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Design of Intelligent Management System for Underground Cable Tunnels and Integration of Robotic Inspection and Defect Recognition Technology

Xinglong Sheng[1,✉], Qing Yan[1], Kaiqiang Hu[1], Chaoju Li[1], Yanghua Xie[1]

[1] Guiyang Power Supply Bureau, Guizhou Power Grid Co., Ltd., Guiyang, Guizhou, 550001, China

ABSTRACT

Underground cable tunnels are important infrastructures to maintain the normal operation of cities, and problems such as cable insulation aging and discharge can easily cause fires or even explosions, so the requirements for maintenance are high. In this study, the DGPS positioning method is used to optimise the positioning system of the intelligent inspection robot for underground cable tunnels, and the LQR controller is used to realise the deviation correction of angle and position in the motion path of the intelligent inspection robot. Then the inspection robot and UHF sensor are used to detect and accurately locate the defects in the cable tunnel, and finally the deviation correction and defect detection methods are integrated to design an intelligent management system for underground cable tunnels. The results of simulation experiments and field surveys show that the proposed method can correct the deviation of the robot in the inspection process in a timely manner, avoiding the problems of hitting the obstacles and the path around the long distance, and the average time consumed in the simulation map scenario is only 6.89 s. The communication scheme of the intelligent management system is practicable, and it can effectively detect and identify the defects and the specific location of the defects in the underground cable tunnels. The system proposed in this paper is able to detect defects and faults in time in practical applications, providing a new solution for the inspection of underground cable tunnels.

Keywords: LQR system, GPS, UHF sensor, path correction, underground cable tunnels

1. Introduction

In order to make the city more beautiful and more efficient use of land resources in the process of modern urban construction, a large number of underground tunnels are constructed for power transmission, communication and underground transport. With the increase of tunnel construction, regular inspection of lines and equipment in tunnels becomes particularly important [1-2]. Taking the

✉ Corresponding author.
E-mail address: shengxl00123@163.com (X. Sheng).
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high voltage transmission cable as an example, the above ground transmission system needs to set up more transmission line towers and poles during the construction, which will take up relatively more land resources, and the transmission lines on the ground also have greater safety hazards, for example, due to the short circuit of the line caused by foreign objects on the line will cause a fire, which will bring great difficulties to the maintenance work in the later stage. If the construction of underground tunnels, the transmission cable can be transferred to the ground, which can effectively avoid the many problems that exist on the ground transmission cable. For safety reasons, underground cables must be covered with a thick layer of insulation [3-4]. The insulation layer works under high voltage for a long time, and due to the complex environment inside the tunnel, the air is humid, which will lead to physical and chemical changes of the cable protection layer inside the tunnel, and ultimately lead to a decline in the performance of the protection layer, and lay a hidden fire hazard. Therefore, in order to ensure the safety of equipment and cable operation in tunnels, it is necessary to carry out regular inspections of tunnels [5-6]. For important tunnels and failure-prone tunnels need to be frequently detected, which will cost a lot of manpower and material resources. Tunnel inspection work mainly includes checking the tunnel equipment operating status, tunnel ventilation, lighting, drainage and tunnel cable joints temperature, grounding current, whether there is partial discharge. At present, tunnel inspection is mainly manual inspection, underground tunnels are often very long, tunnel inspection workload is very large [7]. In addition, the tunnel environment is poor, there may be toxic and hazardous gases, and the tunnel equipment operation may appear in the sudden failure, if it leads to a fire is not easy for inspectors to quickly evacuate, which will be a threat to the personal safety of inspectors in the tunnel [8].

In summary, the complex and changing tunnel environment constrains the tunnel inspection work. In order to solve the above problems of tunnel inspection work, tunnel inspection robots came into being. Currently there are some tunnel inspection robots on the market, these robots can replace the manual completion of some of the inspection work in the tunnel. For example, through the sensors carried by the robot, some parameters in the tunnel for real-time detection, and real-time display on the host computer, reducing the workload of the inspectors, but also more safe and reliable [9-11]. However, these robots in the mechanism are basically only with the function of walking along the tunnel or attached to be able to move up and down the moving platform, but does not have a close to the tunnel equipment and transmission cables of the robotic arm part, so it can only be achieved through the sensors of the tunnel temperature, humidity, and the internal environment of the video monitoring, and can not be close to the tunnel equipment and cables for detection and operation, the current part of the detection work also need to be This part of the detection work still needs to be carried out manually [12-13]. Therefore, there is an urgent need for an intelligent management system for underground cable tunnels in the electric power industry to solve the problem that the current tunnel inspection robots are not comprehensive in their inspection and defect identification projects, and the inspection of equipment and cables in the tunnels that need to be operated in close proximity still needs to be carried out manually, which can help to realise intelligent management of various inspections in the tunnels [14-15].

In the process of urbanisation and power development, cable tunnels are an important guarantee of the safety and reliability of power supply system operation, therefore, it is necessary to establish a new management approach to implement monitoring and control of cable tunnels. Literature [16] analyses the main challenges faced by utility tunnels today, in order to be able to carry a variety of water and energy utilities in an accessible underground space, the use of smart technologies and advanced monitoring systems to can develop a comprehensive digital tunnel management solutions, which to a certain extent can improve the safety and performance of the tunnel. Literature [17] tries to design an online monitoring platform for power cable tunnels that integrates cable monitoring, environmental monitoring, personnel management, etc., in order to reduce the difficulty of cable tunnel maintenance work and ensure the safe operation of urban cable tunnels. Literature [18] uses discrete fracture network (DFN), neural network and numerical simulation calculation methods to optimize the prestressed anchor support model, and manages the soft rock tunnel support problem by predicting and analysing the surrounding rock deformation under different support parameters.

