

## Research on the motion location of a substation inspection robot

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**Abstract:** A kind of inspection robot which can be applied to smart substation is introduced. Starting from the mechanical structure of mobile robot, the kinematics analysis model is established. Aiming at the characteristics of smart substation, a magnetic navigation system is designed, and the optimal path planning and two-way walking are realized by applying radio frequency identification. Autonomous or remote control can be used to make the robot detect the operation and discover abnormality of the substation equipment in time. The inspection robot can replace manual labor and become the main monitoring and testing tool for substations in the future.

**Keywords:** inspection robot; motion control; magnetic navigation; radio frequency identification; path planning

### 1. Introduction

The number of substations is increasing year by year, and the workload of the substation inspection is becoming more and more heavy. The traditional way of inspecting substations requires lots of manual inspection[1]. This kind of inspection method not only has great labor intensity and low working efficiency, but also is unable to inspect in time on the condition of heavy wind, heavy snow and thunderstorm. It is difficult to meet the requirement of increasing the quality of power supply, improve the intelligence of the substation. In this case, the intelligent substation inspection robot was gradually applied to the substation instead of manual inspection[2]. The substation inspection robot is combined with the integrated centralized monitoring system, so that it can periodically inspect the operation of each equipment in the substation and achieve the function of video surveillance, information collection, data detection, intelligent analysis and early detection of security risks in the substation environment. Compared to manual inspection, the inspection robot not only has more flexibility and high intelligence, but also can overcome the defects, and provide reliable guarantee for the safe operation of the facilities in the substation.

### 2. Overall structure design

For inspection robot, outdoor working environment and the full autonomous operation put forward higher requirements for the reliability and intelligence of the robot[3]. So its reliability and intelligence are the key points of the robot design. According to the demands, the robot mainly includes the following modules:

- (1) Embedded main control module: the module needs industrial level embedded control module.
- (2) Vehicle battery and charging module: the robot needs a power battery without explosion, high safety and long service life.
- (3) Navigation and positioning module: this module is the key part of the robot system.
- (4) Security protection module: install various sensors on the robot, to detect the working environment and inspection path of the robot, to ensure the safety of the robot and the substation equipment.
- (5) Motion control module: the robot runs slowly in substations and needs high reliability.

The main structure of substation inspection robot consists of chassis structure, charging structure, shell and sensors. The overall structure diagram is shown in Fig.1. Its main function is to display the overall structure of the substation inspection robot, to display the installation position of each device

and the corresponding structure, and to show the logical relationship of the various functional modules.

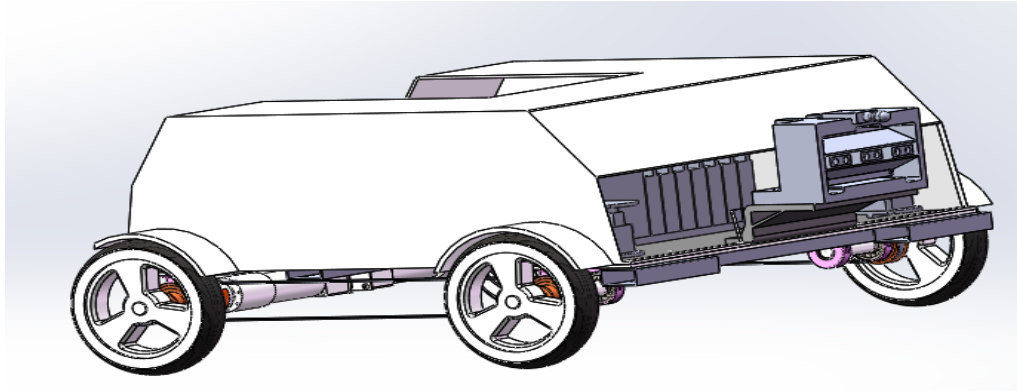


Fig. 1 Overall design diagram of the robot

### 3. Motion control

The motion control of substation inspection robot requires higher stability. Many inspection robots are now using the four wheel structure[4]. Its front wheel is a pair of universal wheels, and the rear wheel is a pair of driving wheels. This kind of robot has a flexible steering, but its running stability is poor. In order to improve the stability of robot operation, the inspection robot designed in this paper adopts four wheels structure with synchronous belts. The structure is simple and easy to control the moving direction. Compared with other structures, it can greatly improve the stability of the robot operation and meet the operation requirements of the substation inspection robot. Through the differential speed of the drive motors, the robot can easily make adjustments of its position posture and direction. The overall structure is simple, stable, easy to process, with good movements performance. It has strong adaptability to the complex environment of substations.

