Comprehensive Analysis of Inspection Robot Technology and Application in Substation

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Abstract. For the past few years, with the development of smart grid and Industry 4.0 concepts, global industrial development has continued to accelerate, followed by a substantial increase in the demand for electricity by users. As a result, there is a sharp rise in the number of electrical equipment and electrical places, which not only adds to the workload of inspection and maintenance staff but also leads to unsatisfactory industrial production efficiency. The emergence of intelligent inspection robots has solved this problem to a great extent. In this paper, the main technology and application of inspection robots in substations are summarized and analyzed comprehensively. In view of the current research history and development status in this field, the working principle, core technology, optimization measures, and development trend of substation inspection robots are studied and discussed. Based upon this, the future research and development direction is proposed with a summary discussion on the research status of substation inspection robots completed. This paper has certain guiding capabilities and reference values for the investigation of substation intelligent inspection robots.

Keywords: intelligent inspection robot; substation intelligent inspection; computer vision; autonomous navigation; SLAM

1 Introduction

In the traditional industrial field, real-time monitoring of equipment safety and timely investigation of possible safety problems are the primary goals and necessary conditions for the normal operation of substations. Therefore, the equipment inspection of the power system has become the most important part of the industrial process. For the past few years, the concept of smart grid and industry 4.0 has gradually improved the development level of the industry. People's demand for power supply continues to increase and the electricity load of the whole society has increased significantly. Therefore, the security of substations is an important research topic. It is helpful to

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ensure the safe operation of substations by patrolling the equipment and environment in substations [1].

At present, many substations in developing countries are still operated by manual inspection, which can not adapt to the current situation of the rapid increase of electricity facilities. The work efficiency and accuracy of manual inspection are greatly limited by the working level, proficiency, and working status of inspection personnel, which indicates that there is a high possibility of missing detection and misjudgment of equipment in the inspection process and even power accidents in serious cases. It can be seen that the operation mode of manual inspection is not reliable, but the use of intelligent robots for substation equipment inspection not only improves the reliability of the work but also makes up for the defects and deficiencies in the process of manual inspection. The comparative analysis of manual inspection and robot inspection is shown in Table 1.

Table 1. Comparative Analysis of Manual Inspection and Robot Inspection

	Manual Inspection	Robot Inspection
Inspection Mode	The process is cumbersome and complicated.	The process is simple and flexible.
Workload	The number and scale of equipment are large, and the workload is large.	Robot automatic inspection analysis effectively reduces the workload.
Objectivity	There are many influencing factors and different objectivity.	The robot works according to preset values and is more objective.
Accuracy	Affected by positions and angles, the accuracy is low.	Relying on high-definition cameras and recognition patterns, the accuracy is high.
Convenience	Need operation and maintenance personnel to check the station, the convenience is poor.	Single-station and centralized control applications are more convenient than manual inspection.
Defect Tracking	Defective devices need to be checked periodically.	Real-time tracking and monitoring can be achieved according to preset tasks.

Computer vision technology uses machines instead of human eyes to capture and judge information, which can not only improve the accuracy and rapidity of identification and positioning but also save labor costs to a great extent. Automatic navigation technology uses the mainstream Lidar SLAM (Simultaneous Localization and Mapping) technology as the main body to conduct real-time positioning and map construction, which can reduce human errors in inspection work and improve the reliability and accuracy of data. The intelligent robot patrol using computer vision and automatic navigation technology will also become the inevitable trend of substation equipment inspection, its research space and application prospects are very broad [2].

Therefore, this paper studies and discusses the inspection robot used in substation from many aspects, and completes a review of its research status. Among them, the second chapter introduces the composition of the intelligent inspection system and the application of key technologies, the third chapter introduces the application cases of intelligent inspection robots, and the fourth chapter discusses the limitations, optimization measures, and development trends. The fifth chapter gives a summary of the full text.