In order to ensure the safe operation of underground cable tunnels, regular inspections of the lines and equipment in the tunnels are required. Literature [19] indicated that the emergence of tunnel mechanical inspection methods can make up for the shortcomings in manual inspection methods, reviewed the shortcomings of tunnel inspection equipment in recent years in terms of technology and function, and looked forward to the future development direction of tunnel inspection technology. Literature [20] emphasises the importance of urban underground infrastructure, reveals the limitations and challenges in the construction and operation and maintenance of underground infrastructure through a literature review, and teases out the possibilities for future research into the use of digital technologies for the construction and maintenance of urban underground infrastructure. Literature [21] designs an intelligent inspection robot and proposes a path planning method that combines the improved A∗ algorithm and the dynamic window method, as well as constructs an extended neural network model for assessing air quality, aiming to accurately assess the condition of the cable trench in order to realise the linkage control of the cable trench operation and maintenance. Literature [22] mainly analyses the current research and future development direction of underground detection in railway tunnels, and proposes a 3D visualisation framework that can satisfy all the required standards to achieve effective detection, localisation and description of faults in railway tunnels, which in turn improves the technological level of the data acquisition and information transmission schemes for underground detection in railway tunnels.

In this paper, GPS positioning system is installed in the intelligent inspection robot, and DGPS method is used to improve the accuracy of the positioning system. Then, based on the LQR quadratic performance index, we design the deviation correction controller system in the travelling path of the intelligent inspection robot. The electromagnetic induction coil in the inspection robot is used to detect the alternating magnetic field around the cable line in the underground cable tunnel, and the offset of the travelling path of the intelligent inspection robot is analysed by the relative position of the coil induced electromotive force and the cable line, in order to realise the correction of the deviation of the robot's inspection path. Subsequently, the robot is used to detect the abnormal signal of cable discharge, and the distance between the UHF sensor in the intelligent inspection robot and the defect location is calculated to obtain the defect location in the underground cable tunnel. Finally, an integrated system for intelligent management of underground cable tunnels is designed by combining the robot inspection path correction and defect identification methods. In this study, after the simulation verification of the robot inspection path correction method, the practical application of the system is carried out in a city underground cable tunnel to explore the application effect of the system.

2. Intelligent robot inspection and defect identification method design

2.1. Planning and Correction of Robot Inspection Paths

2.1.1. General Architecture of LQR Controller System. In this paper, the system structure of the deviation correction controller for the inspection robot in the underground cable tunnel is shown in Fig. 1, which is based on the detection signals from the electromagnetic induction coil to determine the angular deviation and positional deviation of the robot, and then the controller calculates the corresponding commands, and finally the drive motor performs the operation to achieve the purpose of eliminating the deviation.

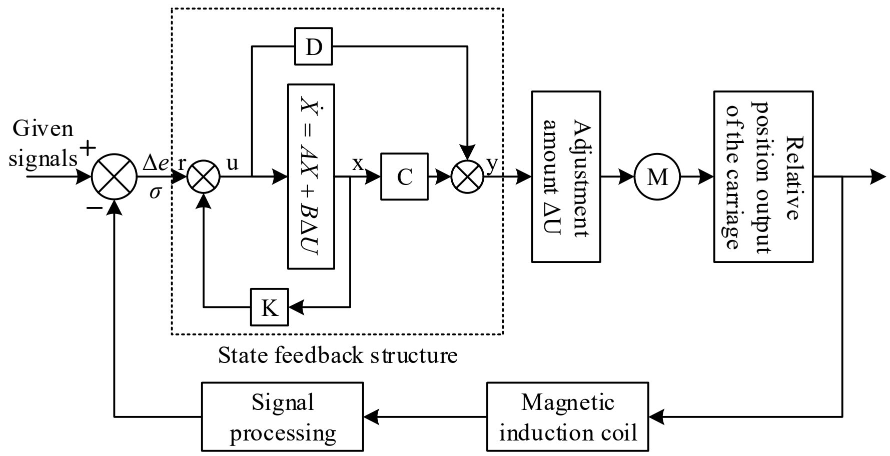


Fig. 1. Control system structure diagram

With the introduction of state feedback, the control law of the system is:

$$\begin{cases} \Delta U = -\left(k_1 \Delta U + k_2 \sigma + k_3 \Delta e\right) \\ U_{or} = r \pm \Delta U/2 \\ U_{ol} = r \mp \Delta U/2 \end{cases} \tag{1}$$

where $k = \left[k_1 \quad k_2 \quad k_3\right]$ is the state feedback gain matrix. The LQR -quadratic performance index is utilised to design the deviation correction controller as a function of the performance index:

$$J = \frac{1}{2}\left(\int_0^\infty X^T \left(Q + k^T Rk\right) X dt\right) \tag{2}$$

Since the control system is closed-loop stable, when $t \to \infty$, $X(t) \to 0$, differentiating it gives:

$$\dot{X}^T PX + X^T PX + \dot{X}^T QX + X^T RkX = 0 \tag{3}$$

$$X^T \begin{pmatrix} A^T P + PA + Q \\ +k^T Rk - k^T B^T k \end{pmatrix} X = 0 \tag{4}$$

Assumption $k = R^{-1} B^T P$, which can be derived by substituting into the above equation:

$$\left(A^T P + PA + Q - PB\left(R^{-1} B^T P\right)\right) = 0 \tag{5}$$

This equation is the Riccati equation and its solution is P.

