# Mobile Robot for Power Substation Inspection: A Survey

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***Abstract*—This paper presents the most important achievements in the field of electric power substation equipment's inspection by mobile robot. To accelerate the realization of unattended substation, which would improve the reliability, safety and intelligence of power substation, the field of automated power substation equipment's inspection has been greatly developed over the last decade. The paper addresses the power substation inspection robot, which is considered as one of the most active fields of research on mobile robot, from its history to design requirements, the robot system architecture analysis and modeling, reliability technology of the robot, autonomy and universality of substation equipment inspection. Besides, summaries and suggestions on the development and research trend of inspection robot, which should be addressed in the future, are given. The present work may serve as reference for initial design of robots for some complex and dangerous working environments. And some unique insights for the inspection robot provided in this paper may be of help to further research and application of power facilities inspection.**

***Index Terms*—Autonomic behavior, equipment inspection robot, navigational positioning, power substation.**

## I. INTRODUCTION

ALONG with the quick development of the electric power business, there is a growing requirement of power due to high dependency of people on electrical equipment. In order to minimize failures of power facilities and avoid the huge economic losses caused by power outages, transmission line and substation equipment ought to be regularly inspected for detecting defects as soon as possible to arrange the maintenance plan. It is well known that, as an essential part of modern power systems and future smart grid, the safe and stable operation of the substation equipment plays a very important role in the entire power system. And substation equipment inspection is an important means for operation and maintenance, which can ensure the secure working of the electric grid, improve power grid to run economically and afford good service for user [1]−[3]. There are, roughly speaking, two common methods of power equipment inspection, which are foot patrol and inspection by mobile robot [4]−[6]. In the foot patrol inspection, usually a team of two people traverse the substation along the scheduled route and inspect the power equipment such as transformer, circuit breaker, load switch, generatrix, current transformer, voltage transformer and so on. This kind of inspection is slow, tedious, monotonous and subjective so that even larger faults can sometimes be neglected [7], [8]. In order to improve the reliability, safety and intelligence of power substation and accelerate the realization of unattended substation, the problem of automated inspection of power substation equipment has become an important issue of the electric power industry at home and abroad [9].

With the development of robot technology and visual inspection methods which are carried out with the help of binoculars and sometimes with Infrared Ray(IR) and corona detection cameras, an available solution is to develop autonomous mobile robots, and then develop an automatic inspection approach that would be more accurate, less expensive and at least as fast as foot patrol inspection [7], [10]. Besides, another kind of power facilities inspection mobile robot is also developed to inspect and maintain power transmission line [4], and the technology of power substation equipment inspection robot can also be applied to the other hazardous environment. In comparison to the substation equipment manned patrol inspection, inspection by mobile robots would be less objective, with better inspection accuracy, better price performance, greater market space and development prospects. In this paper, we only focus on discussing power substation inspection robot.

Power substation inspection robot plays an important role in the field of electricity power facilities application special robot research. There is considerable research on the technology of power substation inspection robot, and there have been a large number of literatures published. In the 1980 s, the research work on power substation inspection robot had been carried out and achieved the valued research results by American, Japanese and other foreign scholars. The robot BIG MOUSE [11] designed by Japan Shikoku Electric Power Company and Toshiba Corporation and other research institutions was a kind of power substation inspection robot suitable for 500KV substation. Another power substation inspection robot, which can be tele-operated and controlled in real-time, was also developed by Hydro-Quebec Research InstituteCanada [12].

Since 2002, with the support of the National High-Tech Research and Development Program (863 Program), the research on power substation inspection robot (see Fig. 1) has

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been conducted by State Grid Corporation of China. And four generations of the power substation inspection robot, which is composed of mobile vehicle platform, testing sensors such as IR and corona detection cameras, the control and communication unit, and so on, have been developed successfully [2], [10], [13]. The inspection system based on the robot, the infrared thermography and sensor of visible Charge-coupled Device (CCD), can help people achieve the visible and infrared detection result for high voltage substation equipment. Since 2010, with the development of society and population ageing phenomenon becoming more severe, and the continuous increase in human resource cost, the demand for the power equipment inspection robots is becoming increasingly urgent, hence a lot of scientific research institutions have developed various conceptual prototypes of inspection robot, respectively, in China [14].

Fig. 1. Power substation inspection robot developed by Electric Power Robotics Laboratory.

So far, many research institutions at home and abroad have been carrying out active research on such robots and have made great progress, greatly promoting the development and application of power substation inspection robots. But a review on the key technologies of power substation equipment's inspection problem has not been published yet, with an exception of a short technical review, addressing exclusively inspection with robot [14]. In this paper, key technologies of power substation equipment inspection robot involving inspection requirement analysis, multi-sensor information-fusion, navigation and intelligent control, advanced application of inspection and its present domestic and abroad development state are summarized. Its existent problems that still need to be solved efficiently are analyzed, the proposed solutions are critically assessed, and other tasks that could be performed by an inspection robot and its application foreground are also put forward.

## II. Problem Description

This section briefly describes the inspection tasks, which need to be undertaken for power substation equipment, and it involves the most common robotic inspection technology.

### *A. Substation Equipment Inspection Tasks*

Power substation equipment inspection is an important technology to ensure the safe operation of power equipments. According to the relevant provisions of the State Grid Corp of China, the substation equipment inspection can be mainly classified into four types, which are as follows:

1) Normal inspection (including handover inspection).

In power system, the inspecting of electrical equipments, especially substation equipments plays a very important role in daily substation operation. And the normal inspection must be completed within the specified period, for example, it should be inspected once a day for unmanned substation and at least 3 times a day for manned substation.

2) Inspection after light out at night.

Check the phenomenon of corona and discharge, and check the temperature and overheat of the connector contacts and joints in substation equipments such as the high-voltage switchgear, and determine the overheat degree, when temperatures exceed preset threshold, a warning instruction is received. It should be inspected at least once a week for manned or unmanned substation.

3) Comprehensive inspection (Standardized inspection).

Check the overall external inspection of equipments, the weakness of the equipment, the integrity of anti-misoperation lockout device and grounding grids, and identify the equipment defect. It should be inspected twice a month for unmanned substation.

4) Special inspection.

Special inspection depends on specific circumstances and it should be carried out in the following circumstance: before or after high wind, thunderstorm, equipment overhaul, during statutory holiday or in case of equipment abnormality. It should be inspected once a day for manned or unmanned substation.

### *B. Power Substation Inspection By Mobile Robot*

Technology of power substation inspection robot is one of the frontier research topics in the field of robot research, which is a combination of many disciplines, such as mechanics, high voltage insulation technology, electronics, control theory, computer science and artificial intelligence and so on. And the robots, assisting or replacing staffs, detect thermal defects and abnormalities and other issues of substation equipment. Then the fault accidents and potential risk data are provided to staffs [15]. However, on account of the complex working environment of the power substation inspection robot, there are some key technologies that are difficult to achieve breakthroughs. These key technologies are as follows.

*1) Design Requirements of Inspection Robot:* Power substation inspection robots based on mobile vehicle are designed with mechatronic features. The structure compacts, dexterity and particularity of inspection robots have higher requirements than the general mechanical. Hence, the design of mobile robot body is the carrier and base of inspection robot system [16]. Then, the following several basic technical indicators need to be met:

1) Smooth movement can be implemented in the substation, and with climbing, downhill ability;

2) Braking and anti-skid capability;

3) Flexible enough to walk autonomously, avoiding obstacle, crossing obstacle and wading ability;

4) Fault self-diagnosis and self-protection measures;

5) With comprehensive preset Pan/Tilt/Zoom (PTZ) device, the status, appearance anomaly, abnormal sound and infrared thermal defects of substation equipment can be detected and diagnosed;

6) Teleoperation and background monitoring. To meet the above basic technical indicators of inspection robot, while while ensuring the rational use of materials, convenient installation and high reliability issues should be also considered.