2 Intelligent Inspection System

2. 1 System Composition

The intelligent inspection system can be deployed in the substation, and the three-dimensional inspection system is built with a laser navigation wheeled robot, orbital robot, and fixed point camera as the core, to realize intelligent inspection, intelligent operation, intelligent linkage, and intelligent safety inspection system [3, 4].

The architecture of an intelligent inspection robot consists of three layers: in-vehicle subsystem, local monitoring backend, and remote centralized control background. The in-vehicle subsystem transmits inspection data from the Intranet channel to the local monitoring backend through the wireless network. The remote centralized control background obtains inspection results from the monitoring backend through the self-built private network to achieve remote monitoring. The architecture composition of the inspection robot is shown in Fig. 1.

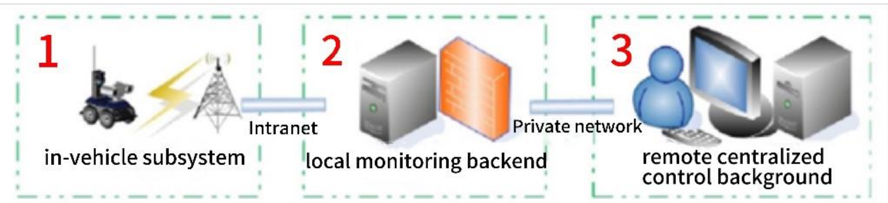

Fig. 1. Inspection robot architecture diagram [5].

In order to achieve autonomous power supply of inspection robots, charging piles are equipped in most substations, and are connected with the monitoring center through a wireless network to complete real-time communication. In addition, most robot bodies are equipped with vision systems, automatic navigation systems motion control systems, etc., which can realize automatic substation inspection. Due to the requirements of instrument data reading and monitoring in substation scenes, computer vision perception technology and autonomous navigation technology are important technical cornerstones for efficient task execution.

2.2 Computer Vision Technology

Computer vision is a technology that obtains image information through the camera and perceives it through software algorithms. In terms of image acquisition, there are various types of cameras based on imaging principles, such as long-wave infrared cameras, short-wave infrared cameras, RGB cameras, etc. In terms of software algorithms, it mainly includes image preprocessing, image feature extraction, information analysis, etc. Computers can use a variety of imaging systems rather than the visual system of the brain to process and interpret, and eventually can observe and understand the world through vision, and gain the ability to adapt to the environment independently. The power intelligent inspection robot takes images of the equipment through the high-definition visible light camera and uses computer vision technology to independently identify and judge the running state of the equipment.

Substation-integrated monitoring technology based on the process of digital image and computer vision technology has become a significant segment of making certain operations and maintaining substations. The task of monitoring the substation is mostly achieved by the cloud platform system, which usually consists of the cloud platform and detection facilities. A stable cloud platform is the hardware premise of obtaining high-quality information, and a real-time robust vision processing algorithm is the guarantee of detecting software efficiently. In order to operate substation checking work stably, the cloud platform needs to satisfy the requirements of high control accuracy, nice performance of dynamics, and convenient secondary development, so that the equipment examination information can be obtained smoothly and rapidly with electrical and magnetic strength in the substation [4].

Among the technologies mentioned above, there are two main recognition technologies carried by robots:

1) Automatic localization and recognition technology based on local feature matching: it adopts the Canny algorithm to extract image edges, SURF feature algorithm to match regions, and digital template image library for SVM classification training to obtain final accurate recognition results.

2) Automatic indication recognition technology based on virtual line segment determination: that is, the coordinate position of the component in the image is obtained through the ROI extraction method [6] based on the feature matching of the template image. This technology can construct a graphic model through computer graphics, then cut the area of interest in the original image by image processing means, and determine the location of the component by using the relevant line segment detection technology.

Compared with other visual recognition technologies, machine vision has faster recognition speed, higher accuracy, and stronger data reliability.

