Design of Cable Trench Inspection Robot System Based on Improved D*Lite Algorithm

Faqiang Zhao* and Kun Zhou
Shenzhen Power Supply Bureau Co., Ltd, Shenzhen, Guangdong Province, China

*Corresponding author. Email: 13902968330@139.com

Abstract. Aiming the problem of on-line monitoring of the running state of underground cable trench, a cable trench inspection robot system is designed according to the cable trench environment, the requirements of on-line monitoring of underground cable trench, as well as the constraints brought by the underground cable trench environment are analyzed, and an inspection robot, including image module, temperature and humidity detection, combustible gas detection, motion mechanism, automatic navigation module, host system etc., are built. Multi-joint series structure crawler and dual central processing unit (CPU) are used to reduce the whole volume and weight of the robot. D*Lite algorithm is improved by fireworks algorithm. In this way, the distance between robot body and obstacles is increased, the smoothness of planning path is improved, and the path planning for cable trench environment is realized. Experiments of the scene show that, the robot system realizes the automatic inspection of the underground cable trench, and the required various cable operation information are obtained. It shows good crossing ability in the cable trench environment and satisfied the demands of the online monitoring of the underground cable trench.

Keywords: cable trench inspection, inspection robot, D*Lite algorithm, automatic navigation.

1. Preface
Underground cable trenches are responsible for the transmission of electrical energy and sometimes include functions such as metering, communication, and relay protection [1-2]. However, the discharge caused by the aging of the outer insulation of the cable, and the accumulation of flammable gas in the cable trench may cause fire and explosion in the underground cable trench. Therefore, it is necessary to strengthen the inspection of underground cable trenches to find and eliminate internal hidden dangers as soon as possible. However, due to the small and complicated internal environment of the underground cable trench, it is particularly difficult for staff to inspect it, which makes the operation of the underground cable trench lack of prevention of cable insulation and temperature monitoring of aging cable, lack of flammable gas concentration monitoring, and management of water and tide in the cable trench. In response to these problems, the use of robots instead of manual inspections to achieve online monitoring of underground cable operating conditions is of great significance for improving the stability and reliability of cable operations [3-4].

For the online monitoring of underground cable conditions, the Eastern Power Corporation developed the online monitoring cable system "PCJMS" in 2004, which can monitor the temperature of...
the power connector [5]. In 2007, Beijing Electric Power Company proposed a remote monitoring system for underground cable tap temperature [6]. In 2011, Shanghai Jiao Tong University developed a "Computer Comprehensive Monitoring Device for Underground Cable Tunnels" detecting temperature, humidity, and flammable gas concentrations in underground cable tunnels. The United States Alfredo-Vaccaro designed an integrated framework for smart grids in 2013, which combines equipment control and online monitoring of underground cables for the data link control of cable tunnel status. These achievements focus on the online monitoring of simple objects such as temperature and combustible gas concentration, which is difficult to cope with complex fault situations.

The inspection robot is a feasible way to realize the online monitoring of underground cable trenches more effectively in real time. In 2005, the University of Washington designed the “Router” underground cable monitoring robot [7]. The robot carries a variety of sensors that can upload the temperature and dielectric loss information of the power cables in the tunnel to a remote host, which still remains some problems such as short working time, short communication distance and poor waterproof performance. In 2009, Shanghai Jiao Tong University developed a cable tunnel condition monitoring robot [8], but this robot needs to be manually controlled, and its volume is not suitable for narrow underground cable trenches. Zhejiang University cooperated to develop an underground cable tunnel condition monitoring robot in 2012 [9], which has an independent inspection function. The drawback is that it is too large and only suitable for inspection in relatively wide cable tunnels.

The cable ditch inspection robot system designed in this article is completely designed for the environment of underground cable ditch, which can realize automatic cruise monitoring.

2. System structure and principle

The inspection of the internal lines of the underground cable trench mainly includes: whether rubble and garbage are accumulated inside the underground cable trench; whether the power cable is damaged or broken; whether the cable is deformed in the normal and the joint position; whether the temperature of the cable’s outer sheath exceeds the regulations; whether the humidity and the flammable gas concentration exceeds the standard.

The space of the underground cable trench is narrow with the space for robot moving no more than 500mm. There are many obstacles and ups and downs in some areas.

