# Design and trajectory planning of 3+2 DOF manipulator for inspection robot

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## ABSTRACT

On the basis of the 3-DOF of the traditional track inspection robot manipulator, a mechanical arm with 3+2 DOF was designed by adding the telescopic and pawl rotational DOF, which expanded the working scene of the manipulator and met more inspection requirements. The improved D-H method was used to establish the kinematics equation of the manipulator. The 3+2 DOF manipulator was modeled by the Robotics Toolbox in Matlab, and the trajectory planning was carried out by quintic polynomial interpolation method. Then, the position model of the manipulator and the curves of joint Angle, angular velocity, angular acceleration and angular acceleration change rate with time of each joint of the manipulator can be obtained. The simulation results show that the joint trajectory of the designed 3+2 DOF manipulator is smooth and continuous without mutation, which can effectively suppress the vibration of the manipulator and achieve safe and stable work in the underground environment.

**Keywords:** Inspection robot, 3+2 DOF; DH parameters, trajectory planning

## 1. INTRODUCTION

With the development of mine intelligence, inspection robot is gradually applied in the inspection of underground coal mine. The inspection robot can carry out mobile inspection in the whole line from the head of the belt conveyor to the tail, continuously collect, store and transmit the image, sound, temperature, humidity and other data of the site, and judge whether the equipment has faults and the location of faults through the analysis of the field data[1,2]. In general, after the belt conveyor is arranged in the roadway, the remaining space is limited, and the track inspection robot also has blind field of vision caused by the fuselage shielding[3], which affects the monitoring efficiency. The mechanical arm has the characteristics of flexible movement and simple control, which has certain advantages in solving the blind area of inspection robot monitoring.

Many experts and scholars in the domestic and overseas have studied the scheme of carrying the mechanical arm on the inspection robot. The high-pressure chamber inspection robot designed by Shenyang Institute of Automation is equipped with 6-DOF mechanical arm on the mobile platform[4]. It has flexible operation and large scope, but high cost and complex control, so it is not suitable for inspection of coal mine belt conveyor; Southwest University of Science and Technology designed a planar mechanical arm mounted on a wheeled mobile platform for the track inspection robot in the power room, which has 3-DOF, such as lifting, swinging and end-effector rotation[5]. The structure is simple but not flexible enough.

The existing scheme has low applicability in underground coal mine and is difficult to ensure the reliability of monitoring. In this paper, based on the walking, swinging and clamping of the 3-DOF mechanical arm of the traditional inspection robot, a mechanical arm with 3+2 DOF was designed by adding the telescopic and pawl rotational DOF, which expanded the working scene of the manipulator and has more flexible structure. The trajectory planning was carried out by quintic polynomial interpolation method. Then, the position model of the manipulator and the curves of joint Angle, angular velocity, angular acceleration and angular acceleration change rate with time of each joint of the manipulator can be obtained. The simulation results show that the joint trajectory of the designed 3+2 DOF manipulator is smooth and continuous without mutation, which can effectively suppress the vibration of the manipulator and achieve safe and stable work in the underground environment[6-10].

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## 2. THE STRUCTURE DESIGN OF MECHANICAL ARM

### 2.1 The structure design principle of 3+2 DOF

The main application of the mechanical arm is the removal of abnormal faults, so some degrees of freedom can be designed as a mechanical disposable mechanism, and then the cyclic operation function of the mechanical arm can be maintained through cyclic triggering. Figure 1 shows the structure of the 3+2 DOF mechanical arm of the inspection robot[11].

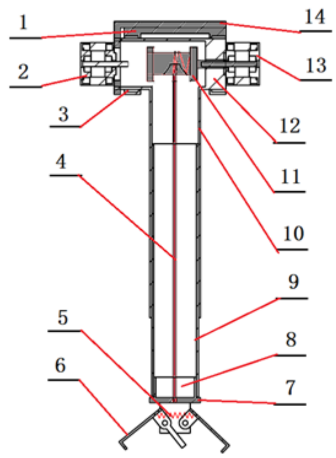


Figure 1. Structure of the 3+2 DOF mechanical arm of the inspection robot.