2.3 Automatic Navigation Technology

In the current industrial field, the positioning and navigation technologies adopted by mobile inspection robots mainly include magnetic navigation technology, orbital navigation technology, inertial navigation technology, GPS navigation technology, and SLAM navigation technology [7-8].

In the existing field of power intelligent inspection, the most commonly used technology is Simultaneous Localization and Mapping (SLAM) technology [8]. SLAM technology is a complete process of robot localization, mapping, and path planning in an unknown environment. If the robot is placed in an unknown space, SLAM means that it will position itself according to location estimates and sensor data as it moves, while building an incremental map [9]. The comparison of the above five types of navigation technologies is shown in Table 2 below.

Table 2. Comparison and Analysis of Positioning and Navigation Techniques

	Working Principle	Working Characteristics
Magnetic Navigation Technology	The track is laid on the road surface, and the track position is sensed by magnetic navigation sensors to achieve autonomous navigation.	Need to lay magnetic track, construction cost is high; And the track is exposed, easy to cause damage, high maintenance costs.
Orbital Navigation Technology	Utilize preinstalled tracks and feature identification points to achieve robot fixed-point detection.	The outdoor area is large and the environment is complex, and the track cannot be lifted. The track navigation method is not suitable.
Inertial Navigation Technology	Based on the measured physical quantity data, obtain human motion information and achieve positioning and navigation.	There is a positioning error in measurement, and the long-term operation of the robot will generate cumulative errors, resulting in navigation deviation.
GPS Navigation Technology	Using GPS satellites to navigate and locate the robot's position.	The positioning accuracy is usually at the meter level, with low accuracy; GPS signals are susceptible to electromagnetic interference and have low reliability.
SLAM Navigation Technology	Using real-time positioning and map construction technology based on Lidar, obtain laser point cloud maps to achieve autonomous operation and precise positioning.	No need for preliminary infrastructure, low construction cost, real-time adjustment of posture, and high positioning accuracy; Optimal path planning can be achieved based on laser maps to improve inspection efficiency.

Xu et al. proposed the loopback detection module and the pose map optimization module by adding hybrid Scan Context and Lidar Iris. In the laser odometer thread, input the point cloud obtained by Lidar, extract corner points and surface points of the point cloud, and then match the current frame with the local map. The residual equation is constructed by the distance from the point to the line and the point to the plane, and the pose of the laser odometer is obtained by iterating the residual equation. In the construction thread, the point cloud is transformed into the world coordinate system by the pose obtained by the laser odometer thread, and the feature map of the point cloud is established. Before the loopback detection process, the keyframe is selected, then the key frame point cloud is used to obtain descriptors, and candidate key frames similar to the current keyframe are searched. Then the feature image is selected by using the Lidar Iris descriptor, and the optimal keyframe most similar to the current keyframe is calculated and obtained. Finally, the pose transformation between the current most similar candidate key frames is solved by the feature matching constraint based on residual weight, and this transformation is added to the position pose map. The global pose map is optimized for solving, to obtain the pose of laser SLAM after loop correction and the globally consistent map, which can adapt to the unstructured operation environment of the substation. It provides a new idea for intelligent substation inspection positioning method [2].

At present, most intelligent inspection robots use SLAM technology to carry out feature extraction, three-dimensional reconstruction, obtaining feature landmarks, and determining site location, to realize autonomous operation and accurate positioning of robots.

3 Intelligent Inspection Application Cases

3.1 Rail Inspection Robots

The sliding rail inspection robot is generally divided into two types: ground and sky, of which the ground inspection robot is mainly a rail truck, and it is installed with a variety of high-tech equipment, such as Lidar, infrared thermal imager, video surveillance machine, and sonar scanner, which can provide an integrated detection scheme for on-site security. The sky inspection robot is based on orbital inspection robots or drones, equipped with a variety of vision sensors, ultrasonic sensors, etc., and can realize the detection and monitoring of large spaces in the air.