*2) System Architecture of Power Substation Inspection Robot:* Each type of mobile robot system has its own architecture characteristics respectively, so it is difficult or impossible to use one kind of architectural pattern to meet the requirements of all the mobile robot system. However, many researchers have devoted themselves to the research of the architecture of the robot system, and several typical architectures of the mobile robot system have been formed in recent years (e.g., [17]−[34]), which could be classified into three types: hierarchical architecture [17]−[24], subsumption architecture [25]−[29], hybrid architecture [30]−[38].

Saridis *et al*. proposed three-tier architectural model [17] in the 1980s, and it is considered relatively representative as hierarchical architecture. According to the level of intelligence with the increase of control accuracy and less hierarchical principle, the whole system is divided into three basic levels: the organization level, the coordination level and the execution level. In addition, each level can also contain multiple layers of tree structure. Furthermore, the basic concepts and ideas related to modeling and analysis of intelligent robot systems are presented and proved in papers [18], [19], and at the same time, the practical application of this hierarchical structure is discussed.

Then Brooks, an American scholar, proposed system architecture, which is called subsumption architecture [25], based on behavior, for mobile robot control system. The subsumption architecture, which is different from hierarchical architecture, is a reactive architecture and a direct mapping parallel structure based on the perception behavior. Besides, this structure reduces the requirement of the internal model of the system, and improves the real-time performance of the system in the dynamic environment. And some successful cases of the robot using the architecture are given in [27], [28]. In later studies, considering the synthesis result of the output of the combination of multiple behaviors to produce a higher level behavior, the Brooks subsumption architecture has been improved appropriately [29], and the flexibility of this class of structural systems has increased.

Furthermore, a hybrid architecture is proposed [30], which integrates the advantages of the above two systems. The hybrid architecture can be applied as the basic framework based on hierarchical architecture. It has ability to enhance transverse information transmission in each layer, which can produce corresponding reactive control behavior, and also make up the lack of flexibility and real time applicability existing in hierarchical architecture.

A hybrid three layer architecture for mobile robots, which are a reactive feedback control layer (Controller), a reactive planning execution layer (Sequencer) and a planning layer (Deliberator), was described by Gat [31]. Then, a hybrid control architecture based on subsumption architecture was described [34]. And under that structure, the planning is regarded as a behavior, and processed synchronistically with the reactive behaviors. At the same time, its corresponding new obstacle avoidance and the planning method based on the sensors was put forward.

Drawing lessons from the existing substation inspection robot system structure [7], [10], [16], and considering the requirements of the substation environment, inspection tasks, stability and flexibility of the robot, and so on, the hybrid architecture should be used in substation equipment inspection robot (see Fig. 2). This helps to improve the inspection robot perception of the environment and the internal information. And the architecture can be broken down into five layers: base station task scheduling layer, communication layer, perceptual layer, planning layer and control layer.

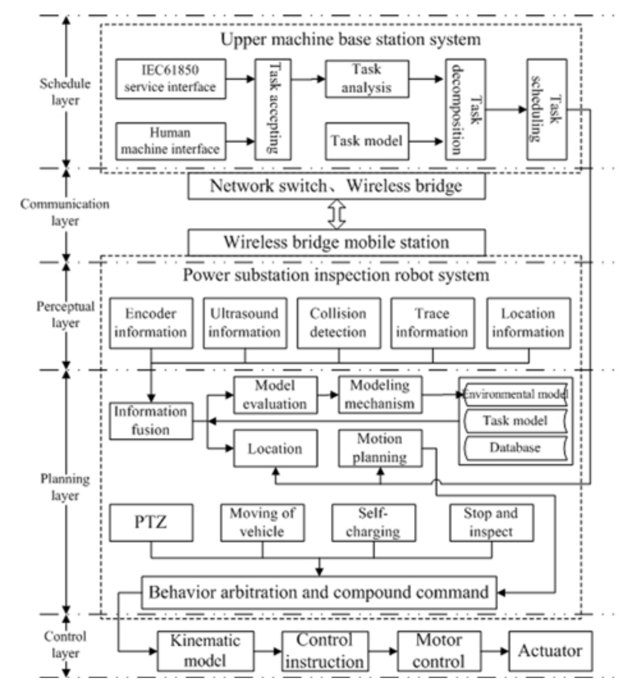



Fig. 2. System architecture of power substation inspection robot.

Scheduling layer, at the top of the architecture, is mainly composed of the IEC61850 service interface, human-machine interface, task accepting, task decomposition, task planning task scheduling and other functional modules, whose functions are primarily implemented in the base station system. Communication layer is consisted of network switches, wireless bridge base station, wireless bridge and bridges mobile station, which provides transparent channel for network communication between base station system and mobile station system with Wifi 802.1ln wireless network transmission protocol.

In order to improve the real-time performance and reaction speed of the system, inspection robot control system can employ the subsumption architecture. And the perceptual layer, planning layer and control layer are designed to describe the subsystems of mobile vehicle, PTZ motion, battery charge, substation equipment inspection, etc., which can share one real-time/historical database. Perceptual layer is located between task scheduling layer and planning layer, and responsible for providing sense information, which is the basis for planning layer to realize the localization and motion planning, and also the information source of internal control layer. Planning layer can integrate information from the encoder, ultrasound, collision detection and vision, and estimate the state information and environmental information of inspection robot. Moreover, control layer is located at the bottom of the structure, which can drive actuator to implement the expectant motion locus by controlling the motor, based on the kinematics model of the inspection robot.

*3) Modeling of Power Substation Inspection Robot:* Power substation inspection robot generally can move along the road in the power substation by using two wheel differential steering mobile platform [7], [16]. In order to accurately locate the equipment which is to be inspected in the substation, the linear degree and the positioning accuracy of the inspection robot posture is required.

A two-wheel differential driving mobile robot ([35]−[37]) is considered, the following illustration, in Fig.3, shows these two coordinate systems: the global coordinate system $\{X\ O\ Y\}$ and the local coordinate system $\{x_1, o, y_1\}$,where $x_1$ is the driving direction, $o$ is the robot center point, and $y_1$ is the robot lateral direction. The global coordinate system is fixed to the Cartesian workspace, and the local coordinate system is attached to the mobile platform.

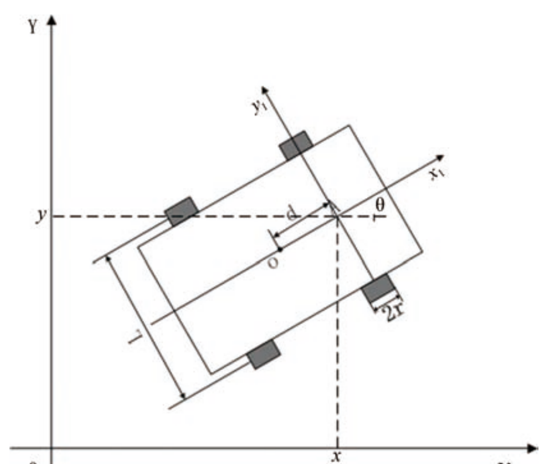



Fig. 3. Model of a nonholonomic mobile robot.

The mobile robot's position, velocity and angular velocity are represented by*((x, y, θ), ν, ω)*, then the equation of motion can be obtained as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} cos\theta & 0 \\ sin\theta & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \nu \\ \omega \end{bmatrix} \tag{1}$$

$$P = \begin{bmatrix} \nu \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{L} & \frac{-r}{L} \end{bmatrix} \cdot \begin{bmatrix} \nu_R \\ \nu_L \end{bmatrix} \tag{2}$$

where $\nu$ represents the center of mobile robot velocity, $\nu_L$ represents velocity of the left driving wheel, $\nu_R$represents the velocity of the right driving wheel, $L$ represents the width of the left and right wheels, and $\omega$ represents the angular velocity of the center.

When $\nu_R = \nu_L$, $\omega = 0$, the mobile robot will drive in straight line.

When $\nu_R = -\nu_L$, the mobile robot will have rotary motion around the center of mass, and reverse driving can be realized.