Inspection targets and environmental constraints above impose the following requirements on the underground cable trench inspection robot:

1. With a camera, the robot can observe outer surface of power cable in underground cable trench.

2. Carrying sensors that can monitor the temperature, humidity, and flammable gas concentration inside the cable trench, as well as equipment that can monitor the outer surface of the power cable and the temperature of the cable tap, uploading data for real-time storage.

3. With certain flexibility and power, the robot can climb over obstacles in narrow and complicated cable trenches and avoid collision with objects around the cable.

Therefore, the overall structure and layout of the robot designed in this article is shown in Fig. 1.

![Figure 1. Block diagram of the overall structure design of a cable trench inspection robot.](image-url)
3. System hardware design

In order to meet the strict requirements on the volume of the robot due to the narrow and complicated internal environment of underground cable trench, a crawler robot with a multi-joint series structure was proposed.

The laser radar is placed at the highest position on the top of the first joint. A camera is placed on the front and back of the robot to observe the front and rear road conditions. A gimbal camera and monitoring sensors are placed on top of the robot's middle joint. An industrial computer is placed inside the first joint, most of the hardware of the control system is placed inside the second joint, and a power module is placed in the third joint. A joint connection component and an adjustable resistor are installed between each joint.

Assuming $T_1$ is the torque to be overcome when the robot walks over obstacles, and $T_2$ is the torque to be overcome during acceleration, the mass is $m$, the climbing angle is $\theta$, the acceleration is $a$, the acceleration of gravity is $g$, and the radius of the driving wheel is $r$, then the maximum torque that the robot driving wheel needs to provide is given by Eq. 1 for

$$T = T_1 + T_2 = mgsin \theta + mar$$

The ASLONG DC geared motor equipped with a reduction gear box is selected as the drive motor of the condition monitoring robot of which the torque and speed can meet the design requirements.

The overall structure of the underground cable trench condition monitoring robot control system is shown in Fig. 2. The robot body control system communicates with the airborne industrial control computer via Ethernet, and the airborne industrial control computer communicates with the human-machine interaction interface of the ground control terminal through wireless Ethernet.

![Overall structure of the robot control system for underground cable trench condition monitoring.](image)
In order to minimize the overall volume and weight of the robot, this system uses a dual CPU design, including main control board of the robot and the airborne industrial control computer. The robot condition monitoring module includes a camera and multiple sensors. The system uses a combination of environmental sensing sensors and proprioceptive motion sensors to autonomously avoid obstacles for the robot [9].

4. System navigation algorithm design

The system navigation strategy consists of two parts: RBPF (Rao-Blackwellized Particle Filter)-SLAM (Simultaneous localization and mapping) algorithm for positioning and map construction, and improved D* Lite algorithm for path planning.

The D* Lite algorithm is a reverse search algorithm which assumes no obstacles in the unknown area. The optimal path is calculated by calculating the rhs (Right Hand Side) value. The cost value from the target point to current position is represented by \( g(s) \), and the heuristic value from current position to initial point is represented by \( h(s) \). To find the smallest cost value, \( g(s) \) will be recalculated when the robot expands the neighboring 8 nodes. The formula for \( rhs(s) \) is as follows:

\[
rhs(s) = \begin{cases} 
0, & s = s_{\text{goal}} \\
\min_{s' \in P_{\text{red}}(s)} (g(s') + c(s', s)), & \text{others}
\end{cases}
\]  

(2)

The formula for calculating the heuristic value \( h(s) \) from the current position to the initial point is as follows:

\[
h(s, s_{\text{start}}) = \begin{cases} 
0, & s = s_{\text{start}} \\
c(s', s) + h(s', s_{\text{start}}), & \text{others}
\end{cases}
\]  

(3)

where \( s' \in P_{\text{red}}(s) \) represents that \( s' \) is the successor node of \( s \), and \( c(s', s) \) represents the edge cost of node, generally denoted as 1.

\( k(s) \) is the evaluation value of the evaluation node, containing \( k_1(s) \) and \( k_2(s) \). When the robot analyzes eight neighboring nodes, it calculates \( k_1(s) \) and \( k_2(s) \). The node with the smallest \( k_1(s) \) is the next node for robot movement. \( k_1(s) \) and \( k_2(s) \) can be calculated by the following Eq. 4 and Eq. 5:

\[
k_1(s) = \min(g(s), rhs(s)) + h(s)
\]  

(4)

\[
k_2(s) = \min(g(s), rhs(s))
\]  

(5)

When the values of \( k_1(s) \) and \( k_2(s) \) are equal, the D* Lite path planning algorithm is completed.