Note: (1): Mechanical arm base; (2): Oscillating DOF explosion insulation motor; (3): Sliding bearing; (4): Telescopic wire rope; (5): Actuator binary spring; (6): Actuator claw; (7): Actuator frame; (8): Actuator turntable; (9): Telescopic manipulator; (10): Telescopic manipulator pipe; (11): Telescopic wire rope regulating wheel; (12): Swing DOF frame; (13): Telescopic motor; (14): Inspection robot hoisting platform.

The mechanical arm is hoisted below the inspection robot. When the inspection robot works, the power system provides power for the walking wheel to ensure the normal movement of the inspection robot on the track, so that the mechanical arm can obtain the freedom of horizontal walking; Motor 2 drives the rotary bearing of the mechanical arm to rotate, so that the mechanical arm can obtain the degree of freedom of swinging. Motor 13 shrinks the telescopic pipe by tightening the wire rope, so that the mechanical arm can obtain the degree of freedom of telescopic. The traditional manipulator with three DOF has some limitations in practical engineering application, and it is difficult to ensure the reliability of monitoring.

The 3+2 degree of freedom mechanical arm proposed in this paper forms a disposable application claw hand with the help of a mechanical binary switch at the end of the mechanical arm, as the actuator of the mechanical arm, the binary switch can rely on a fixed dial block to trigger the cycle and stay in any state. In practical application, the mechanical arm can grasp the object by contacting the object, triggering the grasping switch, tightening the claw hand, and realizing the object grasping. Through manual remote control operation, the claw hand is opened to realize the release of the object, so as to realize the fourth degree of freedom of the mechanical arm. When the captured object is not in the plane Angle state, the actuator turntable can change the direction of the axial rotation of the actuator, adjust the Angle of the mechanical arm to grab the object, so as to form the fifth degree of freedom of the manipulator.

### 2.2 Design of rotational joint

The inspection robot is installed above the belt conveyor, in the plane of the inspection robot's moving direction, the mechanical arm swings back and forth and its length can be telescopic, so as to form the working space of the mechanical arm along the inspection robot's moving track on the belt machine. As shown in Figure 2, motor 1 is the driving device for the swing of the mechanical arm, which is fixed on base 2, base 9 of the regulating wheel can rotate freely and is fixedly connected to the output shaft of motor 1. When motor 1 rotates, it drives the pipe 3 to swing synchronously, so as to realize the rotary joint function of the mechanical arm.

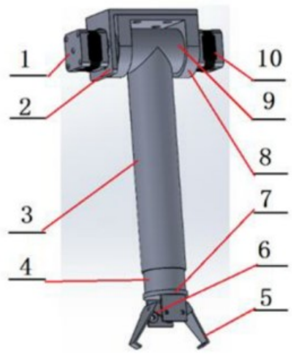


Figure 2. Design of rotation joint of mechanical arm for inspection robot.

Note: (1): Flameproof motor for swing degree DOF; (2): Inspection robot hoisting platform; (3): Telescopic manipulator pipe; (4): Telescopic manipulator; (5): Actuator claw; (6): Actuator binary spring; (7): Actuator turntable; (8): Mechanical arm base; (9): Base of telescopic wire rope regulating wheel; (10): Telescopic DOF motor.

### 2.3 Design of telescopic joint

The telescopic pipe of the manipulator is the second DOF of the manipulator. The design structure diagram of the telescopic joint is shown in Figure 3, the left part is the extended state of the manipulator and the right part is the retracted state.

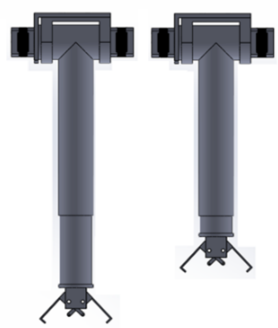

Figure 2. Design of expansion joint drive mechanism of mechanical arm for inspection robot.