In the current field of safety supervision, the application of rail inspection robots is particularly extensive. As early as 1980, Japan began to use magnetic navigation and equipped with infrared thermal imagers to apply mobile robots in substations. This robot can detect thermal defects caused by equipment in 154-275 kV substations, as shown in Fig. 2. (a). In the 1990s, Japan developed a distribution line maintenance robot, as shown in Fig. 2. (b). In 2008, Brazilian scholars designed a sliding substation inspection robot capable of working at high altitudes, which is equipped with a mature Wi-Fi and infrared thermal imager system, as shown in Fig. 2. (c), which can be used to detect the hot spots of substation power equipment [10]. In 2019, China's Nanjing Yijiahe Company launched a rail inspection robot carrying a variety of sensors, which has both an equipment inspection function and an indoor environment monitoring function, as shown in Fig. 2. (d). The KL100 KUKA linear slide KL100, developed by

Kuka, Germany, is an independent single-axis slide mounted on the floor, ceiling, or wall, which operates as an additional axis for the robot. Thus, the control is carried out by the corresponding robot controller, as shown in Fig. 2. (e). In 2022, China's Zhejiang Autonomous Robot launched the MR200 intelligent rail-mounted inspection robot, as shown in Fig. 2. (f). Equipped with an innovative robot arm design, it can carry out full coverage inspection of the equipment on the screen cabinet.

(a) Japan substation inspection robot

(b) Japan power distribution line maintenance robot

(c) Brazil substation inspection robot

(d) China Yijiahe rail inspection robot

(e) German linear slide robot

(f) China Guozi rail inspection robot

Fig. 2. Cases of rail inspection robots [11].

3.2 Wheeled Inspection Robots

Wheeled inspection robots are often used in power generation, cement, chemical industry, coal mines, steel, substation, power transmission and transformation, urban gas pipelines, and other industries to prevent equipment failures through periodic inspection of important equipment. The substation intelligent inspection robot system takes the miniaturized, lightweight, and modular inspection robot as the core, uses autonomous navigation and positioning technology, and is based on the analysis of background big data, to achieve the purpose of non-contact substation detection with multi-sensor fusion. This system can realize the all-around real-time detection of substations and intelligent monitoring with multi-performance autonomous driving. The operation and maintenance cost of the substation and the labor intensity of the staff are effectively reduced, while the quality of the inspection data is improved. The intelligent level of substation inspection is improved through technological innovation.

At the beginning of the 21st century, the United States developed a substation detection robot that can achieve automatic infrared detection of power equipment and use detection antennas to locate partial discharge positions, as shown in Fig. 3 (a). In 2015, Japanese security company ALSOK developed the 10th generation inspection robot Reborg-X, as shown in Fig. 3 (b). This is the 10th generation robot released by ALSOK and the first robot in Japan that can cruise autonomously. When on patrol, the Reborg-X is equipped with an image recognition system that can identify people's attributes by reading their facial features and clothing features to spot suspicious people or search for lost children. When providing guide services, Reborg-X with built-in Japanese, English, Chinese, Korean, and other languages can better complete the specified human-computer interaction tasks. At the same time, Knightscope, an American robot technology company, has developed and produced the K1 (fixed), K3 (indoor), K5 (indoor), and K7 (outdoor) series of inspection robots, as shown in Fig. 3 (c). K1, K3, K5, and K7 series inspection robots all use Wi-Fi networks, telecommunication networks, or a combination of the data transmission modes, the robot can process a large amount of data by itself, and then send the data to the robot control platform, the platform software can be installed on tablets, mobile phones, and other devices. Typically, these robots need to charge themselves every 2.5 hours. In 1999, Shandong Electric Power Company of China started the research and development of a substation inspection robot, and its inspection robot has been iterated to the fifth generation, as shown in Fig. 3 (d). Different from the single positioning method of other manufacturers, Shandong Electric Power Company integrates laser navigation technology and inertial visual navigation technology to improve reliability and accuracy. At the same time, the intelligent wheeled inspection robot developed by Langchi Company in Shenzhen, China, can intelligently plan inspection paths under high voltage and strong magnetic environments, greatly reducing manual workload, as shown in Fig. 3 (e). In addition, OTSAW Digital, a start-up company in Singapore, organically integrates inspection robots and reconnaissance drones. O-R3, developed and designed by them, is the world's first outdoor inspection robot covering ground and air. As shown in Fig. 3 (f), the robot adopts an advanced machine-learning algorithm and 3D SLAM technology. Automatic cruise is realized, and a variety of sensors are also equipped with functions such as ground-air cooperative monitoring[3, 10-13].