The D* Lite path planning algorithm has good applicability, but the algorithm will re-plan new paths only when it encounters an obstacle, which may cause the robot to be too close to obstacles inside underground cable trenches, affecting actual traffic. Therefore, this article uses the firework algorithm to improve the D* Lite path planning algorithm.

Compared with D* Lite algorithm, the improvements are as follows:

When planning the optimal path, the improved D* Lite algorithm adds the mapping operation in the firework algorithm. The modulo operation mapping rules are as follows:

\[
x^k_1 = x^k_{\text{min}} + k_1 \% (x^k_{\text{max}} - x^k_{\text{min}})
\]  

(6)

where \( x^k_1 \) denotes the i-th position of the fireworks beyond the boundary on the k-dimensional plane, while \( x^k_{\text{max}} \) and \( x^k_{\text{min}} \) denote the upper and lower boundary values on the k-dimensional plane, and \( \% \) denotes the modulo operation symbol.
(i) Choose important turning points. Delete waypoints in the same direction as the parent of the previous node. All path nodes are planned with this method, then the combination called important turning point is obtained which consists of only the starting point, turning point, and ending point.

(ii) Construct the fitness function of the firework algorithm. Use Eq. 7 to express the cost value of the path:

\[ C = \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} p_{ij} \]  

Eq. 8 as an individual fitness function

\[ T = \begin{cases} 
P_{\text{max}} - C, & C < P_{\text{max}} \\
0, & C \geq P_{\text{max}} 
\end{cases} \]  

where \( P_{\text{max}} \) is a relatively large, suitable number.

(iii) Smooth paths between important turning points. Use the firework algorithm generates an approximate optimal solution at two adjacent important turning points.

![Figure 3. D* Lite algorithm planning path.](image)

Fig. 3 shows the comparison between the route smoothed by the D* Lite algorithm improved by the firework algorithm and the route without the fireworks algorithm. The improved D* Lite algorithm has fewer turning points and farther distance from obstacles.

5. Experimental results and analysis
The robot can construct an environment map and run automatically in underground cable trench as shown in Fig. 4. The experiments show that the designed robot can effectively perform simultaneous positioning and map construction in the underground cable trench, and can perform real-time autonomous navigation and avoid obstacles.
6. Conclusion
The experimental results show good underground cable trench motion capabilities of this design, which can implement map construction and autonomous navigation to avoid obstacles, and monitor the internal conditions of the cable trench in real time, with good human-computer interaction. The main shortcomings include dead angles in the camera, limited communication distance and limited running time. The improvements will reduce the inspection intensity and difficulty of staff while improving the stability and reliability and bringing significant economic and social benefits.

References
[1] Guan Yulong, Analysis and Thinking on Problems Related to Power Grid Planning, J. Technology and Market. 1 (2015) 118-118.
[2] Liang Wei, Analysis of Causes of Power Cable Explosions and Study on Solutions, J. Jiangxi Electric Power. 2 (2017).
[3] Jongen R, Quak B, Tenbohlen S, et al. New developments in on-site testing of long lengths of (E)HV power cable, C. International Conference on Condition Monitoring & Diagnosis, 2012.
[4] Hepburn D M, Zhou C, Song X, et al. Analysis of on-line power cable signals, C. International Conference on Condition Monitoring & Diagnosis, 2016.
[5] Siddiqui B A, Pakonen P, Verho P. Novel inductive sensor solutions for on-line partial discharge and power quality monitoring, J. IEEE Transactions on Dielectrics & Electrical Insulation. 24 (2008) 209-216.
[6] Lin Yongfeng. Research on Computer Integrated Monitoring System for Power Cable Tunnel, D. Shanghai Jiao Tong University, 2007.
[7] Vaccaro A, Popov M, Villacci D, et al. An Integrated Framework for Smart Microgrids Modeling, Monitoring, Control, Communication, and Verification, J. Proceedings of the IEEE, 99 (2011) 119-132.
[8] Feng Liuzhong. Research on mobile robot navigation and positioning technology based on multi-sensor information fusion, D. Southwest Jiaotong University, 2011.
[9] Zhang Weihua, Feiling Ling. Hangzhou Electric Power Bureau Enables Intelligent Robots to Care for Cable Tunnels Under the Lake [EB/OL]. http://www.sgcc.com.cn/ztzl/newzndw/sdsf/05/273693.shtml, 2016.05.31