The optimal feedback gain matrix k is related to the value of P only. Usually Q and R are taken as diagonal matrices and then using the LQR function [23] $\left[k \quad P \quad r\right] = lq\left(A \quad B \quad Q \quad R\right)$ in Matlab, it can be concluded that LQR the mathematical model of the designed controller is:

$$\Delta U = -\left(2.7182\Delta U + 9.4196\sigma + \Delta e\right) \tag{6}$$

2.1.2. Positioning function implementation method. Intelligent inspection robots in underground cable tunnels are equipped with position sensors and pre-input inspection maps and routes, with positioning accuracy within 0.1 metres. When the inspection robot runs to the joint position of the cable tunnel, the configured automatic braking device operates and the brake stops. When the inspection robot passes through a bend in the cable tunnel, it automatically decelerates until it reaches the permissible speed before passing through the bend and passes through the bend at the pre-set permissible speed. The mobile robot is fitted with a GPS positioning system.

In order to improve the accuracy of the system, a more reliable method called differential, known as DGPS, is used [24]. In this method, two receivers called reference station (fixed station) and positioning station (mobile station) communicate with the satellite simultaneously. In the reference station, the true data and the data received by the GPS receiver are known, similarly. But the real data of the mobile station is unknown. The formula is as follows:

$$S_m = (S_m)_{error} + (S_m)_{original} \tag{7}$$

$$(S_m)_{original} = S_m - (S_m)_{error} \tag{8}$$

$$S_r = (S_r)_{error} + (S_r)_{original} \tag{9}$$

$$DD = (S_r) - (S_r)_{original} \tag{10}$$

$$(S_m)_{original} = S_m - DD \tag{11}$$

Where, $(S_m)_{original}$ denotes the true position of the positioning station, $(S_m)_{error}$ is the station reception error of the positioning station, $(S_r)_{original}$ denotes the true position of the reference station, and $(S_r)_{error}$ is the reception error of the fixed station.

Since the receiver is located at the reference and positioning stations and receives signals simultaneously, and the satellites in the two stations are similar, $(S_m)_{error} = S_{error} - (S_r)_{error}$ is valid, where S_{error} is the differential data. The differential data in equation (10) represents the reference point shown in (DD), and the actual position of the mobile station is determined by (11).

2.1.3. Magnetic field and signal detection methods. In the underground cable line with a certain frequency of alternating current, the cable line will produce the same frequency around the alternating magnetic field, then placed in the magnetic field in the electromagnetic induction coil will produce an induced electromotive force, the induced electromotive force E and the strength of the magnetic field $B(t)$, the number of turns of the induction coil N, induction coil cross-sectional area S between the relationship is as follows:

$$E = NS \cdot \frac{dB(t)}{dt} = -N\frac{d\Phi(t)}{dt} \tag{12}$$

A point at a distance of h from the horizontal plane where the cable line is located and at a shortest distance of r from the cable line has a vector magnetic field of $\vec{B}$, which is obtained by decomposing $\vec{B}$ into a horizontal component $\vec{B}_H$ and a vertical component $\vec{B}_V$:

$$\vec{B} = \vec{B}_H + \vec{B}_V \tag{13}$$

$$\begin{cases} B_H = B\sin\theta = \dfrac{\mu_0 I}{2\pi} \cdot \dfrac{h}{x^2+h^2} \\ B_V = B\cos\theta = \dfrac{\mu_0 I}{2\pi} \cdot \dfrac{d}{x^2+h^2} \end{cases} \tag{14}$$

A horizontally placed induction coil is used to detect $\vec{B}_H$ and the induced electromotive force is calculated for E_H. A vertically placed induction coil is used to detect $\vec{B}v$ and the induced electromotive force is calculated for E_V:

$$\begin{cases} E_H = \mu_0 NSfI_m \cdot \dfrac{h}{x^2+h^2} = k \cdot \dfrac{h}{x^2+h^2} \\ E_V = \mu_0 NSfI_m \cdot \dfrac{d}{x^2+h^2} = k \cdot \dfrac{x}{x^2+h^2} \end{cases} \tag{15}$$

Where k is a constant of proportionality, related to parameters such as the size of the wire current I_m, frequency f, number of turns of the inductor coil N and area S, which can be experimentally measured to determine its size.

Let $k=1$, $h=5$, give the magnitude of the induced electromotive force at different positions of the horizontal and vertical coils respectively. E_V is a non-monotonic function on both sides of $x=0$, and E_H is a monotonic function on both sides of $x=0$. Therefore, a horizontally placed induction coil is chosen to detect the magnetic field size, so as to determine the deviation value of the inspection robot from the preset path and realise the deviation control.

An induction measuring coil is placed on each side of the cable line, and the difference between the induced electric potentials of the two coils is:

$$\Delta E = E_{H1} - E_{H2} = k\left(\frac{h}{x^2+h^2} - \frac{h}{(L-x)^2+h^2}\right) \tag{16}$$

Measurements ΔE can be taken to determine the position of the centre point of the inductive measuring coil relative to the cable line, which in turn gives the offset of the inspection robot.

The induced electromotive force signal obtained directly from the inductive coil induction is weak and noisy, so the signal needs to be amplified by frequency selective amplification to reduce the influence of the peripheral signals on it. In this scheme, the LC parallel resonant circuit [25] is selected to achieve the frequency selection of the detection signal, and the size of the resonant capacitor is:

$$C = \frac{1}{(2\pi f_0)^2 L} \tag{17}$$

where f_0 is $20kHz$ and L is the inductance size of the induction coil.

2.2. *Defect detection methods in cable tunnelling*

2.2.1. Method of determining the location of cable defects. In the step of solving for the location of the local defect signal source in an underground cable tunnel, the intelligent inspection robot first solves for the values of the unknowns z and t_1 according to the following equation:

$$\begin{cases} 4zr = v^2\left(2t_1 + t_{13} + t_{12} + \Delta t_{12}\right) \times \left(t_{13} - t_{12} - \Delta t_{12}\right) \\ r^2 - 2zr = r^2 \times t_{12} \times \left(2t_1 + t_{12}\right) \end{cases} \tag{18}$$

In the above equation, z is the z coordinate value of the partial discharge signal source, t_1 is the time for the local defect signal to propagate to the round point $(0,0,0)$, and v is the speed of light.