When $\nu_R \neq \nu_L$, the robot will do a certain radius $\rho$ of the circular motion, he formula to find $\rho$ is as follows:

$$\rho = \frac{\nu}{\omega} = \frac{L(\nu_L + \nu_R)}{2(\nu_L - \nu_R)} \tag{3}$$

By formulas (1) and (2), and linear and circular motion velocities formulas, the mobile robot's kinematics equation can be derived as follows:

$$P = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}cos\theta & \frac{r}{2}cos\theta \\ \frac{r}{2}sin\theta & \frac{r}{2}sin\theta \\ \frac{r}{L} & \frac{-r}{L} \end{bmatrix} \cdot \begin{bmatrix} \nu_R \\ \nu_L \end{bmatrix} \tag{4}$$

It is generally assumed that the mobile robot can only roll in the lateral direction without sliding, and the constraint equation is as follows

$$\dot{x}sin\theta + \dot{y}cos\theta - d\dot{\theta} = 0 \tag{5}$$

*4) Servo Motion Control of Power Substation Inspection Robot:* According to the control instructions are given by the Industrial Personal Computer (IPC), the motion control of power substation inspection robot can be realized to ensure robot to complete the accurate and stable inspection tasks. In the process of inspection, the inspection robot will be affected by friction, obstacle, skidding, wading, climbing and other uncertain factors, which should increase the difficulty of the robot motion controlling. So, traditional control strategy is difficult to achieve accurate controlling requirements.

In order to solve the problem of precise servo motion control of inspection robot in uncertain environment, many researchers have tried to use a lot of intelligent control methods to reduce the impact of the above uncertainty factors, such as visual servo control [38]−[42], sliding mode control [43]−[46], adaptive control [47]−[49], robust control [50]−[52], fuzzy control or neural networks [53]−[57] and other intelligent control methods [58]−[64].

## III. THE KEY TECHNOLOGIES OF INSPECTION ROBOT

The substation inspection robot, which works in the environment of the substation with strong electromagnetic interference, is different from the general industrial robot. And it is difficult to achieve the control of autonomous movtion, avoiding obstacle and navigation. In order to improve the intelligent level of inspection robot, there are some technical problems to be solved, which are as follows:

### *A. Autonomous Behavior Control and Navigation Technology of Power Substation Inspection Robot*

*1) Kinematics and Dynamics Modeling and Analysis of Power Substation Inspection Robot:* Accurate kinematic and dynamic model is the prerequisite to achieve the motion control, navigation and obstacle avoidance of inspection robot. Because of the robot working environment with strong electromagnetic interference and dynamic characteristics, and the inspection robot system has the characteristics of the strong coupling and highly non-linear with nonholonomic constraints structure [65], [66], the power substation inspection robot becomes a very complex system. At the same time, there is a need to consider the sliding motion between robot and the ground. Consequently, it is difficult to establish accurate kinematics and dynamics model of inspection robot, and only the approximate system model can be established, as shown in [67], [68]. So the precise control variable identified by theoretical analysis would often not be achieved, i.e., the generated velocity commands with respect to time are not smooth curves, which may lead to have discontinuities in the robot velocities ([69], [71]). When power substation inspection robots are working in such complex substation environment, its own structure parameters are often changed. So the noises and errors are always existing in the detected signal. In order to solve the above problems, it is necessary to research on power substation inspection robot dynamics.

*2) Autonomous Navigation Technology of Power Substation Inspection Robot:* Autonomous navigation is the basic condition for substation inspection robot for safe and reliable motion in a complex environment, and for the guarantee of basic inspection tasks, including global path planning and local obstacle avoidance planning [72]−[75]. Inspection robots move and inspect on the road of substation equipment inspection area which is a kind of unstructured environment of strong electromagnetic fields and equipment shades. Furthermore, the substation environment scope is large and the ground natural features that the computer vision can recognize are little (see Fig. 4). The information that can be perceived by the sensor is limited, and this is a challenge for inspection robot autonomous navigation. In addition, in order to ensure the accuracy of the positioning of the inspecting equipment, the robot needs to have the centimeter accuracy level for navigating and positioning.

(a) a large range (b) less features

Fig. 4. Substation environment.

Currently, there are so many methods employed in inspection robot navigation and positioning in substation, such as magnetic track guidance and Radio Frequency Identification Devices (RFID) positioning [2], [7], [76], [77], [81]−[83], GPS navigation [78], [84]−[89], laser positioning navigation [90]-[97] and visual navigation [79], [80], [98]−[104].

*a) Magnetic Track Guidance and RFID Positioning:* Based on magnetic track guidance and RFID positioning, the navigation and positioning method adapted to the strong electromagnetic interference environment has the advantages of high reliability, strong anti-jamming capability, etc. And the working principle of the robot navigation and positioning system is as follows:

1) The inspection robot collects the magnetic track information through the magnetic sensor, which is used as the guidance information for the robot.

2) RFID tag information, detected by RFID reader, is uploaded to the control system via the communication port to achieve the positioning of the inspection robot parking or turning movements.

Considering the substation environment adaptability and cost, the magnetic navigation is selected in [81]. The pre-centered sensor layout is taken to ensure prospective detection. The robots based on the magnetic guidance technology have been successfully used in [2], [7]. Magnetic track places running and testing equipment in the middle of the road, and the RFID tags are required to be buried in every corner of intersection and testing point. When substation inspection robot reads RFID tags, it can identify walking, turning and current location positioning. When the substation inspection robot detects the RFID tags at a smooth parking and low-speed turns, the distance is hence measured. Therefore, the RFID tags should be buried early in corner of intersection and testing point with a certain distance to test the equipment precisely. The optimal path planning and precise positioning can be achieved by reading the magnetic track and embedded RFID tags [82]. However, when adjusting the inspection robot, the robot will run unstably, swinging back and forth. In order to get rid of this situation, two-dimensional fuzzy controller is designed in [83] to control the wheel differential speed. The problem of posture oscillation and wagging tail of substation inspection robot could be overcome effectively.

*b) GPS Navigation:* With the development of GPS technology and application of differential GPS positioning and Real Time Kinematics (RTK) technology [84], the real time performance and accuracy of navigation is greatly improved. It can achieve centimeter level dynamic positioning accuracy, and fully meet the navigation and positioning accuracy requirements of the inspection robot. In differential GPS navigation system, GPS mobile station is installed on the robot body, and the base station is in the open position. According to the GPS data collected by the mobile station and the data of the differential, which is received from the GPS base station, the mobile station can calculate the location data of the inspection robot. The working environment of inspection robot is a typical outdoor unstructured environment. The absolute position coordinates of the current measuring points can be obtained directly from the GPS receiver, and there is no error accumulation. In theory, one can get the coordinates of the arbitrary position in the substation. Based on the Differential Global Positioning System (DGPS) and RTK technology, the inspection robot navigation system was designed and researched by Xiao P. *et al*. [85] and Zhang C Y *et al*. [86]. Nevertheless, navigation control can be obtained to adjust the positional deviation $\Delta S$ and course deviation $\Delta\theta$, relative to the robot current running path:

$$\Delta S=\frac{(y_2-y_1)\cdot x-(x_2-x_1)\cdot y+(y_1\cdot x_2-y_2\cdot x_1)}{\sqrt{(y_2-y_1)^2-(x_2-x_1)^2}} \tag{6}$$

$$\Delta\theta=\arctan(\frac{y_2-y_1}{x_2-x_1})-\theta \tag{7}$$

where $P(x, y)$ denotes the current location state of the inspection robot, $P_1$ ($x_1$, $y_1$) and $P_2$ ($x_2$, $y_2$) denote start and end of the route under global coordinate system, respectively. The range of $\Delta\theta$ is [0, 360), positive and negative $\Delta S$ and $\Delta\theta$ can reflect the inspection robot with respect to the right or left running path. Positive and negative of $\Delta S$ and can reflect the deviation from tracking trajectory.

The experimental evidence, which is obtained by using GPS1200 as the GPS signal receiving device, suggests that electromagnetic wave radiation produced due to the hot-line high voltage substation equipment will interfere with the GPS information receiving system nearby. So, the position deviation can be controlled within 5 cm in the substation area where the electromagnetic interference is weak, and there is considerable variation in v12alue of position deviation $\Delta S$ and course deviation $\Delta\theta$, when the GPS receiver is in area near the hot-line high voltage substation equipment.

