Research on an intelligent electric inspection robot

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Abstract. Due to the bad environment of electric power inspection, it is easy to cause physical injury to the inspectors. Besides, the heavy workload of inspection is easy to cause the omission of the wireman that leading to major accidents. In order to avoid the mistakes in the process of electric inspection, an intelligent robot for independent inspection instead of manual operation is proposed in this paper. Firstly, the overall configuration of the robot is designed, a four-wheel active driving mobile mechanism is adopted and the dual parallel camera with three degrees of freedom is carried to inspect the faults existing in the power equipment. Secondly, based on the nonholonomic constraints, the kinematics analysis of the robot is carried out, and the variation laws of the velocity and angular velocity are obtained. In addition, based on the theory of finite element analysis, the modal analysis of the key parts of the robot is carried out to avoid resonance when working to affect the inspection accuracy. Finally, the motion process of the robot in various environments is simulated to verify the correctness of the robot kinematics model and the rationality of the structure design. According to the simulation results, the robot can run stably in typical environments.

1. Introduction

With the rapid development of the State Grid, the scale of substations is increasing day by day, and the demand for power inspection is gradually increasing [1]. The traditional method is manual inspection which is not only inefficient but also threatens to the safety of electrical workers. It leaves inspectors physically and mentally exhausted which affects the quality of monitoring and poses a danger when they are working in a high-intensity environment for a long time [2]. Besides, the ability of the staff is uneven, will also affect the quality of inspection, leading to major accidents. In a word, the traditional method is unable to meet the needs of substation inspection anymore. Therefore, scholars put forward the intelligent inspection robot replaced human to test the power equipment, which can work efficiently all day and improve the safety, reliability and stability of the substation [3]. Tokyo Electric Power Company proposed a high-voltage transmission line inspection robot, using the form of multi-wheel combination to cross the obstacles on the wire with 8 cameras, can detect the condition of the circuit in various directions and eliminate the safety risks of the circuit [4]. In Canada, a LINESCOUT high-voltage inspection robot designed by Hydroelectric Station Quebec, is equipped with a modular robotic arm which can solve some simple equipment problems [5-8]. The electric inspection robot developed by Huazhong University of Science and Technology adopts a wheeled chassis. The front two wheels are universal wheels, and the rear two wheels are large-diameter driving wheels, which can realize the robot's omni-directional movement [3]. The track-type inspection robot developed by Shenyang Institute of Automation can conduct inspection along a specific track and has been deployed in State Grid Anshan Power Company, which can effectively reduce the pressure of the staff [9-11].
In recent years, power inspection robot technology has been developed rapidly, but there are still many problems. Firstly, most robots need to travel along a fixed trajectory and cannot move in all directions. Secondly, mobile robot adopts a single fixed camera, which is not flexible enough. To solve these problems, an autonomous electric inspection robot is designed in this paper. The robot which can move in all directions with wheeled mobile site and monitor without any dead Angle with a high-definition camera and an infrared camera can effectively improve the correctness of electric power inspection.

2. Design of Robot’s Structure
Restricted by the surrounding environment, the electric power inspection robot needs to meet the following conditions:
(1) The size of the robot should be as small as possible because of the compact space between the electrical equipment. Besides, the robot should also be considered portable, so the quality should be as light as possible.
(2) Must have a certain barrier, shock absorber ability.
(3) It is necessary to realize high-definition imaging in both X-Y directions, video the target in real time and record the scene without dead Angle.
(4) Considering the high motion precision of the robot, brushless DC motor is needed to drive the robot.

According to the above requirements, the robot system is shown in Figure 1, including: chassis, driving wheel, brushless motor, cradle head, camera, battery and so on. The weight of this robot is 20kg, the rated load is 10kg, the climbing Angle is 35°, the obstacle crossing ability is 50mm, and the overall size is 860mm*600mm*700mm. The robot chassis is made of carbon fibre, which is used to support other auxiliary parts directly or indirectly. Brushless motor is used to drive the driving wheel to realize the robot forward, turn, acceleration and deceleration. The camera is mounted on the gimlet, which can shoot the electric equipment in all directions without dead Angle. As the power supply system of the whole robot, the battery can work continuously for 6 hours.