According to the following formula to solve for the value of unknowns x and y, so as to obtain the coordinates of the local defect signal source (x,y,z):

$$\begin{cases} \sqrt{\left[x^2+y^2+(z-r)^2\right]} = v\left(t_1+t_{12}\right) \\ \sqrt{\left[x^2+(y-d)^2+(z+r)^2\right]} = v\left(t_1+t_{13}\right) \end{cases} \tag{19}$$

The distance between the coordinates (x,y,z) of the localised defective signal source and the UHF sensor B is calculated from the coordinates (x,y,z) of the localised defective signal source according to the following equation:

$$vt_1 = \sqrt{\left[x^2 + y^2 + z^2\right]} \tag{20}$$

In the above equation, vt_1 is the distance between the coordinates of the localised defect signal source (x,y,z) and the UHF sensor B [26].

The length of all robotic arms of the robot is known, and a spatial coordinate system is established in the three-degree-of-freedom robotic arm 3. Setting the coordinates of the UHF sensor B as $(0,0,0)$, and the coordinates of the position P as (x,y,z), the coordinates of the UHF sensor A are $(0,0,r)$, and the coordinates of the UHF sensor C are $(0,d,-r)$, and the position of the localised defective signal source is P to the sensor propagation speed v (the speed of light). The distance from the position P of the source of the localised defect signal to the coordinates $(0,0,r)$ of the UHF sensor A can be given as equation (21):

$$\sqrt{\left[x^2 + y^2 + (z-r)^2\right]} = v\left(t_1 + t_{12}\right) \tag{21}$$

The distance from the position P of the localised defect signal source to the coordinates $(0,0,0)$ of the UHF sensor B can be listed as Eq:

$$vt_1 = \sqrt{\left[x^2 + y^2 + z^2\right]} \tag{22}$$

The distance from the position P of the localised defect signal source to the coordinates $(0,d,-r)$ of the UHF sensor C can be listed as Eq:

$$\sqrt{\left[x^2 + (y-d)^2 + (z+r)^2\right]} = v\left(t_1 + t_{13}\right) \tag{23}$$

After controlling the robot's third robotic arm 33 to rotate $+180°$, the new coordinates of UHF sensor A and UHF sensor B remain motionless, and the new coordinates of C change to $(0,d,r)$. Let the time for the localised defect signal to propagate to the UHF sensor $A(0,0,r)$ be Δt_1 (unknown), and obtain the time difference Δt_{12} (known) between the UHF sensors A, UHF sensor C, then the time for the localised defect signal to propagate to the new coordinates $(0,d,r)$ of the UHF sensor C at this point is $\Delta t_1 + \Delta t_{12}$. Since the UHF sensor A and UHF sensor B remain motionless after the robotic arm adjusts its position, it can be seen that the time for the localised defect signal to propagate to the UHF sensor $A(0,0,r)$ is $\Delta t_1 = t_1 + t_{12}$, and then the time for the localised defect signal to propagate to the new coordinates $(0,d,r)$ of the UHF sensor C is $t_1 + t_{12} + \Delta t_{12}$. Therefore, the relationship equation for the distance from the position P of the source of the localised defect signal to the new coordinates $(0,d,r)$ of the UHF sensor C can be listed as:

$$\sqrt{\left[x^2 + (y-d)^2 + (z-r)^2\right]} = v\left(t_1 + t_{12} + \Delta t_{12}\right) \tag{24}$$

Subtracting equation (23) from equation (24) gives:

$$4zr = v^2\left(2t_1 + t_{13} + t_{12} + \Delta t_{12}\right) \times \left(t_{13} - t_{12} - \Delta t_{12}\right) \tag{25}$$

Subtracting equation (21) from equation (22) gives:

$$r^2 - 2zr = r^2 \times t_{12} \times \left(2t_1 + t_{12}\right) \tag{26}$$

According to equations (25) and (26), the values of unknowns z and t_1 can be solved by association, and the values of unknowns z and t_1 can be solved by substituting them into equation (19) to obtain the values of x and y in the coordinates (x,y,z) of position P, and the value of position 10 can be obtained by substituting the value of z into equation (20) or equation (22) to obtain the value of position P's coordinates (x, y, z). The value of coordinate (x, y, z) of position P is then substituted into equation (20) or equation (22) to obtain the distance vt_1 between coordinate (x, y, z) of position P and coordinate $(0,0,0)$ of UHF sensor B.

2.2.2. Overall process of defect detection. The implementation steps of the cable local defect localisation method of the inspection robot in the underground cable tunnel are shown in Fig. 2, which includes six steps, and the specific flow is shown below.

1) Due to the unequal lengths of the cable tunnels and the distance limitation of the UHF sensors for the detection of the localised signals, the cable tunnels to be inspected are divided into N inspection areas of the same lengths, each of which is the localised detection and localisation area to be inspected by the inspection robot in the underground cable tunnels.

2) Select a detection area as the current detection area in the direction of the underground cable tunnel inspection robot from the starting point to the end point.

3) Control the underground cable tunnel inspection robot to travel to the current detection area, adjust the three segments of the three-degree-of-freedom robotic arm of the underground cable tunnel inspection robot, and collect the local discharge signals through the three UHF sensors A, B, and C installed on the three segments of the three-degree-of-freedom robotic arm of the underground cable tunnel inspection robot.

4) Judge whether the local discharge signal is collected, if the local discharge signal is collected, then jump to execution step 5), otherwise jump to execution step 6).