In order to avoid or weaken the impact on the GPS receiving information error caused by the number of satellites, multi-path effect, randomness, and the substation electric field and strong electromagnetic interference, Dead Reckoning which can avoid the influence of signal shielding and interruption is used, and the GPS/DR navigation system was designed in [87], [88]. The smoothness and constant availability of DR signals can be used to correct the errors of GPS signals, while the absolute position accuracy of GPS can be used to provide feedback signals to correct DR. And, the navigation accuracy of inspection robot can be ensured by using federated Kalman filtering algorithm for data fusion. According to the characteristics of GPS output, Zhang Y L [89] uses Back Propagation (BP) neural network to estimate the output of GPS receiver, and a new GPS/DR date fusion method, as follows, is designed.

$$x(k) = \frac{Q_x}{Q_x + R_x} x_{DR}(k) + \frac{R_x}{Q_x + R_x} x_{GPS}(k) \tag{8}$$

$$y(k) = \frac{Q_y}{Q_y + R_y} y_{DR}(k) + \frac{R_y}{Q_y + R_y} y_{GPS}(k) \tag{9}$$

Where one can get the current time DR system based coordinate $x_{DR}(k)$ and $y_{DR}(k)$ at time $t = ks(k = 1, 2,$ from the DR system. The reliabilities of $x_{DR}(k)$ and $y_{DR}(k)$ are $Q_x$ and $Q_y$, respectively. One can predict the current sampling time GPS based coordinate $x_{GPS}(k)$ and $y_{GPS}(k)$.The reliabilities of $x_{GPS}(k)$ and $y_{GPS}(k)$ are $R_x$ and $R_y$, respectively, and x(k) and y(k)are fused robot's position results.

Comparing data fusion method based on Kalman filter with the presented method, experimental results show that the GPS performance degrades at about t=1800s and then recovers gradually at t = 2600 s. But this method has flexible weight adjustment ability that can have comparatively better result, so the precise and robust navigation information for the inspection robot can be provided.

*c) Laser Positioning Navigation:* Compared with other positioning and navigation methods, the laser positioning and navigation, which are free from electromagnetic interference, have the advantages of accurate position calculation and convenient path planning [90]. At present, there are at least two types of laser systems applied and verified in the inspection robot system.

- Laser positioning navigation system based on artificial landmarks

Laser positioning navigation system, which is based on artificial landmarks, is composed of laser scanner (laser, scanning rotating device), photoelectric signal acquisition instrument, navigation controller and artificial landmarks of known position. Laser scanner is installed on the inspection robot. And artificial landmarks are placed around the road of inspection where the robot is moving. Laser beams are emitted by laser scanner of laser navigation system. The laser beam signals, reflected from the artificial landmarks, are collected at the same time. And then the coordinate position of the robot is obtained by continuous triangular geometry.

Because of the substation electromagnetic interference, navigation equipment costs, and the requirements for reliability and accuracy of navigation systems, substation environment has less features at the same time but artificial landmarks have obvious features that robot sensors can easily recognize. Based on above, Xiao P [91], [92] develops the navigation system of power substation inspection robot that uses SICK company's NAV200 system. In order to estimate the state of the inspection robot, a kinematic model should be built first. But the kinematic model of the inspection robot is nonlinear, so the Extended Kalman Filter (EKF) is used in paper [93], and the whole processing sequences are as follows:

$$s_{k+1,k} = f(s_{k,k}, u_k, 0) \tag{10}$$

$$P_{k+1,k} = A_k P_{k,k} A_k^T + B_k C_{k,k} B_k^T \tag{11}$$

$$K_{k+1,k} = (P_{k+1,k} + R_{k+1})^{-1} \tag{12}$$

$$s_{k+1,k+1} = s_{k+1,k} + K_{k+1}(Z_{k+1} - s_{k+1,k}) \tag{13}$$

$$P_{k+1,k+1} = (1 - K_{k+1}) P_{k+1,k} \tag{14}$$

where $s = (x, y, \theta)$ is the state of the system, and $u_k = (u_{vk}, u_{\theta k})$ is the control input vector, the $u_{vk}$ and $u_{\theta k}$ denote the control input values of moving distance and yaw angle, respectively; $Z_{k+1}$ is the measurement vector, including the coordinate and orientation provided by NAV200; $P$ is the error covariance of the state; $A_k$ and $B_k$ are the Jacobian matrices; $C_k$ is the control error covariance matrix; $K_{k+1}$ is the Kalman gain; And $R_{k+1}$ is the measurement error covariance matrix.

Then the test has been carried out in a 500KV substation, which shows running status of inspection robot was steady, and the trajectories are overlapped well. When the robot ran straight along the route, the deviation of lateral position and heading angle were in the range of $\pm 15\,mm$ and $\pm 1.5°$, respectively. And, navigation system can be affected by the substation environment such as temperature and humidity and climatic change, and the stability issues can also be emerged when the navigation system works long hours.

- Laser navigation based on environment map.

Laser navigation system can use the laser sensor and the odometer, which is carried by inspection robot, to build a large scale and feature sparse substation 2D environment map, and then the robot's location information (position and heading) can be obtained by map-matching algorithm, which uses the digital road 2D map and the distance information measured by laser ranging sensor to correct the position error [94], [95]. Finally, the positioning and navigation of robot can be achieved. Without relying on artificial landmark, the laser navigation system for power substation inspection robot was designed by employing SICK companys LMS111 laser sensor to scan running environment, and the electronic map was created by effectively eliminating the cumulative errors using can-matching algorithm [96], [97].

By matching the data obtained by the laser sensor and the pre- created map by ICP-EKF algorithm, the robots locating information can be obtained to achieve inspection robot navigation and location in the substation environment. In order to test the repeated positioning accuracy of laser navigation system, an experimental investigation is conducted in 500 kV substation, which indicates that most of position data is within the error range of $\pm 2\,cm$, and the heading angle error does not exceed $\pm 1.15^{\circ}$. And, this navigation and positioning accuracy can meet robots requirements.

*d) Visual Navigation:* The vision-based navigation is an important way of the navigation of the autonomous mobile robot. The goal of the navigation system based on vision is to calculate the navigation parameters by collecting the image of the road surface and the surrounding environment, which is acquired by the visual sensor, to control robot to walk along with the navigation path [98]. By using image recognition technology to process image information, the routes to be tracked can be identified [99], [100]. And up to now, the visual navigation can be broadly divided into three types: based on guide line, extraction of road sidelines and segmentation of road area.

- Navigation based on guideline.

The navigation method is to enable the inspection robot to travel along the guideline which can be set up in advance and identified by visual identification system of the inspection robot. The navigation method can be implemented economically even if it is adapted to the complex road surface environment.

Taking into account the visual navigation with a wide range of signal detection, the integrity of the target information and other advantages, as well as the requirements of navigation accuracy and stability in actual situation of the substation, a visual navigation method based on red guideline recognition for unattended substation equipment inspection robot is presented in [80]. The fusion algorithm of Red Green Blue (RGB) and intensity and chrominance (YUV) is used to improve the recognition rate of pixels in the varying illumination condition. According to false detection and miss detection caused by varying illumination and the interference of the similar background color, the "regional equilibrium" distinguishing algorithm and identification by "stages" algorithm are proposed respectively. The "$16\times16''$ area is as the distinguishing area, and one can calculate the RGB averaged numerical in this area by the discriminant which is as follows:

$$P_k = \sum_{i=1}^{16}\sum_{j=1}^{16} A_{ij} \tag{15}$$

$$A_{ij} = \begin{cases} 0 & no\ red\ pixels \\ 1 & red\ pixels \end{cases} \tag{16}$$

$$P_k > \delta, P_k = 1 \quad otherwise \quad P_k = 0 \tag{17}$$

where the judgment of $A_{ij}$ is based on red pixels discriminant condition as follows:

$$\begin{cases} (R-G) > Y*12/255 \\ (R-G) > Y*10/255 \\ R > 100 \end{cases} \tag{18}$$

And $\delta$ is discrimination threshold of "$16\times16''$ distinguishing area, and the value of $\delta$ is 180.