When the mechanical arm needs to retract operation, telescopic motor drives the telescopic rope wheel rotation, the wire rope on the regulating wheel shrinks synchronously, to drive the mechanical arm pipe back movement, mechanical arm needs to stretch out, telescopic motor drive wheel reverse rotation, wire rope, wire rope has certain rigidity, can withstand the tensile strength of the casing back, realize mechanical arm stretched out.

The maximum expansion length of the mechanical arm can be determined by the distance between the track of the inspection robot and the surface of the belt conveyor. Multiple pipe structures such as double pipe and three pipe can be used to meet the actual monitoring distance requirements.

### 2.4 Design pf actuator

The actuator is an important part of the inspection robot's mechanical arm. As a part of grasping and placing objects, the actuator has an important influence on the completion of system commands. The traditional mechanical arm generally adopts the way of adding additional motor to control the actuator claw, and the mechanical and electrical structure is complicated. The underground space of coal mine is narrow, and the electrical equipment needs to meet the explosion-proof requirements. Reducing the complexity of mechanical arm is of great significance to improve the monitoring efficiency of inspection robot.

The actuator claw of the manipulator designed in this paper adopts mechanical binary switch mechanism. Its structure is shown in Figure 4. The potential energy balance of spring is used to control the actuator claw, with simple structure and no additional motor to provide power. When the mechanical arm needs to grab the object, the actuator is adjusted to open mode, the spring will push the claw, while the telescopic pipe will push the claw to the object, when the object touches the trigger roller, the claw will automatically merge and grab the object. When the object moves to a predetermined position, the manipulator actuator will push into a specific trigger block, and the claw hands loosen the object, so as to complete the system's object movement command.

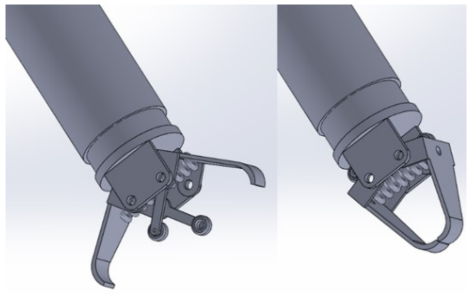

Figure 3. Design of binary claw hand mechanism of mechanical arm actuator.

In order to improve the spatial flexibility of the manipulator, the base of the manipulator in this paper is a rotatable turntable structure, and its rotation is indirectly controlled by the swing motor and the telescopic motor, which increases the DOF of rotation along the pipe direction of the manipulator.

**2.5 Idle mechanism**

In the normal inspection process, the mechanical arm is in the switching state of working mode and idle mode, and the working environment of underground coal mine is complicated, in order to reduce the failure rate of the mechanical arm, the idle trigger mechanism is designed to protect the mechanical arm in idle mode and improve the working efficiency of the mechanical arm. The triggering mechanism is composed of a right Angle hook and a diagonal hook below, as shown in Figure 5, the left figure shows the working state of the mechanical arm, and the right figure shows the state of the mechanical arm placed in the idle mechanism after recovery. When the mechanical arm is idle, first switch the telescopic pipe of the mechanical arm to the shortest state, then operate the mechanical arm to run at a parallel Angle with the lower end of the inspection robot, and finally control the mechanical arm to extend a short section, place the actuator part in the idle mechanism, and trigger the right Angle hook above the mechanism to store the mechanical arm, the diagonal hook below is used to change the attitude of the actuator claw hand relative to the axis of the manipulator.

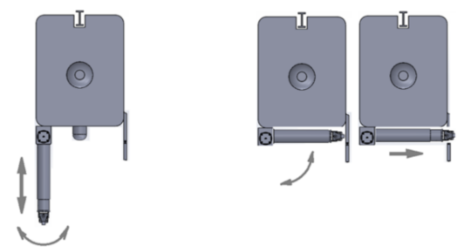

Figure 4. Idle and working state of mechanical arm.

## 3. STUDY ON WORKING MECHANISM OF OPTIMIZED MANIPULATOR

**3.1 The working space of mechanical arm**

The mechanical arm designed in this paper acts on the inspection robot of the belt conveyor. The inspection robot adopts track structure and is located above the belt conveyor. The working state of the belt conveyor is monitored by the camera system. When abnormal state is found, the mechanical arm can handle the fault.

