Application of Environment-perception Intelligent Control Technology in the Inspection Robot of Coal Conveyance Corridor in Thermal Power Plant

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Abstract. In thermal power generation, coal transport is an important link in the production process, and corridor is the key space of a relatively closed environment. It is fatal to ensure the accurate transmission of coal, no coal leakage and scattering, timely maintenance of the belt with crack, keep the temperature, humidity, and dust concentration within the threshold. Traditionally, manual inspection is mostly used, which is difficult to meet the requirements of modern thermal coal transportation inspection due to large amount of labor and high intensity of labor. According to the performance requirements, operating mode, and function in space orbit, an inspection robot is proposed, replacing the manual labor, by use of machine vision, sensor technology, logic judgment algorithm, and combined with kinematics and dynamics analysis. The modular design of hanging rail type mobile robot system is carried out in layout with closed "O" type suspension orbit in the inspection area, realizing the robot's inspection and monitoring, warning and prompting, for the safety and smoothness of the coal supply.

1. Introduction
In thermal power generation, coal transport is an important part of the production process. In addition to ensuring the normal production time for coal supply, it is more important to ensure the accurate transmission of coal when it passes through the corridor, no coal leakage and coal spraying, and no excess temperature and humidity. In the past, most of them used manual inspection, large amount of labor, labor intensity and so on, it is difficult to meet the requirements of modern thermal coal transport inspection.

The development direction of modern patrol inspection is mainly to design and adopt patrol robot and has made some progress. Fan, Jianbin et al. Designed and developed a routine inspection robot system for GIL pipe gallery[1]. Shi, Congling et al. research on Laser Positioning System of a Underground Inspection Robot Based on Signal Reflection Principle[2]. Xu, Wei et al. [3] designed the inspection robot based on substation with modularization to meet the different substation requirements. Alhassan, Ahmad Bala et al. [4] investigated the aerodynamic stability of a lightweight dual-arm power transmission line inspection robot under the influence of wind. Teng, Yun et al. [5] proposed an application of intelligent inspection robot system in Sutong GIL Utility Tunnel Project. Wu, Gongping et al. [6] presented an auto-docking charging control method for the inspection robot. Dehne, Andre et al. [7] put forward a so-called MARWIN: A mobile autonomous robot for maintenance and inspection in a 4d environment. Li, Peng et al. [8] presented an active screw-driven
in-pipe robot for inspection. Kim, Sanghyun et al. [9] put forward an analysis of industrial accidents causing through jamming or crushing accidental deaths in the manufacturing industry in South Korea: Focus on non-routine work on machinery. Jalal, Muhammad Fairuz Abdul et al. [10] designed and developed of robotic system for visual inspection of boiler tube inner surface. In this study, the space orbit robot is intended to replace the human inspector, and by using machine vision, sensing technology and logic judgment algorithm, the determination and prediction of the working status of the conveyor belt will be done to check whether there is coal leakage, or a crack in the conveyor, or some damage on the reels, so as to ensure the safety and smoothness of coal supply.

2. Operating Condition Requirements and Principles
The internal environment of the coal transportation corridor is relatively harsh, with a lot of dust and combustible gas. If the inspection system is fixed in a position through traditional cameras and sensors, certain monitoring blind spots will inevitably be there. In order to reduce the labor intensity and improve the overall inspection efficiency, intelligent mobile robot is proposed with the following functions to replace manual inspection:

(1) Image recognition: Use the HD camera mounted on the mobile robot body to monitor and identify belt deviation, foreign bodies on the coal conveying line, belt tearing, coal plugging, coal leakage, fire hazard (smoke, fire), fire water leakage, etc., and judge each fault point by combining with the visual system.

(2) Infrared thermal imaging: The infrared thermal image mounted on the mobile robot can monitor and identify the over temperature alarm of the end cover of each drum spindle, the cable tray cable, the reducer and the motor.

(3) Voice recognition: The noise analyzer mounted on the mobile robot is used to monitor and identify the running sound of belt idler and drum (driving drum, driven drum, reversing drum, and surface increasing drum), and the fault is judged by combining with the background software system.

(3) Coal dust concentration detection: during the coal conveying operation, coal ash will be heaver in the corridor, deteriorating working environment and raising the probability of damage and accidence. So some several requirements and solutions must be taken.