According to the different classification criteria used in each segment which can be divided by the difference of luminance data, tests were carried out. Test results show that the visual navigation system based on the proposed "guideline" can satisfy the demand of robot automatic inspection work under the condition of the traveling speed in 0.4 m/s to 1 m/s range, and minimum illumination of the environment is 0.5 lux, and the system has the advantages of strong anti-interference performance and high recognition accuracy.

In order to verify the real-time performance and accuracy of vision navigation, the visual navigation problems are studied in papers [101], [102], and the results of the study indicate that the method by replacing monochrome CCD with Color CCD, and using the former image processing ($graying \longrightarrow smoothing \longrightarrow segmentation \longrightarrow edge\ \ detection$), cannot achieve the desired results. In order to overcome the above disadvantages, a method for extracting target color of image by HSI model is proposed, then the mathematical morphological processing method is used to remove the interference information, finally the trajectory and stop marks are segmented and extracted by calculating the 8-adjacent connected areas. The navigation parameters are calculated by the sampling estimation method, and the control of the robot's motion is realized by the fusion of the proportional coefficient and the navigation parameters which can be used to control the two driving wheel motors.

By using the method above, the robot navigation can be realized, and it has good real-time performance and reliability,. But in fact, the inspection robot will be sliding between vehicle wheel and ground. Besides, errors are caused by lack mechanical precision and gear backlash, even though the encoders have a high accuracy. Then utilizing the accuracy of camera rotation to control robot is studied in paper [80]. For example, if we hope the robot to rotate by angle $\theta$, then first the PTZ of camera rotates $\theta$ to save the taking picture, which is marked as picture "A" (see Fig. 5 (a)). Second, the PTZ backs to the original position (see Fig. 5 (b)). Third, robot rotates until camera scenes perfectly fit with the picture "A" (see Fig. 5 (c)), then robot rotates $\theta$. To control robot left and right wheels, the vision based navigation system tracks the gestures of the robot and at the same time hunts the environment information to identify its location.

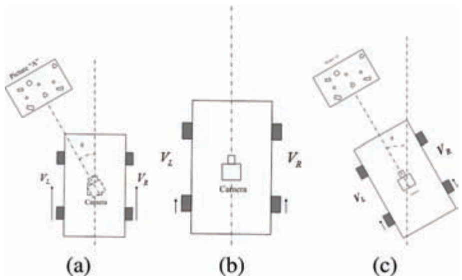


Fig. 5. Posture adjustment of inspection robot.

- Navigation based on extraction of road sidelines.

The principle of this method is as follows: extracting the coordinate value of the roadside lines on both sides of the road being traveled by robot visual system; then calculating the intersection of two road sides; the angular bisector of two road sidelines is the required route that inspection robots need to travel. This navigation method does not need drawn marks on the road surface. But there is no obvious influence on the navigation when the clear line of the road cannot be well recognized, the turning angle of the robot is too large or the road surface is undulating greatly.

To ensure the inspection robot moving on a pre-defined path, and avoid obstacles autonomously at the same time, paper [103] presents a road edge and obstacle detection system based on the stereo vision system. From the vision system structure and the road plane in the substation, the Inverse Perspective Mapping (IPM) structure is constructed to remove the perspective effect. Through the monocular image transform, the edge of the road based on the line detection can be obtained. In order to make the obstacle (repairing vehicle, people, etc.) detection result more exact and less complex, the stereo IPM method based on the transformed images is used. Then the obstacle information is made more exact with a hypothesis testing obstacle detection approach. The 2D map, which can be constructed from the obstacle's projection on the road plane and the road edge, could provide enough information for the robot navigation with accuracy of the centimeter level.

- Based on segmentation of road area.

Using image recognition technology and chain code tracking method, the images of the road area can be segmented into two parts: road and non-road, and the inspection robot is always in the middle of the road to move. The brightness is generally different from the road and surrounding environment, so, the segmentation quality and navigation stability will be affected if the brightness difference of road surface and surrounding environment is not obvious.

In complex unstructured road environment (such as rural roads, substation road, etc.), the road surface condition is complicated and changeable, and the roadside line extracted from the image is not clear. In order to solve the problem when the extraction of road sign or road boundary is very difficult, a novel dictionary learning and sparse representation based road segmentation algorithm was proposed in [104].

According to the algorithm, the local image patch was used as the processing unit. Moreover, the initial dictionary would be got by learning based on man-selected typical road image, and the dictionary should be updated in real time by online dictionary learning with a little piece of image right before the vehicle as supervision, because it is difficult to meet the requirements of complex scene for fixed dictionary. With this dictionary, the on-road patches could be sparsely represented precisely while the off-road patches could not. Then, unstructured road segmentation issue will be well solved with good adaptability and robustness in complex environment. It can overcome impact caused by illumination, weather and so on. However, it is not mentioned in the literature that the road surface area segmentation method had been applied to the substation environment.

In order to complete the robot inspection task, the appropriate navigation mode should be chosen to adapt the specific environment. For example, the methods of the magnetic track guidance navigation and visual navigation can be difficult to apply in the substation inspection by mobile robot, if the pavement marks and road edges are covered by thick snowfall, and the navigation running route cannot be identified by visual system and collection of the magnetic track information by the magnetic sensor is difficult. In addition, GPS navigation has more interfering factors and high-cost. Based on such reasons, the laser navigation method (based on the environment map) can be used as a priority scheme for substation complex environment.

To achieve the safe and autonomous operation of the power substation inspection robot and ensure to complete inspection tasks, it is necessary to consider the problems such as the presence of large sensor noise, the lack of a single navigation and positioning technology etc. And a variety of navigation and positioning techniques, which can be combined with the multi sensor fusion technology, and the intelligent behavior control technology such as fuzzy logic control method [105]−[109], neural network control method [110]−[112] and other intelligent behavior decision methods [113]−[118], should be adopted to ensure that the inspection robot can successfully complete the inspection tasks.

### *B. Equipment Detection Technology Based on Power Substation Inspection Robot*

Power substation detection system is an important part of the inspection robot system. With the development of the substation automation degree, substation Remote Maintenance System (RMS) has been realized in some areas, which adequately makes use of the hardware resource of network communication to improve automation system. Even so, equipment inspection is still an indispensable means of substation operation and maintenance. And the detection system of the inspection robot should be able to automatically inspect the appearance image of equipment, running equipment sound, the temperature of the equipment joint and other information of the substation running equipment, and identify the status of the preparation [72], [119].

So, the detection system, which can be shown in Fig. 6, should carry the corresponding sensors with the visible light, infrared and sound and other equipment status data acquisition and analysis functions, then, thermal defects and abnormal appearance of substation equipment can be detected.

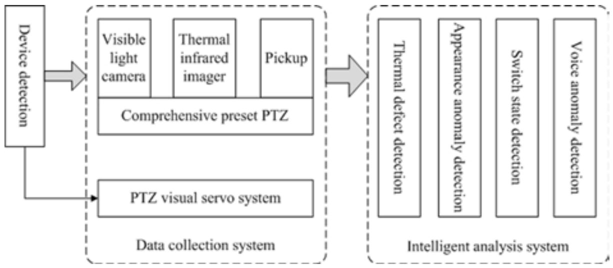



Fig. 6. Detection system of power substation inspection robot.

In order to achieve the above functions, the accuracy of inspection operation and equipment identification of inspection robot is required, and the key issues to be addressed are as follows.

*1) Design of Comprehensive Preset PTZ:* A substation not only covers large area but also has the layout of intensive equipment, and the distance from the inspection robot to the detection equipment is far, even up to tens of meters. To ensure the detection effect, the PTZ needs to support multiple preset position and high positioning accuracy, and some non-contact remote detection device such as sound pickup device, visible and infrared detection equipment with larger optical zoom should be installed on the PTZ. Therefore, it is necessary to employ the omni-directional PTZ with precision and more preset positions [120], [121], and PTZ control system is shown as in Fig. 7. Omni-directional preset PTZ with horizontal rotation and vertical rotation should be employed with anti-interference and optimization control circuit to accommodate the strong electromagnetic environment of substation. The PTZ control system consists of PTZ control panel, hardware limit, DC servo motor and angle sensors, etc., which can achieve movement in horizontal and vertical, position information feedback, travel motion protection and other system control functions.