In order to increase the working space of the mechanical arm and improve its fault handling ability, the telescopic length and swing Angle of the mechanical arm need to touch the cross section of the belt conveyor.

Suppose that the installation height of the inspection robot is H and the width of the belt conveyor is B, then the shortest length L of the mechanical arm can be obtained:

$$L = \sqrt{B^2 + H^2} \tag{1}$$

The mechanical arm is telescopic pipe structure. The specific length of the mechanical arm can be determined comprehensively according to the installation position of the inspection robot and the actual spatial distribution of the belt conveyor. The manipulator designed in this paper is a double pipe structure, which can meet the working distance requirements of the manipulator.

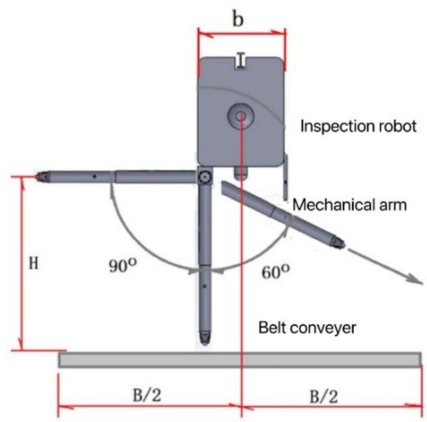


Figure 5. Mechanical arm workspace.

The working space of the mechanical arm is shown in Figure 6. Design mechanical arm swing to the left in 90°, considering the limited spare institutions, the design of mechanical arm to the right in 60°, so the actual mechanical arm work space for a 150° sector, as the inspection robot run along the track, the sector working space form orbit with the inspection robot along the track of arc column work space, It can meet the monitoring requirements of belt conveyor.

### 3.2 Research on kinematics of mechanical arm

The improved DH coordinate system method is used to mark the inspection robot manipulator. In the improved DH method, the transformation sequence of coordinate system $i$-1 to coordinate system $i$ and the definition of DH parameters are as follows:

(1) Twist angle of connecting rod $\alpha_{i-1}$: The $Z_{i-1}$ axis of frame $i$-1 are rotated by Angle $\alpha_{i-1}$ about the $X_{i-1}$ axis so that the $Z_{i-1}$ axis is parallel to the $Z_i$ axis.

(2) Length of connecting rod $a_{i-1}$: Frame $i$-1 is shifted along the $X_{i-1}$ axis by distance $a_{i-1}$, so that the $Z_{i-1}$ and $Z_i$ axes are collinear.

(3) Angle of joint $\theta_i$: The $X_{i-1}$ axis of frame $i$-1 are rotated by an Angle $\theta_i$ about the $Z_i$ axis so that the $X_{i-1}$ and $X_i$ axes are parallel to each other.

(4) Deflection distance of connecting rod $b_i$: Frame $i$-1 is shifted by distance $b_i$ along the $Z_i$ axis so that the $X_{i-1}$ axis rejoins the $X_i$ axis.

As shown in Figure 7, the labeled coordinate system $X_1Y_1Z_1$ is the coordinate system of the degree of freedom of swinging, and the labeled coordinate system $X_0Y_0Z_0$ is set as the reference coordinate system. When the initial swinging Angle is zero, the coordinate system $X_1Y_1Z_1$ and the coordinate system $X_0Y_0Z_0$ completely coincide; The labeled coordinate system $X_2Y_2Z_2$ is the coordinate system with telescopic DOF; The labeled coordinate system $X_3Y_3Z_3$ is the tool coordinate system of the claw, and the tool coordinate system $X_3Y_3Z_3$ should be determined according to the actual working conditions. According to the improved DH coordinate system, the DH parameter table is shown in Table 1.