In order to accurately describe the movement of the inspection robot, establish the mathematical model, then solve the kinematics equations. The motion diagram model of the robot is shown in Fig.2.

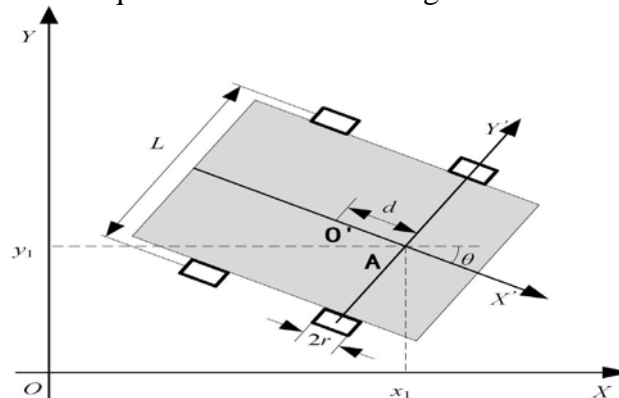


Fig. 2 Robot motion diagram

The coordinate system XOY is the absolute coordinate system of the robot. Take the centroid of the robot as the original point O', and establish the relative coordinate system X'O'Y' of the inspection robot. In this coordinate system X'O'Y', A is the center point of the front wheel axis; d is the distance between O' and A; the deviation angle of the inspection robot is  $\theta$ . The location of the inspection robot can be expressed as  $(x, y, \theta)$ . The velocity of centroid is  $v$  and the angular velocity is  $\omega$ . By controlling the speed of the two driving wheels of the left and right wheels, the robot's motion position control is realized. Its equation of motion can be expressed as equation (1).

$$P = \begin{bmatrix} x' \\ y' \\ \theta' \end{bmatrix} = \begin{bmatrix} \frac{r}{2} \cos \theta & \frac{r}{2} \cos \theta \\ \frac{r}{2} \sin \theta & \frac{r}{2} \sin \theta \\ \frac{r}{L} & -\frac{r}{L} \end{bmatrix} \begin{bmatrix} v_R \\ v_L \end{bmatrix} \quad (1)$$

In equation (1),  $L$  represents the distance between the left and right wheels;  $r$  is radius of wheels;  $v_L$  represents speed of the left driving wheel;  $v_R$  represents speed of the right driving wheel speed. From the above analysis, it's obvious that by using the differential speed driving principle, the current state of motion can be changed very easily and quickly. In this design,  $L=757$  mm,  $r=90$  mm and the mass is 50 kg; the motor's nominal speed is 8380 rpm; the reduction ratio is 53:1; calculated from the motor parameters, the nominal angular velocity of the driving wheel is about 16.25 rad/s. When  $\theta=0^\circ$ , the robot moves along the X axis in a straight line ( $v_R = v_L$ ), the speed of the robot  $v = v_R \times r = 1.463$  m/s, which meets the requirement that the maximum speed exceeds 1 m/s.

The nominal torque of the motor is 0.285 Nm. According to  $F = T/r$ , the output force of the driving wheel is  $F = 335$  N. Fig. 3 is the force analysis diagram for robot climbing.

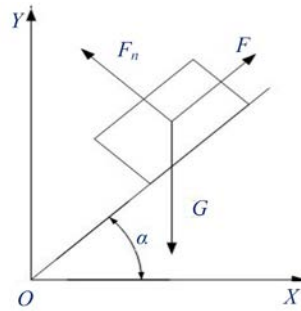


Fig. 3 Force diagram of Robot climbing

The driving force of the robot is determined by the torque of the wheel and the friction between the ground and the tire. The parameters are  $f=0.4$ ,  $\alpha=15^\circ$ :

$$\begin{cases} F_f = F_n \times f \\ F_n = G \times \cos \theta \\ G = mg \end{cases} \quad (2)$$

From the equation (2), the maximum driving force of the robot ( $F$ ) is 189 N when climbing ( $F > G \sin \alpha$ ), so the robot can meet the requirement of climbing slopes with no less than  $15^\circ$ .

In view of the discontinuity in algorithms of linear acceleration and exponential acceleration and deceleration, the algorithm of S curve acceleration and deceleration is adopted in this design. The algorithm consists of three acceleration sections, one uniform velocity section, and three deceleration sections. It can ensure the smooth transition of the system speed. The ideal accelerometer is shown in Fig. 4.

