Technology and Application for Substation Automatic Inspection Based on “Robot +” Mode

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Abstract. Daily substation equipment inspection is important for safety production of the power grid. To improve the safety and reliability of the traditional substation instrument inspection mode, this paper aims on the technology and application for substation automatic inspection based on "robot +" mode. Upon the foundation of substation inspect robot, we expand the cover range and types of monitoring devices. We first introduce the system architecture and inspect data type of the proposed “robot+” mode, and then show the data access architecture of all the monitoring devices related to the system. The processing strategies for two typical kinds of structured and unstructured data which are not from the robot are explained. For structured data, we adopt the ARIMA model to predict the time series data. Meanwhile for unstructured data, we take advantage the concept of sparse representation to recover the deformation of the monitoring object. With the newly automatic inspection mode, we can achieve an all-round three-dimensional inspection of substation equipment and environment, which can improve the coverage, the quality and efficiency of substation operation and maintenance. Through the work of this paper, we can reduce the working pressure of team members and enhance the condition control and operation inspection management penetration of substation equipment.

1. Introduction

It is an important daily work for electric operation and maintenance personals to inspect substation equipment, which directly affects the production safety and reflects the level of production management. It is a huge work for them to carry out regular inspections on the substation equipment to meet the demands of current management requirements [1-3]. With the development of power systems and the growth of power networks, the shortage of operation and maintenance personals has become increasingly prominent, and the mode of traditional substation inspection is obviously backward. The intelligent inspection robot is an effective technical way for substation to operate in an unattended environment [4]. However, the automatic detection of the equipment status is still incomplete and the inspection points cannot be fully covered. It is still a question to optimize the inspection mode and content under the premise of improving the quality and ensuring the safety of electric power production.

This paper develops a new substation automatic inspection management system based on the further study from the substation robot named “Robot +” automatic inspection mode. The system accesses various inspection data and images through various interface modes to realize remote inspection instead of on-site inspection. It alleviates the work pressure of operation and maintenance personnel and improves the management level of substation operation and maintenance.
2. The proposed mode

2.1. System structure
The whole system architecture is shown in figure 1. The application logic can be divided into four layers: the communication processing layer, the data processing layer, the business application layer and the presentation layer.

![System architecture](image)

Figure 1. System architecture.

The communication processing layer is responsible for protocol analysis, stream data analysis, and real-time data storage. The data processing layer classifies the data according to its generation time and priority. The business application layer is the core module, which consists of information overview, inspection points management, task management, real-time monitoring, data management, configuration management, and robot management. The presentation layer provides two interfaces, one is a browser-oriented WEB interface, and the other is a service interface for smartphone platforms. The mobile APP accesses the service server through interfaces such as Flex, Ajax, and JavaScript.

2.2. "Robot +" inspection data
The “Robot+” inspection mode is based on robot inspection technology, supplemented by other data such as main equipment monitoring, auxiliary equipment monitoring, and video surveillance to achieve full coverage inspections indoors and outdoors of the substation. The inspection data collected is as follows:

(a) Robot inspection data: visible light images such as the equipment appearance, opening and closing indication, meter reading, and secondary equipment status, thermal images of equipment bodies and connectors, and operating equipment sounds such as transformers and reactors;

(b) Main equipment monitoring: mainly focus on operating data which cannot be covered by the robot, such as meter reading value of GIS and arresters, voltage and internal resistance of batteries and so on;

(c) Auxiliary equipment monitoring: mainly collects temperature and humidity, indoor SF6/O2 values, fire and flooding warning signals, etc.;

(d) Video surveillance: mainly collects visible light images of equipment appearance, opening and closing indication and meter reading for areas that cannot be covered by the robot.

2.3. Data access
There is an intelligent gateway device in the substation, which integrates the monitoring data of all stations and transmits it to the main server of the city company. The server has an interface service to
transmit data to the database. The data storage module stores the system data, the scheduling data of the massive platform accessed through the interface and the power status monitoring data in the database. The data access architecture is shown in figure 2.

![Data access architecture](image)

**Figure 2.** Data access architecture.

### 3. Real-time data analysis

It should be noted that the data processing methods for different kind of data from the robot is relatively mature. On the other hand, the indoor environment information detected by the auxiliary equipment also has a corresponding alarm mechanism. Therefore, in this section, we mainly discuss the analysis of data which is not from the robot.

#### 3.1. Data categories to be analyzed

The data should be analyzed can be divided into two categories as described in section 2.2:

(a) Structured data: mainly contains numerical data of time series such as battery voltage, internal resistance, as well as meter values of GIS and arresters. The alarm rules of meter values have corresponding specifications, but for the time series data such as the battery voltage and internal resistance, it needs to be analyzed according to the characteristics of the data itself.

(b) Unstructured data: mainly refers to visible light images which from the robot un-covered area as shown in section 2.2(d).

#### 3.2. Data Processing Strategy

**3.2.1. Structured data.** Take the monitoring data of a battery voltage as an example. The battery voltage is around 2~2.2V and the actual monitored value is definitely not guaranteed to be at a constant value (as shown in figure 3(a)). Here, we use the ARIMA [5] prediction model to analyze the historical monitoring data of the voltage and predict the reasonable data interval that the voltage data should be in. 1000 monitoring points were used to verify the effectiveness of the method, within which 800 monitoring points were used to fit the model. In the ARMA (p,q) model, the search range of p and q orders is [0,3], and 200 points are predicted forward. See figure 3 (b) for a comparison of predict and real data. We calculate the accuracy of the prediction method by using the concept of root mean square error.
\[ \text{RMSE}(X) = \sqrt{\frac{1}{M} \sum_{i=1}^{M} (x_i - \hat{x}_i)} \] (1)

The RMSE of the model is 0.004. It can be seen that the prediction curve (as shown in figure 3(b)) is smoother than the real curve, and can effectively reflect the trend of the voltage in a controllable range, thereby rapidly detect the abnormal state of the battery.