3. Design of Inspection and Monitoring Module

3.1. Overall Design of Patrol Inspection
The overall scheme is the rail-mounted mobile robot. According to the requirements and functions of the working conditions, the robot can be divided into inspection and monitoring module, alarm and prompt module, cycle walking module and control module. In order to realize the continuous and efficient operation of the tour, the o-type closed suspension track is set in the patrol area. The robot can extract effective signals from machine vision, and realize straight and turn smoothly with the application and power transmission system. The general service condition of the robot is at limited close space with the ramp angle of coal conveying corridor of 12.6°, dust waft in the air, and the dust accumulation on the track, that may reduce the friction coefficient between the driving wheel and the track.
3.2. Self-cleaning of the Robot and Track Cleaning
The robot works in the dust waft environment and the dust, if in some concentration or accumulation in bulk, might have shaded the sensor on the body, or is easy to cause the drive wheels to skid in orbit. So the robot ontology is required to clear all the time, so might the track. Multiple fans on top of the robot, aiming at cleaning of the front of the robot movement track waft, will blow away the dust. A number of nozzles with high-pressure gas designed and installed in stages of the routine inspection region, called cleaning station, and after the robot enters each station, high-pressure gas is ejected and dust accumulated on the robot body is blown away.

4. Robot Guidance and Turning Operation
The robot is equipped with a steering mechanism of driving module and a steering mechanism of driven module, both of which can rotate around its axis. Each steering mechanism is with four guide wheels, and the outer profile of the stuck track is used for the robot's forward guidance. When the robot enters the curved track, the two steering mechanisms rotate automatically to adapt to the arc, as shown in figure 2.

4.1 Calculation and Determination of the Minimum Turning Radius
If the basic structural parameters of the robot have been settled, the following equation may be used for calculation of the minimum turning radius

\[ r_{\text{max}} = \lambda \left\{ \left( \frac{L}{\sin \theta_{\text{max}}} \right)^2 + K^2 + \frac{2KL}{\tan \theta_{\text{max}}} + w \right\} \]  

where 
- \( L \) — wheel base
- \( K \) — the distance between the intersection points of the center lines of two axial kingpins with respect to the ground
- \( \theta_{\text{max}} \) — maximum angle of internal steering wheel
- \( w \) — the steering wheel arm length

\[ \lambda \] — modifier coefficient, feasible value of it may be 1.05.

4.2 Steering Guidance Algorithm Based on Sensing Technology and Machine Vision
In the straight line running stage, when the conveyor belt does not appear deviating and other abnormal conditions, the two guide wheels of the robot move in a straight line on the suspension beam, each guide wheel is installed with pressure sensors on the guide wheel shafts, and the pressure difference, see figure 3. \( \Delta P = P_2 - P_1 \), fluctuates slightly around 0 when going straight. The deflection Angle also varies over a very small range. At this point, the control system determines that the robot should go straight along the current suspension beam track. When the robot enters the curved stage of the beam, it needs make a turn. CCD3 and CCD4 are used to judge the curve, providing the robot with the appropriate turning angle and make the robot enter the curve properly. The specific algorithm is as follows: The pressure difference on the guide wheels increase with the entry of the curved track. Considering the influence of accidental factors, a pressure difference threshold, \( \Delta P_f \), is then set up, we have

\[ \Delta P = P_2 - P_1 \geq \Delta P_f \]  

When the robot enters the curved orbit, the driving wheel and the guide wheel are supposed to adjust to adapt the influence of the curvature, and the steering angle is

\[ \alpha = \arctan \left( \frac{kn}{km} \right) \]  

where
- \( kn \) — the distance between CCD3 and CCD4
- \( km \) — detecting depth difference between CCD3 and CCD4

After further detection and calculation, its rotation angle is basically stabilized at
\[ \alpha' = \arctan\left( \frac{k'n'}{k'm'} \right) \]  

(4)

When the robot gradually drives out of the curved orbit, the adjustment angle becomes smaller and finally returns to zero, indicating that the robot enters the straight stage.

5. Design of Abnormal, Fault and Alarm Modules

5.1 Deviation of Transmission Belt

Due to uneven load bearing, wear of the reel or other factors, the rubber belt may run away with deviation from the ideal direction, as shown in Figure 3. At this time, the lateral position change of belt edge is measured at a certain interval, and the deflection angle \( \beta \), is calculated with Equation (5)

\[ \beta_i = \arctan\left( \frac{b_{ci}}{a_{bi}} \right) \]  

(5)

If the conveyor belt runs normally at the speed of \( v_C \), and the patrol robot works routinely at the speed of \( v_r \), then we have

\[ a_i b_i = (v_C - v_r) n_i \]

where, \( t_i \) —— time interval for measuring the information of the off-track of the conveyor belt edge

\( b_{ci} \) —— lateral position difference of the conveyor belt edge information is inspected within the time interval \( t_i \), which is the difference between the two measured values of the lateral positions.