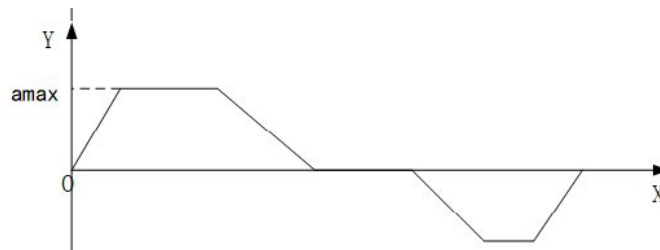


Fig. 4 Robot acceleration sketch diagram

Let  $j(t)$  be the derivative of acceleration,  $a(t)$  be the acceleration,  $a_{\max}$  be the maximum of  $a(t)$ ,  $J$  be the slope of 0 to  $a_{\max}$  and  $v(t)$  be the velocity. Then by calculating, we can get following equations.

$$j(t) = \begin{cases} J & t \in (0, t_1] \\ 0 & t \in (t_1, t_2] \\ -J & t \in (t_2, t_3] \\ 0 & t \in (t_3, t_4] \\ -J & t \in (t_4, t_5] \\ 0 & t \in (t_5, t_6] \\ J & t \in (t_6, t_7] \end{cases} \quad (3)$$

$$a(t) = \begin{cases} Jt & t \in (0, t_1] \\ a_{\max} & t \in (t_1, t_2] \\ a_{\max} - J(t - t_1) & t \in (t_2, t_3] \\ 0 & t \in (t_3, t_4] \\ -J(t - t_4) & t \in (t_4, t_5] \\ -a_{\max} & t \in (t_5, t_6] \\ -a_{\max} + J(t - t_6) & t \in (t_6, t_7] \end{cases} \quad (4)$$

$$v(t) = \begin{cases} \frac{1}{2} Jt^2 & t \in (0, t_1] \\ a_{\max} t & t \in (t_1, t_2] \\ a_{\max} t_2 - \frac{1}{2} J(t - t_2)^2 & t \in (t_2, t_3] \\ v_{\max} & t \in (t_3, t_4] \\ v_{\max} - \frac{1}{2} J(t - t_4)^2 & t \in (t_4, t_5] \\ -a_{\max}(t - t_4) & t \in (t_5, t_6] \\ v_6 - \frac{1}{2} J(t - t_6) & t \in (t_6, t_7] \end{cases} \quad (5)$$

The speed of the robot is 1m/s, the maximum acceleration is 1.3m/s<sup>2</sup>, and the acceleration derivative is 0.5m/s<sup>3</sup>. we carry out Matlab simulation for braking stage of S curve acceleration & deceleration algorithm. The result is shown in Fig.5.

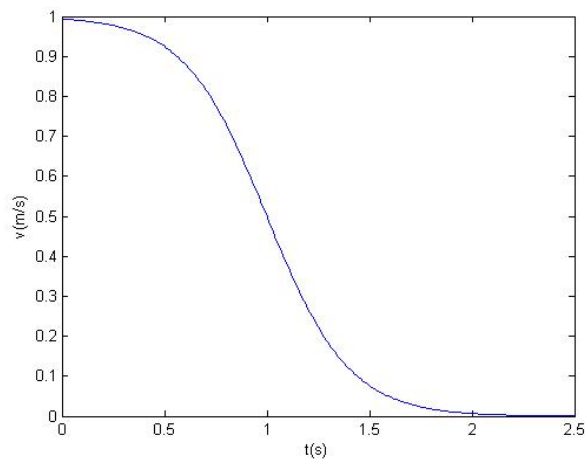


Fig. 5 Robot speed MATLAB simulation diagram

#### 4. Navigation and positioning system

At present, the main navigation methods applied to inspection robot are as follows:

(1) Laser mode[6]: robots rely on laser launchers and reflective symbols. It's necessary to deploy many reflecting equipment. Once any of them is malfunctioning or blocked, the robot will not locate properly. So the reliability will be greatly reduced and the maintenance work will be heavy.

(2) Magnetic navigation: The magnetic stripe is embedded into the ground, and the magnetic sensor is used to detect the magnetic stripe. This enables the robot to run along the buried path. The method is stable and reliable.

(3) Track mode: Lay tracks on the ground of the substation. the robot will run along the track like a train. The operation of the robot is stable and reliable, but the workload is really heavy. Once the inspection path changes, tracks need to be rebuilt. And the cost is very high.