(a) American power inspection robot

(b) Reborg-X robot

(c) Knightscope inspection robot

(d) China Shandong inspection robot

(e) China Shenzhen Langchi robot

(f) Singapore outdoor inspection robot

Fig. 3. Cases of wheeled inspection robots [11-13].

4 Discussion

4.1 Limitations and Optimization Measures

Nowadays, substation intelligent inspection robots are more and more widely used in the industrial field, but there are still many limitations in the working process of intelligent inspection robots:

1) Autonomous charging and insufficient path: The charging mode can be optimized through the development of autonomous charging equipment, and the path problem of the robot needs to be solved in advance to further enhance the visual sensing function so that the robot can achieve accurate obstacle avoidance.

2) The navigation and steering mode make the system cost high and the accuracy low: The industrial cost can be controlled within a certain range by choosing more energy-efficient materials and working methods. For example, by using a laser to illuminate an unknown environment, the time difference between laser emission and reception can be measured, and the distance between the measured object and the measuring device can be calculated indirectly to achieve positioning and navigation.

4.2 Future Technical Requirements and Development Trends

According to a large number of background studies and literature surveys, the working mode of intelligent substation inspection in the future will have the following technical requirements and development trends:

1) Easier positioning and navigation: With the continuous progress of computer control technology, the SLAM algorithm is also constantly innovated and iterated. It will be an inevitable trend for inspection robots to achieve autonomous navigation with high positioning accuracy and strong robustness.

2) More multi-dimensional data analysis: With the popularization and development of big data processing technology, the analysis of inspection data will be more multi-dimensional in the future, and the prediction of operation faults will become more accurate.

3) More diversified detection content: With the development of modern detection technology, inspection robots will be able to carry more types of sensors in the future, and the equipment status information obtained will be more diversified.

4) Better Centralized equipment management: With the continuous advancement of network construction in various power consumption places, the future power equipment system will use more intelligent detection equipment such as robots as nodes to break through the information barriers between various independent scenes and achieve centralized management and control.

5) More automated field operations: With the development of the industrial automation level, the future inspection robot function will be converted to a deeper level of automatic control, reducing the work burdens of power transportation inspection personnel.

5 Conclusion

This paper presents a comprehensive overview and analysis of the main technologies and applications of inspection robots in substations. Firstly, the composition of intelligent inspection systems and the application of computer vision and automatic navigation technology are introduced, and then two types of intelligent inspection application cases are listed. Finally, the limitations of intelligent inspection robots are proposed, and the optimization measures as well as future needs and development trends are proposed.

To sum up, substation inspection robots have great development space and broad application prospects in the future. The emergence of substation inspection robots is conducive to reducing the labor cost of substation inspection, improving efficiency, and meeting the needs of maintaining equipment safety and stability. At this stage, a relatively comprehensive research and development system has been formed for substation intelligent inspection robots. According to the application situation of intelligent inspection robots in real life, the research and development focus of inspection robots should be gradually shifted to breaking information barriers and improving technical deficiencies in the future, and continuous innovation technology will make its operation results more efficient and more accurate.

Generally speaking, the research and development and use of intelligent inspection robots are gradually becoming a hot industry in the international community, and investment in the development of intelligent inspection robots should continue to strengthen, which has a pivotal impact on the future development of global power systems.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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