Figure 3. Data Prediction Result. (a) is the original curve, (b) is the prediction curve.

3.2.2. Unstructured data. As shown in figure 4, there are several typical unstructured images that need to be processed. The specific information of the equipment is covered by yellow blocks. It can be seen that we can judge whether the appearance of the device changes by historical data template matching for figure 4(a). Meanwhile, and the traditional edge detection and morphological processing can handle the meter reading of figure 4(b) (c).

Figure 4. Typical unstructured images. (a) is the equipment appearance monitoring, (b) is the meter reading monitoring and (c) (d) are two types of opening and closing indication monitoring.

Different from other images, there is a rotation within the indicator region in figure 4(d), which makes the traditional ways useless. So a certain process is required to correct the rotation. The proposed process is as follows:

1) Get the edge image with canny operator, as shown in figure 5(a);

2) Use the Hough transform to detect lines \( L = \{l_i\}, i = 1, 2, \cdots, k \) as shown in figure 5(b). Four parameters to represent a line as \( l = \{p^s, p^e, \theta, r\} \), where \( p^s, p^e \) are the starting and ending points of the line in the image. \( \theta \) is the angle in degrees of \( l \), and \( r \) is the distance from the origin to the closest point on \( l \);
3) According to the characteristics that the left and right edges of the indicator region. We can reconstruct the border edge of the region.

3.1) Select the relatively straight lines among the detected lines, where \( L \) is all the straight lines detected, \( \theta_L \) are angles in degrees of \( L \), and \( n \) is the number of straight lines of \( L_1 \).

\[
L_1 = \{l_{1,1}, l_{1,2}, \ldots, l_{1,n}\} \text{ where } \theta(L_1) < 5^\circ \tag{2}
\]

3.2) Go through \( L_1 \) to find straight line pairs in which two lines within the pair are parallel. Furthermore, two lines determined by their starting and ending points are also parallel.

\[
P_1 = \{\{l_{i,1}, l_{i,2}\}, i = 1, 2, \ldots, m\} \text{ where } |\phi(l_{i}^r) - \phi(l_{i}^l)| < 5^\circ
\]

\[
P_2 = \{\{l_{i}^r, l_{i}^l\}, i = 1, 2, \ldots, m\}
\]

Here \( P_1 \) represents the set of line pairs obtained from \( L_1 \). Each line pair \( \{l_{i,1}, l_{i,2}\} \) contains two straight lines. \( \phi(l_{i}^r) \) is the angle of line determined by \( p_{i,1}^r, p_{i,2}^r \) and \( \phi(l_{i}^l) \) is the angle of line determined by \( p_{i,1}^l, p_{i,2}^l \). \( P_2 \) represents the set of line pairs decided by \( p_{i,1}^r, p_{i,2}^l \). \( m \) is the number of lines pairs within \( P_1 \) and \( P_2 \).

3.3) Go through the lines in \( L \) and \( P_2 \) to calculate \( b \) in (4). Find the line pair in \( P_1 \) with the largest \( b \), which are the final obtained lines indicating the left and right edges of the indicator region.

\[
a_{i,j} = \begin{cases} 1 & \text{if } (|\theta_i^l - \phi_j^r| < 5 \text{ or } |\theta_i^r - \phi_j^l| < 5) \text{ and } (\text{dist}(l_i^r, l_j^l) < 10 \text{ or } \text{dist}(l_i^l, l_j^r) < 10) \\ 0 & \text{otherwise} \end{cases}
\]

\[
b_j = \sum_{i=1}^{n} a_{i,j}
\]

The two lines named as \( H_1, H_2 \) finally obtained are marked with red lines in figure 5(c). The green lines in figure 5(c) are straight lines determined the red lines. The four lines reconstruct the border edge of the indicator region.

4) According to the concept of sparse representation, the rank of the indicator region is lowest when its rotation is removed. We here use the TILT method in [6] meet the demand.

We take two points as the initial input points of TILT as marked in figure 5(c) with blue cross. After iterative optimization, the optimized image with rotation removed can be obtained. As shown in figure 5(d), the red windows denote the original input, green windows denote the deformed texture. Figure 5(e) is the rectified region relative to the original input region. Figure 5(f) is the final image with rotation removed. With the rectified image, the position of the opening and closing indicator can be easily recognized.

![Image](a)

![Image](b)
Figure 5. Treating process of figure 4(d). (a) is the edge image, (b) is the vertical edge lines detected, (c) is the reconstructed border edge. (d) (e) (f) are the results of TILT.

4. Conclusion
In this paper, we proposed a new substation inspection mode named “Robot+” mode. It focuses on expanding the cover range and types of monitoring devices on the basis of the existing substation robot. For the complex kinds of data, we introduce the system and data architecture of the substation automatic inspection management system. Furthermore, ARIMA model and TILT method are adopted to process data which are different from the robot detected. At present, the technical solution has been deployed at several 220kV substations of Shandong province, China. The average inspection time is only about 30% relative to the traditional inspection mode. Therefore, the work of this paper contributes high practical value.

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