5) Detect the position of the local discharge signal source using the cable local defect location method of the underground cable tunnel inspection robot described herein.

6) Determine whether the detection area is traversed, if not yet traversed, then jump to the implementation of step 2), otherwise, if it has been traversed, then end and exit.

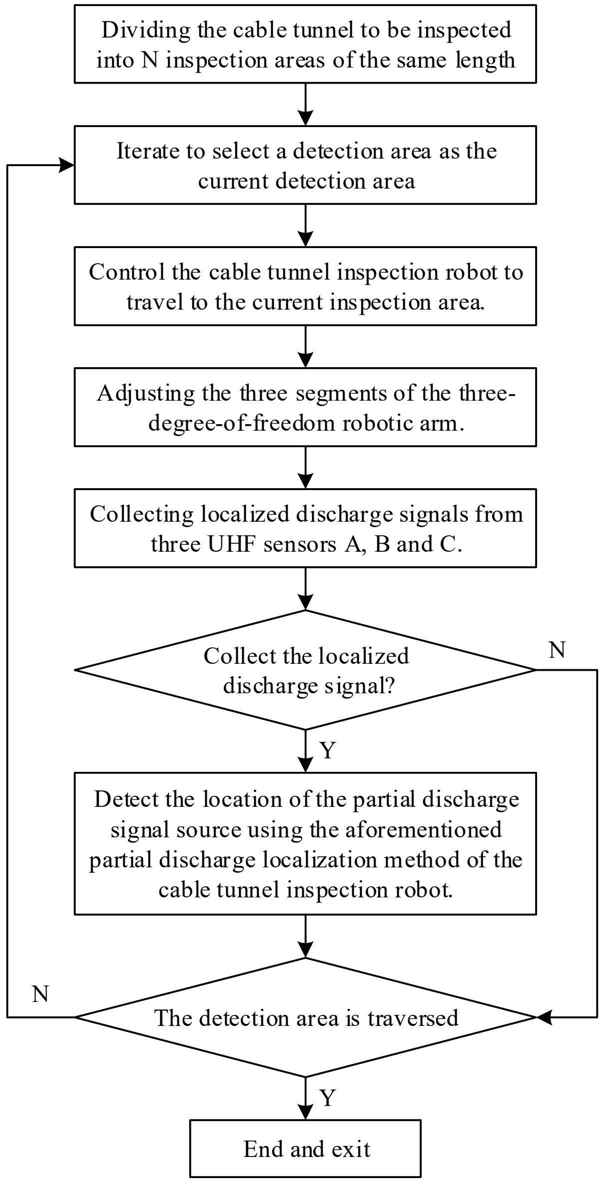


Fig. 2. Local discharge location detection process

3. Intelligent management system architecture for underground cable tunnels

The core component and control centre of the intelligent inspection robot is the CPU main processing module. It mainly includes the following functional modules. Among them, the video server function converts video and audio signals into network interface signals, and the PTZ control. The DSP processor [27] module calculates the infrared and ultrasonic detection signals. Wireless positioning signal transceiver module receives wireless positioning information, determines the position code, and initiates the processing process. DC stepper motor driver, power supply system and various types of sensor data acquisition, mainly including temperature, humidity, power supply voltage, harmful gas content. The overall architecture of the underground cable channel intelligent management software platform integrating intelligent management system, inspection robot and defect detection technology is shown in Figure 3. The software platform, tunnel assembly, power supply assembly, communication assembly together constitute a hanging rail cable tunnel intelligent inspection robot system using wireless fixed-point sensors.

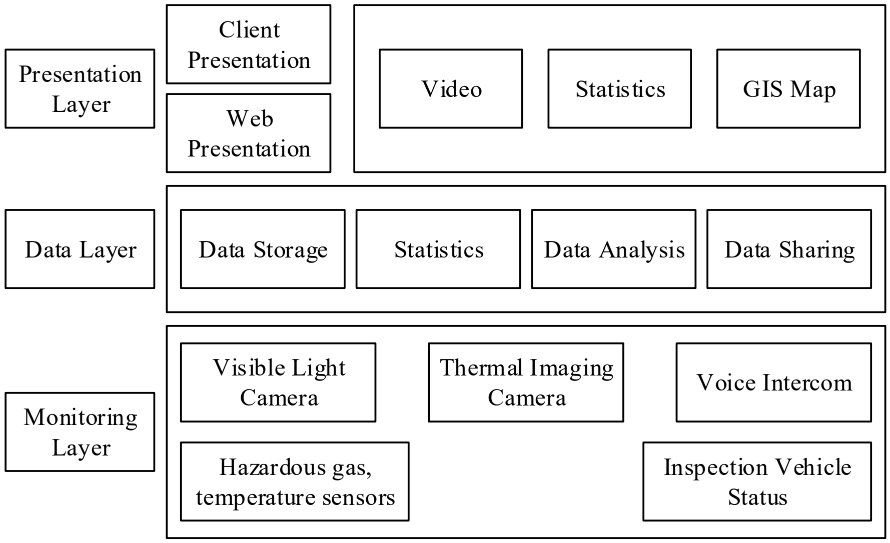
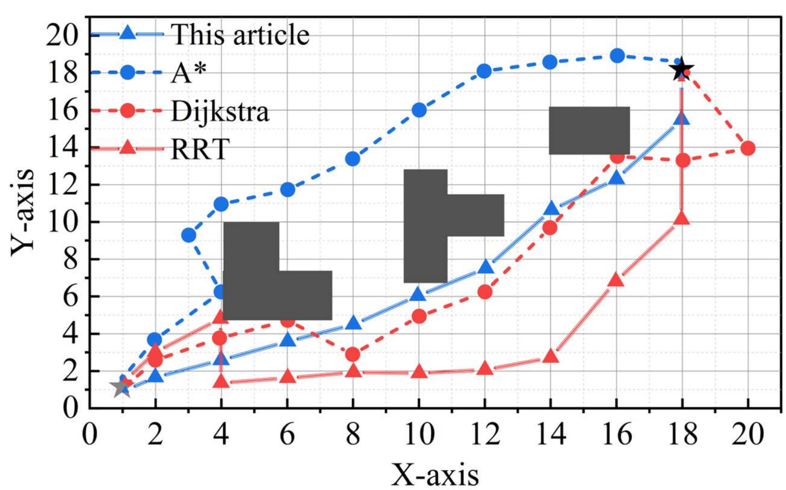