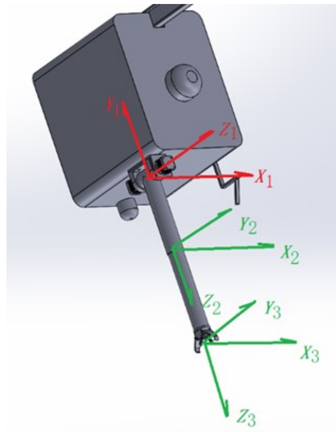


Figure 7. DH parameters and coordinate system of mechanical arm.

Table 1. DH parameters of mechanical arm coordinate system.

| $i$ | $\alpha_{i-1}$ | $a_{i-1}$ | $b_i$ | $\theta_i$ |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | $\theta_1$ |
| 2 | 90° | 0 | $b_2$ | 0 |

Thus, the transformation matrix of each link is calculated and the kinematic equation of the manipulator is established. The transformation matrix between the two links can be expressed by equation (2):

$$ {}^{i-1}_{\ \ \ i}\boldsymbol{T} = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} b_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} b_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

The transformation matrix of each link can be obtained by substituting the parameters of each link:

$$ {}^0_1\boldsymbol{T} = \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

$$ {}^1_2\boldsymbol{T} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & -b_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4} $$

By multiplying the above matrices continuously, the forward kinematics equation of the manipulator can be obtained:

$$ {}^0_2\boldsymbol{T} = \begin{bmatrix} c\theta_1 & 0 & s\theta_1 & s\theta_1 b_2 \\ s\theta_1 & 0 & -c\theta_1 & -c\theta_1 b_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5} $$

Equation (5) describes the position and direction state of the claw of the mechanical arm relative to the inspection robot and its box, where the swinging DOF $\theta_1$ is the direction variable of the mechanical arm, and the stretching DOF $b_2$ is the length variable of the mechanical arm.

In the actual calculation, the telescopic amount of the manipulator $b_2 = c + x$, where c is the minimum value of the telescopic arm, which is the length of the first connecting rod; $x(0 \sim x_{max})$ is the change of the telescopic manipulator.

The swinging Angle $\theta_1$ of the mechanical arm and the telescopic arm length $b_2$ are related to the installation height of the inspection robot. The installation height of the inspection robot is H, and the horizontal displacement of the mechanical arm is $X_1$, then the swinging Angle $\theta_1$ of the mechanical arm and the telescopic arm length $b_2$ are:

$$\theta_1 = \operatorname{arctg}\left(\frac{X_1}{H}\right) \tag{6}$$

$$b_2 = \frac{H}{\sin}(\theta_1) \tag{7}$$

Thus, it can be concluded that the relationship between the forward kinematics equation of the manipulator and its height is:

$$ {}_{2}^{0}T = \begin{bmatrix} \mathrm{c}\cdot\operatorname{arctg}(X_1/H) & 0 & \mathrm{s}\cdot\operatorname{arctg}(X_1/H) & \mathrm{s}\cdot\operatorname{arctg}(X_1/H)\cdot\frac{H}{sins\cdot\operatorname{arctg}(X_1/H)} \\ \mathrm{s}\cdot\operatorname{arctg}(X_1/H) & 0 & -\mathrm{c}\cdot\operatorname{arctg}(X_1/H) & -\mathrm{c}\cdot\operatorname{arctg}(X_1/H)\cdot\frac{H}{sins\cdot\operatorname{arctg}(X_1/H)} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

**3.3 Trajectory planning of mechanical arm**

During inspection, the mechanical arm of the inspection robot needs to execute the command of the control system and complete the specified action tasks, thus forming the motion trajectory. Trajectory planning is divided into joint space planning and Cartesian space trajectory planning. The joint space trajectory planning takes each joint Angle as the planning object and calculates the joint Angle, angular velocity and angular acceleration. Cartesian space trajectory planning takes the end pose as the planning object and usually describes key points in the form of pose coordinates.

According to the working characteristics of the inspection robot mechanical arm for coal mine, joint space planning is selected. The main steps are as follows: (1) The start and end points of a path are determined and multiple sample points are selected; (2) The joint variables of each sample point are calculated based on the inverse kinematics solution; (3) The most suitable interpolation function for curve fitting is selected according to the constraints. The rotational joint space model of the inspection robot's 3+2 DOF mechanical arm is shown in Figure 8.