In order to have reliable robot localization, considering the substation's special and complex environment with large noise and electromagnetic interference, use magnetic navigation technology and radio frequency identification technology, . The positioning error can be controlled within 15mm.

#### **4.1 Magnetic navigation and positioning**

Magnetic navigation and positioning technology is now relatively mature[7]. The positioning is accurate, the reaction is sensitive, and the error is small. A number of magnetic sensor groups are installed horizontally on the robot body, and magnetic strips are placed on the walking path of the robot. When a mobile robot walks along a magnetic strip, the magnetic sensor on the robot's body will generate the induced electromotive force. The distance between the magnetic stripes is different, so the induced electromotive force of each magnetic sensor is different. Thus, the lateral displacement of the robot center relative to the tape can be calculated. Linear correction is adopted to ensure that the mobile robot always walks along the magnetic strip path.

The movement trajectory of the robot is adjusted in real time through the servo control system.

This project adopts the JH-16 magnetic navigation sensor and navigation magnetic strip. The magnetic navigation sensor consists of 16 sampling points output.

The robot runs along magnetic strips laid on the ground. JH - 16 magnetic navigation sensor, mounted on the bottom of the front of the robot car body, is 20 to 40 mm from the magnetic stripe surface. The width of the magnetic stripe is 30 to 50 mm, and the thickness is 1mm. The JH-16 magnetic navigation sensor is able to detect the weak magnetic field below 100 Gauss above the magnetic strip, by using 16 sampling points, each of which will output a signal correspondingly. When the robot is running, a continuous 3 to 5 sampling points perpendicular to the magnetic stripe will output signals inside the magnetic navigation sensor. Depending on the 3 to 5 signal output from the 16 channel, the deviation of the magnetic strip relative to the JH 16 magnetic navigation sensor, can be calculated. Then the robot will automatically adjusts to ensure that the magnetic strip goes along the magnetic strip.

#### **4.2 Radio Frequency Identification Location**

RFID, is the abbreviation for radio frequency identification. The technical principle of RFID positioning[8] is: The reader and writer transmit electromagnetic waves through the antenna into the air; the adjacent tags are activated by electromagnetic waves; the electromagnetic waves stimulate the high frequency current in the antenna on the label, then push the integrated circuit of the label to work; the activated tags will randomly emit the radio waves carrying the label data, then these weak radio waves are read and written. The device receives, demodulates and decodes the signal, then sends it to the built-in data processor module for data processing and analysis to determine whether the electronic label of the transmitted signal is legitimate, and then performs the corresponding operation for different judgment results, such as displaying relevant information, recording related data or issuing instructions to control execution.

In this paper, the laying plan and positioning model of RFID are designed as follows:

The RFID tags used for positioning are laid on the right side of the road. If a robot walks in a single closed path, it only needs to install a RFID tag at each intersection. In order to achieve two-way walking, multiple RFID tags need to be embedded according to the intersection type. The robot has a certain parking distance (about 20 cm) when it identifies the RFID label. Based on the intersection point of all crossings, along the magnetic locus in every direction, embed RFID labels into the right

side of the intersection point (the transverse distance to the magnetic track is about 20 cm, and the longitudinal distance to the road is about 50 cm). The number of RFID labels at the intersection marks is 2 at the turning, 3 at the T-junction, and 4 at the intersection. Both left and right sides of the mobile robot are symmetrical installed with 2 RFID readers, so that when any RFID tags are read by the robot, it can identify its position and direction of walking. Fig.6 shows RFID laying points along the robot patrol route.

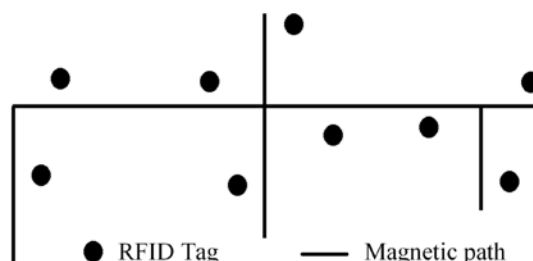


Fig.6 RFID paving point map

According to the complex environment of the substation and the changeable temperature, it is necessary to select the RFID reader with strong reliability and stability. This paper adopts distance reader JT-8280B of Shenzhen Jie Tong Technology Co. Ltd. This product is multi-protocol compatible, with fast reading rate and waterproof appearance. Its working frequency is 902 to 928 MHz 865 to 868 MHz. It can read within 5m steadily with high accuracy and sensitivity. In addition, this card reader also has industrial lightning protection and low temperature protection treatment (working temperature:  $-40^{\circ}\text{C}$  to  $+65^{\circ}\text{C}$ ), very suitable for substation, and can be used in the northwest and cold regions, with a strong regional adaptability, to meet the harsh working environment requirements.