Fig. 3. Intelligent management system platform

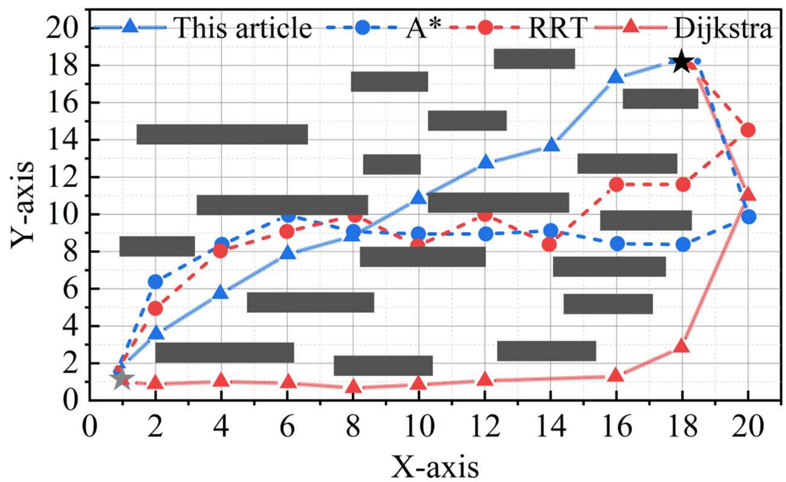
4. Application analysis of intelligent management systems for underground cable tunnels

4.1. Robot Path Planning and Deskew Performance Analysis

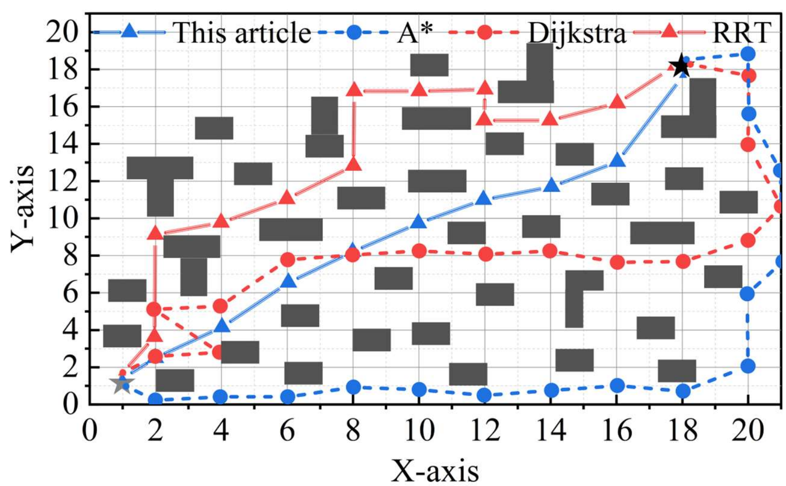
4.1.1. Obstacle avoidance performance analysis results. In order to verify the effectiveness of the previously proposed path planning and deviation correction method for intelligent inspection robots, three raster map scenarios with the same start and end points and obstacles of increasing complexity in turn are constructed in this section in the Matlab simulation environment [28]. The path planning and deviation correction methods in this paper, A* algorithm, Dijkstra's algorithm and RRT algorithm are used for the global path planning of the intelligent inspection robot, respectively. The simulation results of the intelligent robot inspection path are shown in Fig. 4, (a)-(c) represent the simulation results of the obstacle avoidance map scene Ⅰ, map scene Ⅱ and map scene Ⅲ, respectively, and the grey and black five-pointed stars in the figure represent the starting point and the end point of the path, respectively. It can be seen that the method proposed in this paper, due to the combination of positioning and magnetic field signal detection methods, the planning effect of the robot inspection path is better than the comparison methods, and it can correct the deviation of the robot inspection process in time to avoid the problems of hitting the obstacles and the path bypassing the distance.



(a) Map scene Ⅰ



(b) Map scene Ⅱ



(c) Map scene Ⅲ

Fig. 4. The intelligent machine is simulated by the path simulation

Each method was executed 20 times on each scene map with the same starting and ending points, and the corresponding average time consumption, average number of inflection points, and minimum distance from obstacles were calculated. The results of the simulation comparison analysis of different path planning methods to in intelligent robot inspection are shown in Table 1. Compared with Dijkstra's algorithm and A* algorithm, the method proposed in this paper consumes less time, and the average time consumed in the simulation map scenes I, II and III are 6.89s, 7.56s and 9.14s, respectively, and there are fewer inflection points after the curve is smoothed. Meanwhile, the paths planned by the proposed method in this paper have lower collision risk due to the absence of diagonal crossing obstacles. Among the three compared methods, the RRT algorithm has the shortest computation time (t=10.55s, 12.41s and 12.99s), but the RRT algorithm consists of random tree nodes, and the paths have too many inflection points (9, 12 and 18). This will increase the probability of wheel slippage of the intelligent inspection robot, leading to low positioning accuracy and even navigation failure. Simulation results show that the robot inspection path planning method proposed in this paper has better safety, real-time and smoothness, and is more suitable for high-risk environments such as underground cable tunnels.