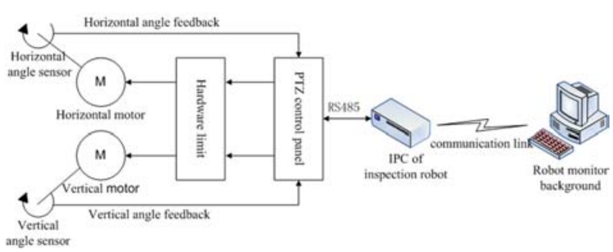



Fig. 7. PTZ control system.

*2) Detection of Thermal Defect in Equipment By Infrared:* To prevent the accidents of the substation, a key method to be taken is to effectively monitor the temperature of substation equipment such as transformers, circuit breakers, mutual inductors, cable connectors, etc., and the conventional method to measure temperatures in substations is manual check with hand-held infrared temperature measuring instruments node by node. The infrared thermal imager can turn infrared radiation of substation equipment into heat distribution image using infrared technology, which not only can measure the temperature without contact, but also can display two-dimensional distribution and changes of equipment surface temperature in real-time [122]−[124]. And the infrared thermometric technology has many advantages of reliability, immunity to electromagnetic interference, as well as the convenience of information collection, storage, processing and analysis.

In general, the method of infrared detection and diagnosis can be divided into the following several methods: Surface temperature estimation method, image feature determination method, the same kind of comparison method, relative difference method and real time analysis method. Furthermore, the infrared thermal imaging diagnostic can detect live-working equipment defects online, and ensure the safe operation of electrical equipment [125], [126]. The infrared detection and diagnosis images of part of the equipment are shown in Fig. 8 [122], [125].

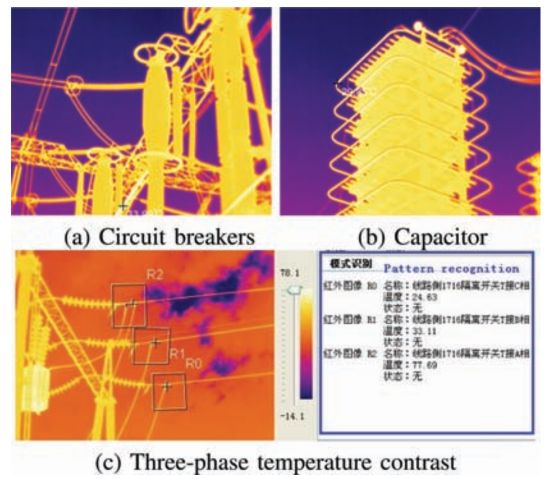



Fig. 8 Infrared detection and diagnosis images of part of the equipment

*3) Identification of Equipment Status:* In addition to the infrared temperature measurement and thermal defect detection, the equipment status recognition, such as opening or closing state of breaker and switch, meter reading, etc., is one of the main tasks of inspection robot system [127]−[130], while monitoring the current operation conditions and forms of equipment in real-time. Equipment status identification is to automatically determine the status of the equipment based on its images by the pattern recognition, image processing and other corresponding algorithm. In order to ensure the accuracy of equipment state identification, one should focus on some key factors, including complex environment illumination, uneven surface illumination, information acquisition noise, low contrast between object and background, edge blurring, that affect the accuracy of image recognition [161], [162].

*a) Breaker Status Identification:* The processing of breaker state recognition steps can be as follows: Firstly, selecting the template image of equipment, extracting Scale Invariant Feature Transform (SIFT) features, marking equipment area with artificial helping and storing into template library; Secondly, detecting to match feature points of image by the SIFT operator (see Fig. 9); Then, the homography matrix between the match image and the template image is obtained by using the algorithm. And according to equipment area marked in the template library, the corresponding area of match image will be got [131], [132]; Finally, the method of image processing is used to identify the status of equipment as shown in Fig. 10 [133], [134].

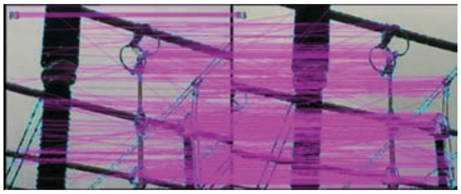


Fig. 9. Detection of SIFT feature.

(a) (b) (c) (d) (e)
(a) Original image (b) Subimage (c) Graying and binarization (d) Refinement (e) Linear filter

Fig. 10. Identification process of breaker.

Judgment of the breaker status:

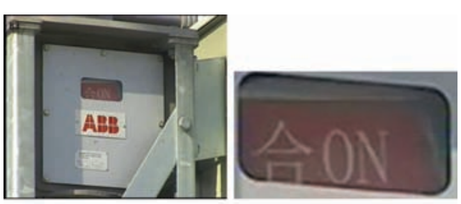
1) If there is no line inside breaker area in the image of equipment, then one can get that the breaker is identified as opening status;

2) If there is a line inside breaker area in the image of equipment, then the angle between the line and the vertical edges of rectangular frame in match image can be detected and calculated. And if the angle between the line and breaker area is less than a certain threshold, then it can be considered that the status of breaker identified is closed.

*b) Switch Status Identification:* Switch status recognition is mainly divided into two steps:

1) The acquisition of the switching area in the image: using the above method (Breaker status area matching) to match and acquire images.

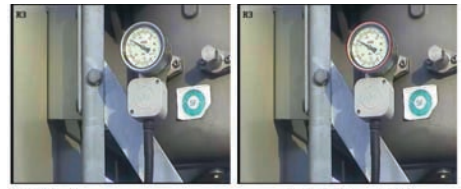
2) The "ON" and "OFF" state of switch recognition: according to the switch region position in the image obtained in the last step, and then Support Vector Machine (SVM) algorithm or other algorithms can be used to determine switch status. The recognition process of switch state is as shown in Fig. 11.




(a) Original image (b) "ON"or "OFF"state

Fig. 11. Recognition process of switch state.

*c) Meter Readings Identification:* In order to achieve the meter readings, we must first make precise positioning of the dial area in the image (Fig. 12), and there usually are three major methods: the ellipse fitting method based on HOUGH transform, the method based on moment invariants, the method based on least squares theory [135]–[137]; And then the images of the meter pointer area are obtained based on dial area by the Binarization, mathematical morphology operation, blob filters and other image processing algorithms; Finally, according to the relationship between meter readings and pointer angle marked in template library, the meter readings can be obtained through the extraction of meter pointer (Fig. 13) [138].



(a) The image pressure gauge (b) Ellipse fitting

Fig. 12. Pressure gauge.


(a) Dial plate (b) Pointer

Fig. 13. Pressure gauge.

*d) Detection of Equipment Appearance Abnormality:* Identification of abnormal power equipment appearance can be achieved by image processing, pattern recognition algorithms, and other related technology to detect image of power equipment [139], [140]. And the abnormal appearance of equipment should be judged by means of the image preprocessing, recognition, texture analysis, etc. The common appearance abnormality of power equipment mainly includes contamination, damaged and foreign matters.

According to different abnormal situation, the selection of image processing method can be determined by trial and the characteristics of the field image [141]. In the actual situation, the type of abnormal equipment is usually not foreseen, so an integrated approach of classification of equipment exception is needed.

*e) Identification of Equipment Sound Abnormality:* To a certain extent, the abnormal sound of substation equipment can effectively indicate the occurrence of major accidents and emergency situations. Collecting and monitoring the abnormal sounds of the running power equipment is also one of the main tasks of the robot, and the operation status of the equipment and its internal operation status can be analyzed and judged by abnormal sound from the equipment such as power transformer, circuit breakeretc. The abnormal sound of the malfunctioning equipment is different from that of the normal equipment, and the sound of the normal equipment has the characteristics of stability and periodicity. Therefore, by sound analysis, one can distinguish the normal operation of the equipment in the substation [142], [143].