3. Kinematics analysis of robot
In the kinematics analysis of mobile robot, the research object is usually the chassis. In this paper, the simplified car body model is four-wheel bar structure, as shown in Figure 2, and assume the following conditions:
(1) In the process of robot movement, all the rods are rigid bodies and do not deform.
(2) When the four rollers contact the ground, they are all in the same plane.
(3) There is no sliding between the wheel and the wall.
Figure 2. Motion diagram of robot

In the motion diagram shown in Figure 2, where L is the middle distance between the two wheels, R is the radius of the wheel, XOY is the fixed coordinate system, the motion attitude of the robot is represented by \((x, y, \theta)\), the forward speed is represented by \(v\), and the rotational speed is represented by \(\omega\). The constraint conditions of the robot are as follows:

\[
x \cos \theta - y \sin \theta = 0
\]  
(1)

According to the geometric relationship of the robot, Equation (1) can be transformed into:

\[
\begin{align*}
x' &= v \cos \theta \\
y' &= v \sin \theta \\
\theta' &= \omega
\end{align*}
\]  
(2)

According to the motion law of the robot, its linear velocity and angular velocity can be known as:

\[
\begin{align*}
v &= \frac{r(w_L + w_R)}{2} \\
w &= \frac{r(w_L - w_R)}{2}
\end{align*}
\]  
(3)

Simultaneous Equations (2) and (3):

\[
\begin{bmatrix}
x' \\
y' \\
\theta'
\end{bmatrix} = \begin{bmatrix} r \cos \theta & \frac{r \cos \theta}{2} \\
\frac{r \sin \theta}{2} & \frac{r \sin \theta}{2} \\
\frac{r}{L} & -\frac{r}{L}
\end{bmatrix} \begin{bmatrix} w_L \\
w_R
\end{bmatrix}
\]  
(4)

By integrating both sides of Equation (4), the forward kinematics of the robot can be obtained. The function of position and pose changing with time is shown as follows:

\[
\begin{align*}
x(t) &= \frac{r}{2} \int_0^t (w_L(t) + w_R(t))(\cos \theta(t)) \, dt \\
y(t) &= \frac{r}{2} \int_0^t (w_L(t) + w_R(t))(\sin \theta(t)) \, dt \\
\theta(t) &= \frac{L}{r} \int_0^t (w_L(t) - w_R(t)) \, dt
\end{align*}
\]  
(5)

In order to ensure the stability of the robot in the inspection process and the real-time performance of image acquisition, the robot's speed is set to be uniform, and the initial speed is \(\omega_0\). Formula (5) can be simplified as:

\[
\begin{align*}
x(t) &= \omega_0 r \sin \theta_0 + x_0 \\
y(t) &= -\omega_0 r \cos \theta_0 + y_0 \\
\theta(t) &= 0
\end{align*}
\]  
(6)

After transformation, we can get:

\[
\frac{y(t) - y_0}{x(t) - x_0} = -\cot \theta_0
\]  
(7)
When the rotation speed of the two rollers is the same, the trajectory of the robot is a straight line with the slope $y(t)/x(t)$, and the posture of the robot will not change. When the rotation speed of the left and right wheels is equal, the following equation can be obtained.

$$\begin{align*}
x(t) &= 0 \\
y(t) &= 0 \\
\theta(t) &= \frac{2\omega \omega}{\ell}t + \theta_0
\end{align*}$$

(8)

According to Equation (8), the displacement of the robot does not change, and the robot only rotates along its own centre.