Table 1. Comparison analysis of different methods of simulation

Method	Map scene	Time (s)	Inflection point	Collision probability
This article	I	6.89	0	Low
	Ⅱ	7.56	2	Low
	Ⅲ	9.14	4	Low
A*	I	13.42	5	Height
	Ⅱ	13.98	5	Height
	Ⅲ	14.26	8	Height
RRT	I	10.55	9	Height
	Ⅱ	12.41	12	Height
	Ⅲ	12.99	18	Height
Dijkstra	I	14.26	7	Height
	Ⅱ	14.89	9	Height
	Ⅲ	15.32	5	Height

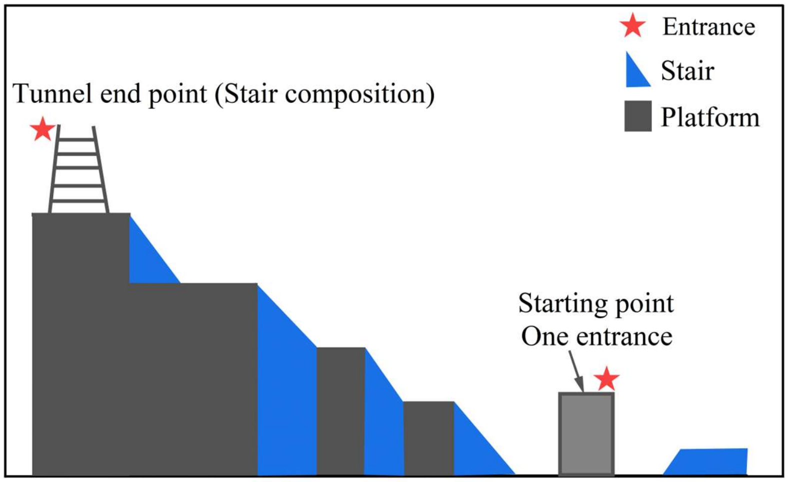
4.1.2. Simulation analysis of underground cable tunnel environment. In order to further verify the effectiveness and operability of the path planning method in this paper, this paper builds the simulation environment of underground cable tunnel in Matlab software, and carries out the verification of the effectiveness of the path planning of the inspection robot in the built simulation environment. Simulation tests show that the underground cable tunnel inspection robot in this paper can complete the construction of the map in the underground cable tunnel, can be designed according to the set target position path and according to the designed path to achieve automatic navigation function. During the simulation inspection process, the robot retains the smoothness of the global path before encountering dynamic obstacles, and when it detects dynamic obstacles appearing on the global path, it automatically filters the global path nodes contained in the dynamic obstacles, so that the path of dynamic obstacle avoidance is smoother, with fewer judgements and higher efficiency. A number of repetitive experiments were conducted using the methods that are currently used more in practical applications and the path planning and deviation correction methods in this paper. The navigation distances were taken as 10m, 20m and 30m, and each group was repeated 5 times, and the experimental comparison results of the simulation environment of underground cable tunnels with different methods are shown in Table 2. Compared with the existing methods, the travelling speed of the intelligent inspection robot under the path planning method proposed in this paper is improved by 12.69%-15.65%, and the actual path is shortened by at least 15.65%. It can be seen that the intelligent inspection robot path planning and deviation correction method proposed in this paper is more suitable for the underground cable tunnel environment.

Table 2. Simulation results of different methods

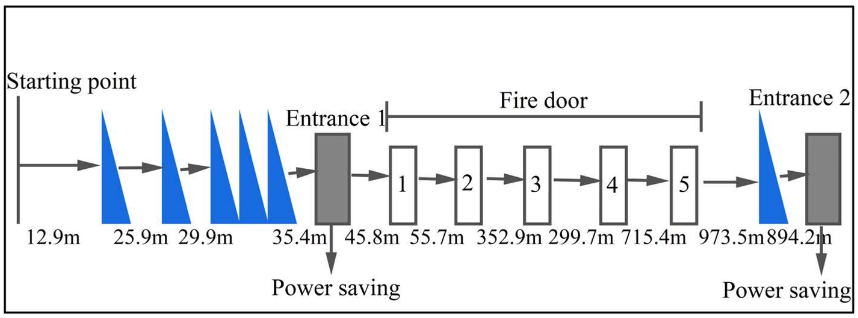
Method	Test channel length	Mean time (s)	Mean path length (m)
Existing method	10	81.26	13.52
	20	142.93	25.94
	30	229.87	39.87
This method	10	68.54	10.98
	20	124.79	21.88
	30	198.65	31.92

4.2. Underground Cable Tunnel Site Investigation Analysis

4.2.1. Underground cable tunnel site structures. December 24, 2023 this paper organises the survey of an underground cable tunnel in a city, the structure of the underground cable tunnel is shown in Figure 5, (a) and (b) represent the staircase structure and route structure schematic diagrams respectively. Underground cable tunnel survey data, the tunnel staircase slope more than 35 °. The underground cable tunnel entrance environment is complicated by the presence of multi-lead downhill sections, non-staircase sections lead to flat and straight, and the equipment cloth shoulders at both ends of the road are similar. The first underground cable tunnel is about 3441m long, the steps are all between 10-15cm in height, the spacing of the steps is 35cm, the width of the road is 75cm, and the width of the road at the fire door is 68cm. Underground cable tunnels are not installed with rail robots, there is no adequate power supply system, there is no other online monitoring system, and the tunnel exists a multi-level continuous downward step section, the straight tunnel environment will subsequently be a very big challenge for the application of navigation and positioning.



