Design and Research of Eight-Degree-of-Freedom Heavy Manipulator

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ABSTRACT

In order to solve the problems of low automation and production efficiency in the process of replacing lining plate of large-scale mining mill, a self-propelled heavy-duty manipulator was developed by using virtual prototyping technology. Firstly, the overall scheme and key parts of the heavy manipulator are designed. Then, the kinematics mathematical model of the whole manipulator is established and the operation path and scope are planned. The results show that the heavy manipulator studied in this paper can efficiently complete the task of replacing the lining plate, and the workspace is a cuboid with a spherical surface around it.¹

INTRODUCTION

With the enlargement of the mining mill, in order to improve the life cycle of the mill liner, as the main wear parts of the mill, the mill liner is getting bigger and heavier. The heavy-duty lining makes it increasingly difficult to replace the liner with traditional non-professional tools such as manuals and winches. Moreover, the traditional way is very inefficient and takes a lot of labor. Because the working space is relatively narrow and dark, the safety of workers cannot be guaranteed effectively, and the labor intensity is high, which affects the occupational health of workers seriously. In the past ten years, with the enlargement of the application scope of the large mills, the weight of liners is generally over 1500kg. On the one hand, the working ability and safety cost of manual mode are restricted. On the other

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hand, the efficiency of production line is becoming more and more important in economic activities, so more and more enterprises use manipulators to replace lining board.

Industrial robots are widely used in nuclear energy, mining, logistics, palletizing and other fields. Manipulators are gradually replacing manual labor to carry, pack and support heavy and boring work. Many scholars and enterprises at home and abroad have made abundant research achievements in kinematics calibration, motion planning and control involved in the application of robots[1,2]. However, due to its non-linear, multi-variable, heavy load and other characteristics, the problems involved in the process of product development, technology application and so on are becoming increasingly prominent. More and more researchers are using the advanced technology in the fields of virtual prototype manufacturing, multi-body dynamics simulation, finite element analysis, and artificial intelligence and so on to solve the key technical problems in structural design, posture adjustment, trajectory planning, and accuracy control of the heavy machinery. Aiming at the characteristics of underwater manipulator, such as compact structure and high power density ratio, Luo Gaosheng and others, established two kinds of dynamic models of elbow joint of underwater hydraulic manipulator and verified that the double screw swing cylinder with axial force compensation has better transmission characteristics[3]. Chen Hongyue established rigid-flexible coupling dynamic model of airborne drilling manipulator based on finite element method and multi-body dynamics software to study the dynamic response of road header manipulator in the process of drilling operation, which provided basis for intelligent control research of the manipulator[4]. Yang Xiuqing and others have studied the key problems of virtual prototype modeling, kinematics and dynamics model analysis in the manufacture of heavy-duty handling manipulator, and designed the handling manipulator which can install, disassemble and transport the sealing plug of heavy nuclear fusion reactor weighing up to 45 tons[5]. Under the guidance of multi-body dynamics theory, Yang Yuwei et al. simulated and analyzed the trajectory optimization problem of a 3-DOF space heavy-duty manipulator by combining the linear iteration method with the system dynamics equation[6]. In view of the strong coupling and difficulty in solving the multi-body dynamic equations of the manipulator on the aluminum casting production line, Wang Guangzhi and others used ADAMS software to carry out kinematics modeling and multi-body dynamic simulation analysis of the key part of the arm of the manipulator[7].

In summary, in order to solve the problems of low operating efficiency, difficult production safety, and high labor costs in the working process of the mill, a large number of foreign mining enterprises equipped with professional manipulators to replace mill liner, which can improve the operation efficiency by 2-3 times effectively. The labor intensity of workers are reduced significantly, the safety of workers is guaranteed effectively, and the comprehensive benefits are obvious. However, China's demand for heavy-duty manipulators is mainly dependent on imports. The multi degree of freedom heavy manipulator which can meet the
replacement needs of large mine grinding liners is still blank. It has far-reaching theoretical value and broad application prospects to develop the virtual prototyping technology for self-propelled heavy-duty manipulators, analyze the structural characteristics of key components of heavy manipulators, explore the hydraulic servo control method of manipulators, and study the multi-actuator coordinated control technology under the condition of full-state perception of heavy manipulators.

**STRUCTURAL DESIGN OF HEAVY MANIPULATOR**

**Design of the Overall Plan**

The main function of heavy manipulator is to replace the manual to complete the installation of mill liners. Through the analysis of the process of replacing the mill liner and the study of the different shape and position of the mill liner, it is found that eight degrees of freedom are needed to complete the installation of the mill liner. There are 3 degrees of freedom on the arm (slewing, luffing, telescopic). There are 3 degrees of freedom on the wrist (swing, roll, lift). There are 2 auxiliary degrees of freedom (the advance and retreat of the boom, the opening and closing of the gripper). For the structural design of heavy manipulator, in order to make it suitable for industrial site requirements, the body of the heavy manipulator is divided into a car body, a forearm, a upper arm, a wrist and a fixture. Schematic diagram of heavy manipulator design is shown in Figure 1.

**Structural Design of the Wrist**

The wrist of heavy manipulator is the key part of adjusting posture. Due to the large weight of the workpiece and the limitation of the size of the mill mouth, the wrist must have a compact structure and can meet the needs of the position and posture change. Finally, we use a combination of hydraulic swing cylinder and hydraulic linear cylinder. The grabbing device and wrist device are highly integrated, and the bearing capacity is high, and the shape size is greatly reduced.