4. Modal analysis of key parts of robot

The lifting rod of the robot head will have a great influence on the accuracy of the inspection results. In this section, the 3D model of the lifting rod is established in the software, converted into the Parasolid-XT format, and then put into the Workbench. The finite element method is used to simulate the actual working state for modal analysis, so as to obtain the natural frequency of the lifting rod. The dynamic equation of the lifting rod is:

$$M\ddot{\delta} + C\dot{\delta} + K\delta = F(t)$$

(9)

Where: $M$ is the mass matrix, $C$ is the damping matrix, $K$ is the stiffness matrix, and $F$ is the exciting force vector.

The modal analysis is carried out on the first six orders of the three points of the cradle head lifting rod, which are respectively the bottom position, the middle position and the upper position. The vibration shapes are as follows:

![Vibration Shapes](image)

- (a) First-order
- (b) Second-order
- (c) Third-order
- (d) Fourth-order
- (e) Fifth-order
- (f) Sixth-order

Figure 3. The vibration shapes of the lifting rod

The frequencies of the lifting rod from the first to the third order are basically 0Hz, the fourth order is 0.889Hz, the fifth order is 1.53Hz, and the sixth order is 9.18Hz. The vibration mode is mainly curved without torsion, and the maximum amplitude occurs at the fifth order frequency. Since the frequency source of the system is 50Hz, it is much higher than the natural frequency of the structure. Therefore, the system will not resonate, camera imaging accuracy can be guaranteed.
5. Motion simulation of robot in typical scenes
In general, the working environment of the inspection robot is complex. If the robot wants to overcome the road obstacles, the torque of the wheel is the key of the design. In order to simulate the actual working environment of the robot, we considered three different situations. Firstly, the robot is driving on a flat road, as shown in Figure 4 (a). The wheel speed of the robot is set to 30°/s, and the change of wheel torque in the process of measuring the wheel is shown in Figure 4 (b). It can be seen from the simulation results that the maximum instantaneous wheel torque is 17.7N∙m when the robot starts to move. After working normally, the torque changes regularly, and the maximum torque of the wheels is 11N∙m.

(a) Model

(b) Simulation results

Figure 4. The robot is driving on a flat road

Figure 5 (a) shows the robot on a steep slope with a slope Angle of 15°. The wheel speed of the robot is still set at 30°/s, and the changes of wheel torque and centre of gravity in the process of climbing are measured, as shown in Figure 5 (b). It can be seen from the simulation results that the wheel torque of the robot will increase with the increase of the climbing height of the robot which driven on a steep slope. During the climbing process, the maximum wheel torque is 37.5N∙m when the robot's centre of gravity reached 280mm.

(a) Model
Simulation results

Figure 5. The robot is driving on a steep road with a slope of 15°

Figure 6 (a) shows that the robot is continuously crossing an obstacle with a height of 50mm and a slope of 30°. The wheel torque of the robot is still set at 30°/s. The changes of wheel torque and centre of gravity are measured in Figure 6 (b). It can be seen from the simulation results that the wheel torque of the robot increases sharply after the wheel touches the obstacle, reaching the maximum of 230N·m, and the wheel torque gradually decreases in the process of crossing the obstacle. Furthermore, when the height of the obstacle is lowered or the slope of the obstacle is reduced, the wheel torque also decreases accordingly.

In summary, the robot designed in this paper can adapt to a variety of complex road conditions, and can autonomously deal with a variety of obstacles in the inspection process.

6. Conclusions
An autonomous cruise electric inspection robot is designed in this paper. The force analysis of the wheel on the flat, steep and rough road is carried out, and the variation law of the robot's velocity and
angular velocity in the process of motion is discussed. It can be seen that on the flat road, the instantaneous wheel torque is largest when the robot starts to move, and then the torque changes regularly. On the steep road, the wheel torque will increase with the increase of the climbing height of the robot, and the maximum torque will appear when the robot reaches the peak. On the rough road, the wheel torque will increase sharply after contacting the obstacle, and then decrease gradually in the process of crossing the obstacle. When the obstacle height is lowered or the slope of the obstacle is slowed down, the wheel torque will also decrease accordingly. In addition, the kinematics and modal analysis of the robot is carried out and the natural frequencies of each mode are solved, which provides a theoretical basis for the design of the key components of the robot.

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