(a) Stair structure schematic



(b) Route structure schematic

Fig. 5. Underground cable tunnel structure

4.2.2. Analysis of communication effects. The intelligent management integration system designed in this paper is applied in this underground cable tunnel, and the intelligent inspection robot moves at a speed of about 0.55m/s in the underground tunnel. The communication signal strength is observed in the background system of intelligent management integration, and the actual bandwidth of wireless communication is tested using win box software. The communication effect of the test results of statistics as shown in Table 3, intelligent monitoring robot in the power tunnel communication signal strength by the distance of the more obvious, the robot from the current establishment of the link to the communication base station the further the signal strength will be lower. In the test, the robot from the communication base station 1 in 210 metres around the communication signal strength to reach the base station switching threshold near, and then switch to the base station 2 after the robot in 212 metres to switch to the base station 2, and its communication signal strength to return to high strength. In the switching instant network delay of about 0.8 seconds, the robot upward transmission of video signals slightly lagging, does not affect the robot's actual monitoring use. In the tunnel at various distances although the signal strength has some enhancement or attenuation, but the communication bandwidth is basically stable, the communication connection is basically normal throughout the test process, the data transmission between the robot and the back-end system is normal, and the communication scheme of the intelligent management system is practicable.

Table 3. Antenna gain and bandwidth test results of different distances

Robot distance bridge position (m)	Antenna gain (dBi)	Communication bandwidth (Mpbs)	Current base name
25	-15/8	100	Base station 1
60	-20/25	105	Base station 1
110	-25/22	111	Base station 1
160	-45/35	109	Base station 1
210	-65/60	109	Base station 1
212	-75/50	110	Base station 2
220	-15/8	107	Base station 2
230	-22/26	108	Base station 2
250	-30/26	108	Base station 2
300	-45/52	110	Base station 2

4.2.3. Analysis of the effect of cable defect detection. When using the intelligent management integrated system to detect and locate defects in underground cable tunnels, it is found that abnormal signals are found in the A-phase terminals of a section of cables in underground cable tunnels, and the analysed spectrogram of the discharge pulse displayed by the system is shown in Fig. 6. It can be found in the 26-32ns and 72-84ns time period, the section of the cable A-phase terminal discharge pulse amplitude abnormalities. The amplitude of the signal pulse fluctuates between -0.05-0.05 V during the rest of the time period, and based on these characteristics, it is initially judged that the signal is the internal discharge signal of the detected phase. Since the cable terminal has been in normal service for ten years, it can be initially judged to be a discharge caused by normal aging of the main insulation. This also shows that the integrated system for intelligent management of underground cable tunnels proposed in this paper can effectively detect and identify the location of defects in underground cable tunnels and upload them in real time. It enables the relevant staff to find abnormalities or defects and solve them in time, effectively preventing the occurrence of fire and other accidents in underground cable tunnels.

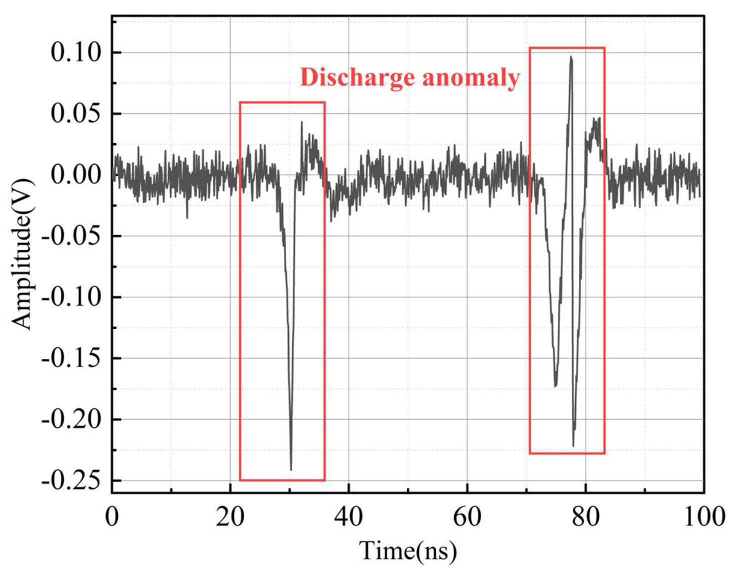


Fig. 6. Pulse analysis of cable terminal discharge

5. Conclusion

The traditional monitoring methods in underground cable tunnels have the problems of insufficient standardisation and intelligence, which make the cable tunnels more difficult to be inspected and overhauled in daily operation. Therefore, this study proposes a correction method for intelligent inspection robot path planning and defect identification and positioning technology, and integrates the two technologies to build an intelligent management system for underground cable tunnels.

The simulation results show that the method proposed in this paper combines the positioning and magnetic field signal detection methods, the planning effect of the robot inspection path is better than that of the comparative methods, and it can correct the deviation of the robot in the inspection process in a timely manner, avoiding the problems of hitting the obstacles and the path bypassing the distance. The average time consumed in the simulation map scenes Ⅰ, Ⅱ and Ⅲ is 6.89s, 7.56s and 9.14s respectively, and there are fewer inflection points after the curve is smoothed, which is more suitable for high-risk environments such as underground cable tunnels. The application in the field survey of underground cable tunnels found that the communication scheme of the intelligent management system is practicable, and the communication connection is basically normal during the whole testing process, and the data transmission between the robot and the backstage system remains normal. At the same time, it is found that the underground cable tunnel intelligent management system proposed in this paper can effectively detect and identify the location of defects in underground cable tunnels and upload them in real time, which has a good application effect.

In conclusion, the underground cable tunnel intelligent management integrated system proposed in this paper can achieve automatic monitoring judgement and early warning, and effectively improve the cable tunnel transmission operation safety system.

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