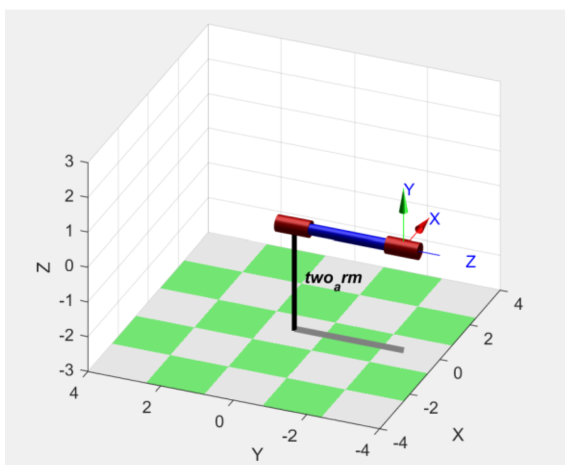


Figure 8. Robotic arm model.

In this paper, the trajectory function of Jtraj() of Robotic Toolbox was called. $H_1$ was set as the initial movement position of the mechanical arm, $H_2$ was set as the end position of the movement of the mechanical arm. $H_1$ was set as the starting point of trajectory planning, $H_2$ was set as the end point of trajectory planning, and the speed and acceleration of $H_1$ and $H_2$ were specified as 0. 50 sampling points were set with a time interval of 0.1s, and the path planning was carried out by using the 5 degree polynomial interpolation method.

Trajectory planning simulation can visually display the motion parameters related to the joints of the mechanical arm. Figure 9 lists the curves of the joint Angle, angular velocity, angular acceleration and angular acceleration change rate with time of the mechanical arm.

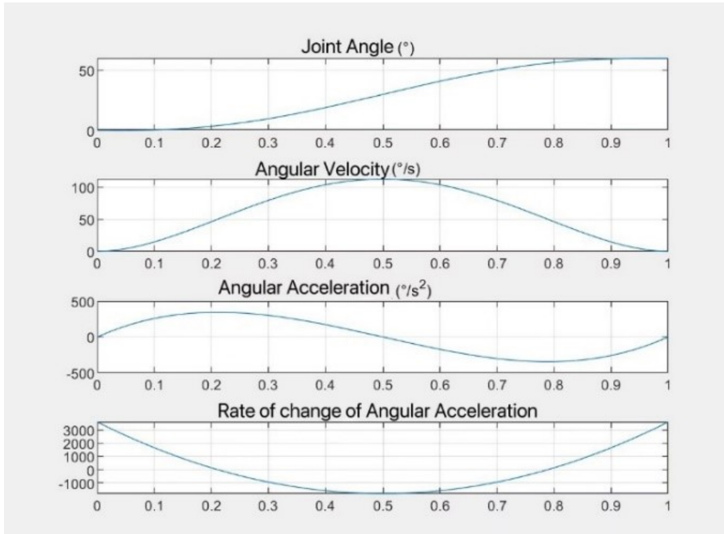


Figure 9. The relative motion parameters of the actuator transform with time.

It can be seen from the figure that there is no sudden change in these parameters over time and they are always smooth and continuous, indicating that the mechanical arm has a small impact force in the movement process and can run stably to meet the monitoring requirements of belt conveyor.

## 4. CONCLUSION

Based on the working environment and requirements of the orbiting inspection robot, this paper proposes a 3+2 DOF mechanical arm, analyzes the structural design principle, and uses the improved D-H coordinate system to carry out kinematic analysis. With the Robotics Toolbox in Matlab, the 3+2 DOF mechanical arm was modeled, and the path planning simulation was carried out by using the polynomial interpolation method to obtain the position model of the mechanical arm and the curve of the joint Angle, angular velocity, angular acceleration and the change rate of angular acceleration of each joint of the mechanical arm with time change.

Through the analysis of simulation results, it can be seen that the designed 3+2 DOF mechanical can meet the inspection requirements of rail type inspection robot, which is of great significance to improve the monitoring efficiency of belt conveyor.

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