![Figure 1. Structural chart of the manipulator.](image-url)
Design of Liner Clamp

Since most of the mill liners are in the form of lugs, simple latch and ejector pin are used to clamp the mill liner. For the position change of the center of gravity of the workpiece in the process of adjusting the posture, the hydraulic cylinder with two handles is adopted. The hydraulic locking technology and the structural design of hydraulic cylinder and gripper ensure the stability of the workpiece during the posture adjustment process. The model of the wrist clamping liner is shown in Figure 2.

THE ESTABLISHMENT OF VIRTUAL PROTOTYPE

When working, the car body is fixed on the ground. The bottom of the arm is equipped with a rack, and the movement of the arm in the plane can be realized by the gear-rack drive. The base of the forearm is fixed at one end of the arm, and the base is a turntable. It can rotate the forearm 360 degrees in space. The forearm can achieve telescopic movement. The pitching motion of the forearm is realized by the variable amplitude cylinder. The wrist of the heavy manipulator has a universal
requirement for the installation of a large mill inner, with three rotational degrees of freedom. The horizontal swing of the wrist is realized by the swing cylinder 1. The rolling of the wrist is achieved by the swinging cylinder 2. The pitch motion of the wrist is achieved by the pitching cylinder. The construction of the model is based on the 3D software inventor, which is commonly used in mechanical design. The model created is shown in Figure 3.

**KINEMATIC ANALYSIS**

**Establishment of Mathematical Model**

A manipulator is a mechanism in which a series of links are connected in series by means of a hinge. It has several degrees of freedom and can be regarded as a space-open kinematic chain. It is a very complicated mechanical system. In order to establish the motion equation of manipulator, the link coordinate system of manipulator should be created according to the principle of D-H parameter method. As shown in Figure 4, X0Y0Z0 is the base coordinate system, and X7Y7Z7 is the end coordinate system.

After the link coordinate system is determined, the D-H parameters of each link can be determined, and the determined D-H parameters are as shown in Table 1.

![Figure 4. Manipulator coordinate system.](image)

The coordinate transformation matrix between two adjacent links can be obtained by the formula.

\[ T_i = \text{Rot}(z, \theta_{ii}) \cdot \text{Trans}(0,0,d_i) \cdot \text{Trans}(a_i,0,0) \cdot \text{Rot}(x, \alpha_i) \]  \hspace{1cm} (1)

By substituting D-H parameters into coordinate transformation matrix formulas of adjacent two connecting rods, T1, T2, T3, T4, T5, T6 and T7 can be obtained.
According to the transformation matrix formula of the end of the manipulator relative to the fixed coordinate system, the kinematics equation of the manipulator is obtained.

\[
^0T_7 = T_1 \cdot T_2 \cdot T_3 \cdot T_4 \cdot T_5 \cdot T_6 \cdot T_7 = \begin{bmatrix}
    n_x & o_x & a_x & p_x \\
n_y & o_y & a_y & p_y \\
n_z & o_z & a_z & p_z \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (2)

### TABLE I. ROBOT D-H PARAMATER TABLE.

| Connecting rod number | Joint variable | \(\theta_i\) | \(d_i\) | \(a_i\) | \(\alpha_i\) |
|-----------------------|----------------|-------------|--------|--------|--------|
| \(i=1\)              | \(d_1\)        | 0           | \(d_1\) | \(a_1\) | 0      |
| \(i=2\)              | \(\theta_2\)   | \(\theta_2\)| 0      | 0      | -90    |
| \(i=3\)              | \(\theta_3\)   | \(\theta_3\)| \(d_3\) | \(a_3\) | 0      |
| \(i=4\)              | \(d_4\)        | 0           | \(d_4\) | 0      | 90     |
| \(i=5\)              | \(\theta_5\)   | \(\theta_5\)| 0      | \(a_5\) | 0      |
| \(i=6\)              | \(\theta_6\)   | \(\theta_6\)| \(d_6\) | \(a_6\) | -90    |
| \(i=7\)              | \(\theta_7\)   | \(\theta_7\)| \(d_7\) | \(a_7\) | 90     |

### Kinematics Simulation

After simplifying the robot model established by inventor, it is saved as STP format, and then the model is imported into Recurdyn for simulation analysis. After the model is imported, the simulation environment needs to be set in Recurdyn. Firstly, the unit is set to MMKS combination, then the acceleration direction of gravity is set to -Z direction, the name of the parts is modified, and the material property of the model is defined as stell. Finally, according to the actual motion of the manipulator, constraints are added between the parts. After the constraint is added, a driving function is added to the driving part, and the manipulator can realize the given motion. In order to reduce the initial concussion in virtual prototyping, STEP function is used to drive.

At the end of the simulation, the displacement value of the manipulator's execution end is output, and the curve is drawn in the recurdyn, as shown in Figure 5. As can be seen from the figure, the Z value does not change for 0-20 s because the manipulator makes a rotary motion in the X-Y plane. But for 90-120S, the Y value does not change because the mechanical wrist is pitching in the X-Z plane.
Through simulation analysis, the graph can truly reflect the motion of the manipulator, and verify the correctness of the motion equation.

![Figure 5. Execution end displacement diagram.](image)

Motion Space

By simulation, when the joint of the manipulator takes the limit position, the range of motion space of the manipulator can be obtained, as shown in Figure 6. The range space provides a reference for manipulator operation.

![Figure 6. Range of motion space.](image)

CONCLUSIONS

In this paper, the virtual prototype technology is used to design the 3D modeling of the heavy-duty manipulator. The conclusions which are obtained by simulation are as follows:
1. A three-dimensional model of eight degrees of freedom heavy for automatic replacement of liner is established. The key mechanical structures such as clamping arms, wrist and the fixture of liner were designed.

2. The maximum workspace of the manipulator is determined by simulation.

3. By simulating the motion process of the manipulator model, the curve describing the dynamic rationality of displacement and time was obtained, which provides a reasonable basis for the structural design of the manipulator and path planning.

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