The system of abnormal sound detection for substation equipment mainly includes: inspection robot platform, audio detection system and analysis system software of base station background. The inspection robot platform is a carrier of the audio detection system; the audio detection system is used to identify abnormal sounds of equipment; analysis system software of base station background is mainly responsible for receiving, analyzing, displaying recognition results and alarming. Furthermore, it can alarm for abnormal sound of equipment and avoid accidents in advance.

### *C. Energy Security Technology of Inspection Robot*

Power substation inspection robot, working in unattended substation for a long time with complex environment, must have a long period of energy supply to ensure the normal operation of the control system, inspection system, communication system, self-protection system, etc. And the energy supply management system of the inspection robot should be able to meet the power supply needs of the climatic impact of all weather operation, self-charging, energy optimization management and other problems. At the same time, the energy supply management system is also restricted by the mobility, size and weight of the inspection robot. Taking into account all factors, the energy supply management system of the inspection robot should be designed to meet the requirements of energy supply and energy optimization management for the inspection robot, and ensure the completion of inspection tasks to maximum extent.

*1) Energy Supply Management System of Inspection Robot:* Energy supply management system of power substation inspection robot [144], [145] mainly includes power management subsystems, power supply unit, charging unit and charging gear and other components. The power management subsystem can be shown in Fig. 14, where the solid line represents the energy flow, the dotted line represents the flow of information.

In Fig. 14, the power supply can provide energy for the inspection robot, the charging device and the charging mechanism can realize the automatic charging of the inspection robot, and the manual charging plug is reserved to provide the manual charging mode for the staff. The power management subsystem can achieve monitoring and control management in real time, and receive the command and feedback information under the operating conditions of control system.

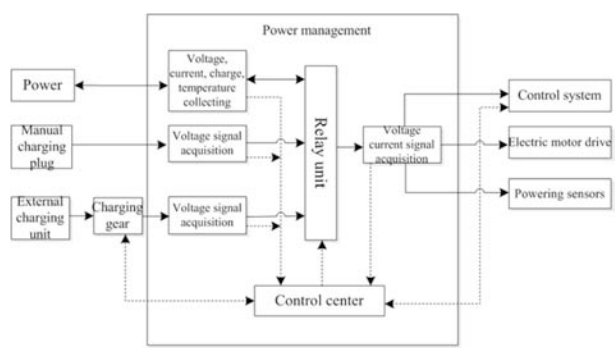



Fig. 14. Energy supply management system structure of the inspection robot.

Energy supply management system mainly consists of five parts, which are as follows: Supply Chain Management (SCM) control center, relay unit, monitoring unit, communication unit and power management module. And, the control center, which is the core of the management system, can control the entire power management system to implement the functions of power management; Relay unit, which is controlled by control center, is an executor to control the flow direction of energy for the power management system, and monitoring unit can check the energy supply unit information of the voltage, current, temperature and quantity in real time, so as to provide the judging data for the control center; The communication module, which can transmit instruction data and state feedback information transparently, can make the connection between the control center and the upper layer.

*2) Power Management Module of Inspection Robot:* The power management module usually includes: power protection module, power control module, power supply monitoring module, display and alarm module, voltage conversion module, which can be shown as in Fig. 15.

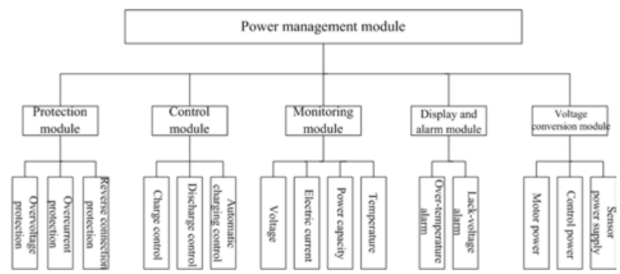



Fig. 15. Function of power management module.

*a) Power Protection Module:* Fig 7 The power protection module, which can provide with some functions of overvoltage protection, overcurrent protection, reverse connection protection and so on, can receive the command sent by the control center, and control the switching state of the relay group switch, while monitoring the voltage and current signal in the real time circuit.

*b) Power Control Module:* The function of the power supply control module is mainly to control the discharge process and to control the battery charging process.

*c) Power Monitoring Module:* The power monitoring module, which can provide information for the control center to judge the status of the system in a timely manner, mainly includes the monitoring units of the voltage, current, capacity and temperature of the power supply system.

*d) Display and Alarm Module:* The display and alarm module can provide the information of the power state and the alarm information by the man-machine interface, which can facilitate the staff to understand the power state, and do timely treatment of dangerous situation.

*e) Voltage Converter Module:* According to the needs of each module, the voltage conversion module, which can receive the command sent by the control center to cut off or turn on the power of the inspection robot.

*3) Self-charging Device:* The self-charging device of power substation inspection robot, whose schematic diagram and the photo are shown in Fig. 16, can employ active contact charging gear [146]. The active contact charging gear comprises the extended mechanism, limit switch, charging contact and other components, the extended mechanism can be installed in the robot vehicle body, the charging contact is installed in front of the extended mechanism for connecting the charging socket on the charging box. In order to connect the charging contact with the charging seat, the charging contact is established by stepping motor and controlled by the command of power management module, when the inspection robot is parked in the charging position. And while connecting the charging contact with the charging socket, and the control regulation of the charging contact should be further controlled by the contact point feedback information between the charging contact and the charging box, and it reduces the accuracy requirements of the inspection robot docking [147].

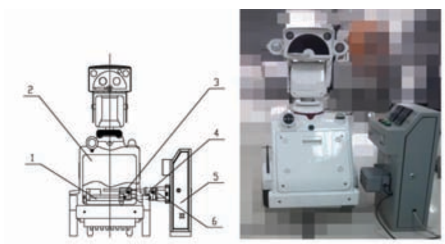

(a) Schematic diagram (b) Actual picture
1– charging gear, 2– robot body, 3– starting position of charging gear, 4– ending position of charging gear, 5– charging case, 6– charging dock

Fig. 16. Self-charging device of power substation inspection robot.

### *D. Base Station Control System and Advanced Application Technology*

The base station control system is the background control and information management system of the power substation inspection robot. And it is a bridge between the robot moving platform and the operator. The base station control system mainly includes some modules of the mobile vehicle motion control, the robot operation mode management, the substation equipment image processing algorithms and software implementation, the real-time/historical database management, communication systems, human-computer interaction interface and so on. The mobile vehicle motion control module is responsible for the communication and control between the robot mobile platform, detecting equipment device and the base station control system. The robot operation mode management module can implement the real-time motion control and inspection task management by means of autonomous control or remote control, and the substation equipment visible light image, infrared image/video. As well as the inspection robot running state data and other monitoring information can be provided by the human-computer interaction interface to the operator [15], [148], [157]. However, the wireless communications will be disturbed by the same-frequency signals and variety of noises, because of the strong electromagnetic complex environment, and the communication between the inspection robot and background monitoring system needs to have the strong anti-interference capability [149], [159]. So, some advanced application technical issues that need to be addressed are as follows.

*1) Reliable Wireless Communication Technology:* Because the robot is working in the environment of the substation, the robot must not only ensure the safety of the robot itself, but also cannot bring bad influence to the operation of the substation equipment. Otherwise, potential faults may bring great harm to the power grid.

In order to ensure its operation safety, the robot inspection operations should be completed under the control of the operator, even if the inspection robot has the ability of autonomous inspection. Under special circumstances such as failure of the robot, receiving special inspection instructions or receiving stop inspection instruction, the remote control mode can be adopted to keep the robot to complete the inspection task or to stop the inspection task back to the robot charging room. So, it is necessary to have reliable wireless communication technology [157], [158].

In order to ensure the safe and stable operation of the robot, the Real-time Transport Protocol (RTP) bi-direction control information link under wireless communication, which can achieve the bidirectional transmission of downlink and uplink information, should be established between the base station system and the robot mobile platform, and, the uplink data is mainly the control command issued by the staffs to inspection robot; downlink data consists of mainly the equipment visible image, infrared image / video, sensor monitoring information and status of the inspection task [150].

