{At_{1x} + Bt_{1z} + C}{\sqrt{A^2 + B^2}} \right|$$

Among them: $A = \left(\frac{q_z - p_z}{q_x - p_x}\right)$; $B = -1$; $C = p_z - \left(\frac{q_z - p_z}{q_x - p_x}\right)p_x$

When any of the above two conditions is established, the sampling end interferes with the walls of the train containers. Such position and attitude should be eliminated during the sampling process.

V. WORKSPACE ANALYSIS

The main advantage of the 6-DOF sampling robot is that it can sample different depths of coal seam more flexibly. The 6-DOF sampling robot can change different postures in the collision presence of the containers, so sampling robot can send the sampling end to the selected sampling point without collision with obstacles.

In the design process, the Monte Carlo method is adopted in this paper[5]. The workspace range map of the sampling arm is made in the symmetry plane of the sampling robot. Analysis of the working space of the sampling arm, the principle is:

$$W = \{\omega(q) : q \in Q\} \subset R^3$$

Among them: W is the workspace; q is a generalized joint variable; $\omega(q)$ is a generalized joint variable function; Q is a joint space; R^3 is a three-dimensional space.

Inequalities represent the range of motion of each generalized joint, i.e. $q_{i,\min} \leq q_i \leq q_{i,\max}$ ($i=1,2,L,6$)

In this way, the joint variable is evenly assigned with a certain amount of random quantities that meet the requirements of the joint change, so that a workspace graphic (called a cloud image) composed of random points is obtained, that is, a Monte Carlo workspace. The result is shown in Figure V. The sampling end can reach the depth of 5m below and the width of 8m away from the base of sampling arm.

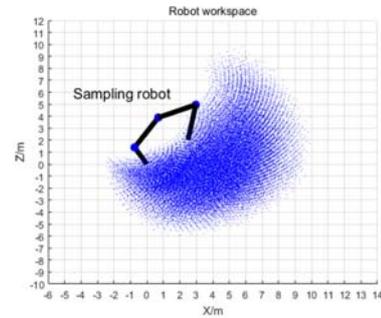


FIGURE V. SAMPLING ROBOT WORKSPACE

However, in the sampling process, the sampling robot needs to avoid interference with the walls of the train containers. When the train container is too far away from the sampling robot, the sampling end of the sampling robot is subject to interference conditions. So it cannot traverse the entire train container. Schematic diagram of the relative position between the sampling robot and the container is shown in the Figure VI. The size of the C62 model is taken as an example for train containers. The specific parameter values are shown in Table III.

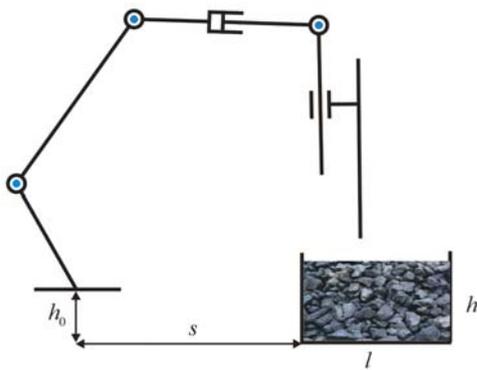


FIGURE VI. SCHEMATIC DIAGRAM OF SAMPLING ROBOT AND CONTAINER

TABLE III. SIZE PARAMETERS OF SAMPLING ROBOT AND CONTAINER

parameter	value
h_0	0.725m
l	2.9m
h	2.05m

Using the Monte Carlo method, the workspace of the sampling robot with different distances away from the train container is shown in Figure VII after eliminating the presence of interference.

As we can see in Figure VII, The sampling robot can sample the entire section of the container within 1-5m from the train container(the blue section is the workspace of sampling robot in train container). When the distance from the train container exceeds 5m, the sampling range which the sampling robot can sample is smaller and smaller in the train container. Therefore, it is necessary to keep the distance between the sampling robot and the train container less than 5m.

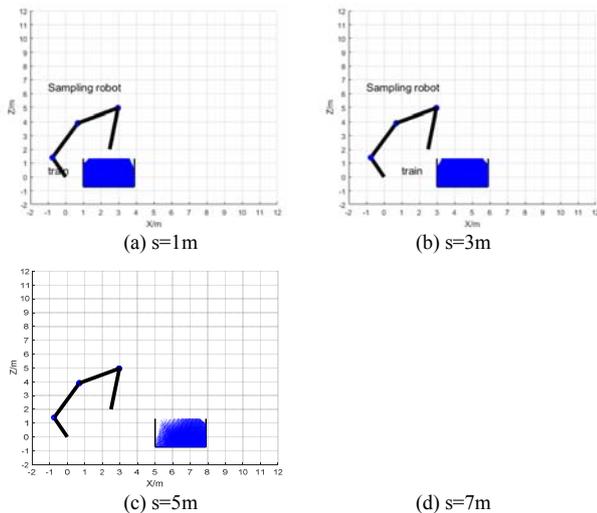


FIGURE VII. SAMPLING ROBOT WORKSPACE IN TRAIN CONTAINER

VI. CONCLUSION

The kinematics of a mobile coal sampling robot was introduced. This paper introduced the mechanical structure of the sampling robot and used D-H method to establish the forward kinematics modeling of the sampling robot. This kinematics model is not only the basis for the analysis of the interference detection in the robot sampling process, but also the basis for the follow-up sampling robot inverse kinematics solution and sampling robot path planning. Based on the forward kinematics model of the sampling robot, and according to the actual working environment of the sampling robot in the coal sampling in train containers, the interference situation in the robot sampling process was analyzed, and the criterion of whether interference has occurred is given. It provides a reference for the sampling path planning because it is undesirable for the sampling robot to interfere with train containers in sampling process. Finally considering the limitations of interference conditions, this paper analyzed how the sampling robot's workspace in coal containers varies with distance from coal containers. The kinematics analysis of this paper provides a reference for subsequent motion planning and inverse kinematics solution of sampling robots. At the same time, the method for studying the kinematic characteristics of coal sampling robot can also be applied to other kinematics analysis of robots.

REFERENCES

- [1] ZHAO Jun. Discussion on mechanical sampling of commercial coal[J]. Coal Quality Technology, 2009.
- [2] Shi QinzhangMa. Research on Unified Automatic Coal Sampler[J]. Coal Processing & Comprehensive Utilization, 1999.
- [3] Jing bo HU, Hong W, Tian H. The design development of new type coal dump sampler[J]. Coal Quality Technology, 2017.
- [4] Siciliano B, Sciavicco L, Villani L, et al. Robotics : modelling, planning and control[M]. Springer Publishing Company, Incorporated, 2010.
- [5] Baofeng L I. Calculation of Space Robot Workspace by Using Monte Carlo Method[J]. Spacecraft Engineering, 2011.
- [6] Liu S, Zhu S, Li J, et al. Research on real-time inverse kinematics algorithms for 6R robots[J]. Control Theory & Applications, 2008, 25(6):1037-1041.
- [7] Chen N, Parker G A. Inverse kinematic solution to a calibrated Puma 560 industrial robot[J]. Control Engineering Practice, 1994, 2(2):239-245.