Similarly, \( \beta_i \) is also compared with the set threshold \( \beta_{\text{threshold}} \) to determine whether the conveyor belt needs to be adjusted or repaired.

5.2 Conveyor Belt Reel Anomaly Discrimination Based on State Point Cloud and Norm

CCD1 is used for accompanying inspection of the reel. First create the point cloud of the normal reel state, and construct a so-called calibrated standard spectrum, \( F_{\text{standard}} \), and store it into the database. During patrol inspection, the actual state spectrum of each reel, \( F_{\text{instant}} \), is compared with the normal reel spectrum, and the norm of the two is compared with Formula (6).

\[ \Delta F = \left| F_{\text{standard}} - F_{\text{instant}} \right| \leq \delta \]  

(6)

The point cloud spectrum of the normal reel state points may be expressed in terms of a \( m \times n \) matrix

\[
F_{\text{standard}} = \begin{bmatrix}
    f_{11} & f_{12} & \cdots & f_{1m-1} & f_{1m} \\
    f_{21} & f_{22} & \cdots & f_{2m-1} & f_{2m} \\
    \vdots & \vdots & \ddots & \vdots & \vdots \\
    f_{n1} & f_{n2} & \cdots & f_{nm-1} & f_{nm}
\end{bmatrix}
\]  

(7)

Similarly, the actual state spectrum of the measured reel has a matrix expression of this kind.

When the maximum difference between the two corresponding elements is within the normal range, that is
\[ D_{\text{max}} = \max_{0 \leq i \leq n; 0 \leq j \leq n} \left\{ |f_{ij} - f_{ij_{\text{std}}}| \leq \delta \right\} \quad (8) \]

then the state of the reel is normal; otherwise, there is a problem with it and an alarm signal will be sent for the repair or replace of reel.

5.3 Transmission Belt Fracture and Coal Powder Leakage

CCD2 is used to inspect rubber with no tearing and coal leakage, as shown in Figure 4. Under normal situation, there should be no coal powder leakage, and no coal powder accumulation. If there is coal flow in the air or coal accumulation on the ground, it can be determined that the conveyor rubber belt has crack damage and needs to be stopped for maintenance.

5.4 Dust Concentration Measurement, Dust Removal and Self-cleaning

In the corridor space, with the start and continuous operation of coal powder transported by the transmission belt, the dust dispersed in the air increases in quantity and concentration. After a certain period of coal conveying, the dust concentration is stable at a certain value, as shown in Figure 5. Excessive dust concentration will bring a series of adverse effects and even harm, so it must be restrained. An online dust sensor combined with Zigbee information interaction technology is adopted to measure and prompt PM2.5 or larger particulate dust in real time. If the dust concentration of robot working environment exceeds some value, it is easier to cause the drive wheels to skid in orbit, and may even interfere the sensors and CCDs. Therefore, cleaning of the duct is desperately necessary, and multiple fans on top of the robot are set to blow away the dust.

6. Conclusion

Based on the system engineering principle, a routine inspection robot system was proposed and designed with kinematic and dynamic analysis, and intelligent control, which runs along "O" type closed suspension track in the inspection area of the coal transmission corridor, for inspection and monitoring, alarm, and prompting. The modular design method was adopted to design four functional modules, namely inspection, alarm and prompt, circular walking and intelligent control, with compact, flexibility and reliability. Using machine vision, sensing, and smart algorithms to judge the working state of transmission belt, coal leaking/accumulation and guide robot to go straightly and in turning, totally replacing the inspector.

Anomaly discrimination of conveyor reel was determined based on state point cloud and norm. The normal reel point cloud was constructed and calibrated into the standard spectrum, \( F_{\text{std}} \), and stored in the database while the actual state spectrum of each reel, \( F_{\text{inst}} \), in a similar pattern was compared with the normal spectrum in terms of norm of the two, during the patrol. The "distance" between the two spectrums was calculated as the criterion. Once the calculated distance reached or exceeded the permitted value, an alarm was given for check and repair.

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