### 4.3 Laser obstacle avoidance system

Considering that the substation environment is complex and changeable, robots are likely to encounter obstacles or disturbances on the predetermined path when they are inspecting. In order to ensure the safety of robots and substation equipment, it is necessary to do real-time inspection of path status. This project uses laser radar[9] for obstacle avoidance. The outline of obstacles in front of the robot is scanned by laser, then it can be estimated whether those obstacles are get in the way of the robot's walking. If the obstacle is detected by the laser radar, the robot will stop running to avoid the collision between the robot and the obstacle, which will cause damages to the robot or equipment. A pair of laser radar is installed on both sides of the robot. The installation position is as follows:

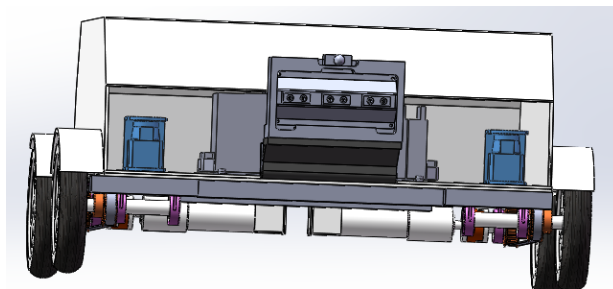


Fig. 7 Laser radar installation diagram

Taking into account the changing environment of substations, this paper adopts the HOKUYO-2 laser scanning range finder UXM-30LXH-EWA in Beiyang. The product features and technical parameters are as follows:

The UXM-30LXH-EWA laser scanning measures the distance within 80 m and the angle's resolution is  $0.125^{\circ}$ . It is suitable for measuring the distance of the next RTG. It can detect the size, location and direction of movement of objects. It is suitable for harsh environments such as rain, snow and fog. The heater inside make it be used normally in cold environment. The interface of the sensor is Ethernet. The scanning time is 50 ms, and the scanning angle is  $190^{\circ}$ . Through experiments, the laser radar can be fully competent for the substation's working environment and meet strict performance requirements.



#### 4.4 Shortest path planning

A global path planning topology method is used to build modeling for the patrol road[9]. Based on the connectivity of RFID tags, a topological network diagram is established. First, multiple RFID tags at the intersection are merged into the nodes in the graph, and the magnetic trajectories are used as one of the edges of the drawing. Through the traversal of nodes and edges, the shortest path between 2 nodes is calculated, and then converted to a driving path marked by RFID tags. Among RFID tags in each intersection, the rotation angle of the robot is calculated according to the connectivity of the path.

At present, some mature path search methods include Dijkstra algorithm, Floyd algorithm, A\* algorithm, genetic algorithm, ant colony algorithm and wave propagation algorithm[10].

The inspection robot takes magnetic navigation as a navigation mode. The robot's walking path needs to lay a good magnetic strip in advance, to guide the robot to walk. All the walking paths of the robot will not be changed again. Therefore, the path planning of the patrol robot belongs to the static state planning. According to the scale of the existing substations, there are hundreds of map nodes in the largest substation, so the number of nodes is not very large. According to the applicable scope of the various path planning methods and the actual inspection road conditions in the substation, the Dijkstra algorithm is selected as the path planning method of magnetic navigation.

#### 5. Conclusions

In this paper, a mobile robot, which can independently inspect and patrol, with autonomous navigation, and intelligent detection, is designed and used in substation instead of manual inspection. The robot adopts four-wheel structure with synchronous belt, which is simple and flexible. Compared with other structures, the robot's operation stability is greatly improved. In the process of robot's operation, navigation and localization play a key role. The technology of magnetic navigation is now mature. In this paper, the navigation system with two rows of magnetic sensors is adopted. At the same time, the robot uses RFID to locate and detect. By positioning different RFID tags buried under intersection of turning, T-junction and crossroad, the robot can localize itself accurately. After using this robot, the intelligent substation inspection task can greatly reduce the manpower input, improve the safety and reliability of the equipment operation. What's more, the inspection task is not affected by weather and other factors. It has both good economic value and practical value.

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