*2) Teleoperation Technology of Inspection Robot:* Power substation inspection robot is a kind of special robot for long time working in harsh outdoor environment, some of the unexpected situation may be encountered, and a lot of problems need to be solved under the intervention of people. So, inspection robot needs to be employed with remote control technology [151], [160].

In general, motion information of inspection robot, which includes the dynamic angle displacement, dynamic angle velocity, dynamic angle acceleration, can be detected by its onboard sensors, and are sent to the background monitoring system and provided to the operator with the robot operating base [152]−[154]. According to the working environment and working characteristics of the robot, the inspection robot should be operated by remote control in the following situations:

1) robot faults, such as power shortage, sensors, etc.;

2) the special inspection tasks, which are not included in the autonomous inspection tasks.

*3) Background Monitoring System of Inspection Robot:* In order to ensure the safety of the inspection robot and its detection operation, the inspection robot state and the inspection process need to be monitored by operators in real time, then the operators and inspection robot need the information exchange interface [155], [156], which can also provide the platform for the analysis and early warning of substation equipment. The background monitoring system, which includes the monitoring system, analysis and early warning system, is such an information interaction platform between inspection robot and the operators.

*a) Monitoring System:* The system is a typical monitoring system that can deal with Geographic Information System (GIS), real time data access, dynamic display and other requirements. The monitoring system can display the visible light image / video and infrared video collected by power substation inspection robot in real-time, and generate the robot operation analysis report. The operator can monitor equipment status via the monitoring system instead of on-site manual inspecting. The virtual-reality environment for substation equipment inspection system can be designed by use of three-dimension graphic technology, and the reality scene of substation can be considerably improved. The right side of monitoring system screen, which is shown as in Fig. 17 [2], shows three-dimensional virtual model of the substation, which can display the location and posture of inspection robot in real-time inspection, and also show the feedback information of running status of the inspection robot.

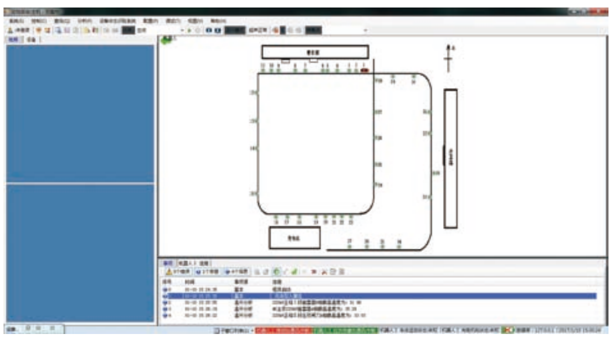
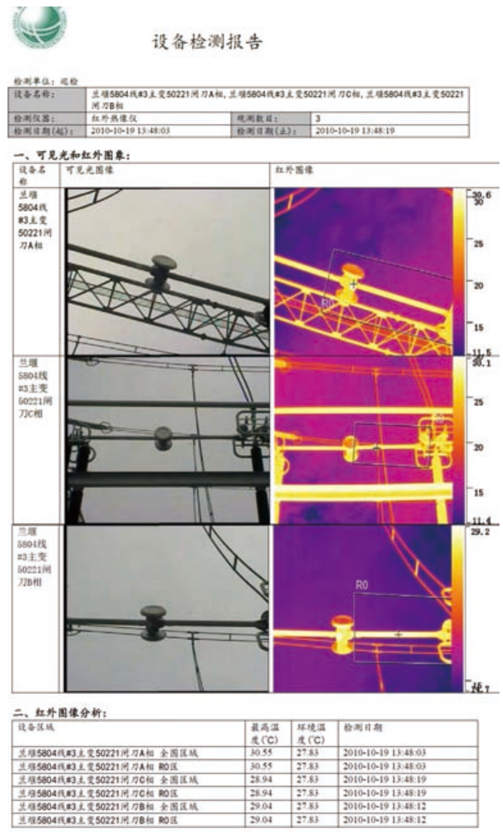


Fig. 17. Monitor background of substation inspection system.

*b) Analysis and Early Warning System:* The background monitoring system has the appropriate analysis and early warning system of substation equipment status. And for the equipment state analysis and early warning, the inspection data storage and other functions can be also realized. Through the database development, the storage, query and export and other functions of image data can be achieved. According to the information received by detection system, the current status of substation equipment can be obtained, then one can combine it with historical data and similar equipment status information to make analysis of the three-phase contrast, the trend of equipment history data and early warning (shown in Fig. 18). In addition, the system can also generate the inspection report of the analysis and early warning system for substation equipment that includes the inspection data, test results, defects alarm information and other information, as shown in Fig. 19. And the failure cause analysis and treatment schemes, which are based on equipment type, inspection data and defect type, can be achieved to improve equipment defect identification and processing capabilities.

Fig. 18. Analysis and early warning of substation equipment.



设备检测报告

检测单位：巡检

| | | | |
|---|---|---|---|
| 设备名称： | 兰塘5804线#3主变50221闸刀A相，兰塘5804线#3主变50221闸刀C相，兰塘5804线#3主变50221闸刀B相 | | |
| 检测仪器： | 红外热像仪 | 观测数目： | 3 |
| 检测日期(起)： | 2010-10-19 13:48:03 | 检测日期(止)： | 2010-10-19 13:48:19 |

一、可见光和红外图象：

| 设备名称 | 可见光图像 | 红外图像 |
|---|---|---|
| 兰塘5804线#3主变50221闸刀A相 | | |
| 兰塘5804线#3主变50221闸刀C相 | | |
| 兰塘5804线#3主变50221闸刀B相 | | |

二、红外图像分析：

| 设备区域 | 最高温度(℃) | 环境温度(℃) | 检测日期 |
|---|---|---|---|
| 兰塘5804线#3主变50221闸刀A相 全图区域 | 30.55 | 27.83 | 2010-10-19 13:48:03 |
| 兰塘5804线#3主变50221闸刀A相 R0区 | 30.55 | 27.83 | 2010-10-19 13:48:03 |
| 兰塘5804线#3主变50221闸刀C相 全图区域 | 28.94 | 27.83 | 2010-10-19 13:48:19 |
| 兰塘5804线#3主变50221闸刀C相 R0区 | 28.94 | 27.83 | 2010-10-19 13:48:19 |
| 兰塘5804线#3主变50221闸刀B相 全图区域 | 29.04 | 27.83 | 2010-10-19 13:48:12 |
| 兰塘5804线#3主变50221闸刀B相 R0区 | 29.04 | 27.83 | 2010-10-19 13:48:12 |

Fig. 19. Inspection report of power substation inspection robot.

## IV. SUMMARY

With the constantly growing and in-depth research on power substation inspection robot, the first inspection robot was officially launched in 500kV power substation, Jinan, China, in October 2005, after six months trial operation. Along with the application of inspection robot in substation, it can not only reduce the labor intensity of staffs, but also improve the work efficiency, and the corresponding frequency of inspection by robot can be set arbitrarily. However, there are still a number of key technologies to be achieved breakthroughs. In order to improve the development and application of inspection robot system, further study on the development and research of power substation inspection robot should focus on the following issues [163]−[165].

1) Mechanism optimization.

The new anti-static, anti-electromagnetic interference, high-strength materials need to be explored. The appearance design and mechanism optimization of the inspection robot should be further improved, and it can be developed with the abilities of reconstruction and modularity.

2) Multi-sensor information fusion technology.

Combined with multi sensor information fusion technology, the study between multi sensor redundant information and complementary information should be researched to further improve the robot movement precision, detection performance, the equipment identification, the accuracy of navigation and positioning, and the robot autonomous behavior, etc.

3) Remote centralized control system.

With the promotion of large scale application of substation inspection robot, a centralized control system used for remote control of multiple substation inspection robot should be considered, which can realize the centralized storage, centralized distribution, centralized use for multiple inspection robots, and provide sufficient technical support for the popularization of the unattended mode of the substation.

4) Integrated substation automation technology.

In order to monitor, control and manage all the equipment in the whole substation, one should establish and perfect the substation automation system based on the IEC 61850 standard, and realize the information sharing of equipment through the substation integrated automation technology.

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