Control Optimization Method of Substation Inspection Robot Based on Adaptive Visual Servo Algorithm

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Abstract—In order to enhance the accuracy of the target image captured by the substation inspection robot, this paper proposes an AVS algorithm based control optimization method for the substation inspection robot, which uses the feature transformation method to match the image and template image of the substation equipment captured by the robot, verifies the existence status of the target image elements in the image, and calculates the offset pixel correction results to capture more accurate target image. The experimental results show that the method effectively improves the efficiency of image capture of inspection robot in substation equipment, and has good practical performance.

1. INTRODUCTION
The inspection robot of substation equipment is a multi-functional mobile detection platform. The inspection robot of substation equipment can plan the driving path based on RFID tag, and obtain the inspection image of substation equipment by using multimedia equipment. The real-time working state of the equipment can be identified by comparing the inspection image with the template database. Combined with the operation sequence control system of intelligent substation, the robot can realize full-automatic detection [1-3]. In the detection process, the acquisition of visible and infrared images is related to the quality of the detection task [4-5]. However, in the daily detection task, the images of the robot's PTZ real-time acquisition equipment are often biased due to the accumulation of errors, which leads to the robot's failure to recognize the working state of the equipment, resulting in hidden dangers in the power system.

In this paper, a control optimization method of inspection robot in substation based on adaptive visual servo (AVS) algorithm is proposed. The visual servo system of inspection robot is established on the basis of considering the visual field deviation caused by the image error of acquisition equipment. According to the characteristics of inspection task in substation, the traditional visual servo algorithm is modified to improve the calculation accuracy and save the computer resources to extend battery life.
2. HYBRID VISUAL SERVO SYSTEM OF INSPECTION ROBOT

2.1. Structure of visual hybrid servo system
The application of visual servo algorithm can solve the problem of visual deviation when robot collects and checks images to a certain extent. In this paper, a hybrid vision servo system which combines position, motion and image is used. The core of the system is the hybrid Jacobian matrix. The overall structure of hybrid visual servo system of inspection robot is shown in Figure 1.

![Image of the overall structure of hybrid visual servo system of inspection robot](image)

Figure 1. The overall structure of hybrid visual servo system of inspection robot

2.2. Hybrid Jacobian matrix of visual servo system
The space velocity and joint velocity of the inspection robot can be expressed by formula (1) when the inspection robot's visual controller detects the electrical equipment in the substation. Setting \( R = R(q) \) is a function of the end operation space and its joint motion space during the inspection of inspection robot. When the inspection time is \( t \), the function relationship between the joint motion speed \( Q \) of inspection robot and its end operation motion speed \( R \) is as follows:

\[
R = J_{robot}Q
\]  

\[
J_{robot} = \begin{bmatrix}
\frac{\partial R_1}{\partial Q_1} & \cdots & \frac{\partial R_1}{\partial Q_m} \\
\vdots & \ddots & \vdots \\
\frac{\partial R_n}{\partial Q_1} & \cdots & \frac{\partial R_n}{\partial Q_m}
\end{bmatrix}
\]

Among them, \( J_{robot} \) represents the Jacobian matrix of inspection robot during inspection. When the robot has \( m \) joints, the Jacobian matrix can be obtained as shown in formula (2).

The characteristics of the servo system of the inspection robot in substation can be represented by the image Jacobian matrix, which can be used to represent the differential mapping relationship between the moving area and the visual image characteristics.

Suppose \( Q = [Q1, Q2, \ldots, Qm]^T \) represents the spatial coordinate of the inspection robot performing the inspection task, \( F = [F1, F2, \ldots, Fm]^T \) represents the position corresponding to the vision field of inspection robot PTZ, then the Jacobian matrix of inspection robot image can be obtained from formula (3) and formula (4) as follows:

\[
F = J_{image}(Q) \cdot Q
\]
In the formula, \( F \) represents the image characteristic parameter vector of the inspection robot servo system, \( Q \) represents the joint motion speed parameter vector of the inspection robot, and \( J_{\text{image}}(Q) \) is the visual image Jacobian matrix of the inspection robot servo system, so the mixed Jacobian matrix of the inspection robot servo system can be calculated as follows:

\[
J = J_{\text{image}} \times J_{\text{robot}} \tag{5}
\]

In order to clarify the relative relationship between the robot PTZ position and the detection equipment, realize the PTZ image correction, and effectively improve the accuracy of inspection robot image detection, this paper proposes an adaptive visual servo algorithm.

3. ADAPTIVE VISUAL SERVO ALGORITHM

3.1. Calculation method of image deviation
The image feature matching method of scale invariant feature transform is used to process the feature matching between the real-time detection image of substation equipment collected by the inspection robot and the template image of substation equipment. The positions of the two feature pixels are arranged in order, and then the pixel error offset of the two images can be calculated by the following formula:

\[
OS_{\text{pic}} = \begin{bmatrix} \text{mean}(\sum_{i=1}^{n} (L_{\text{mod}} - L_{\text{det}})) \end{bmatrix} \tag{6}
\]

Among them, \( O_{\text{Spic}} \) represents the result of image pixel error offset in horizontal direction \( H \) and vertical direction \( V \). \( L_{\text{mod}} \) is the position of feature pixel points in the template image of equipment inspection robot, and \( L_{\text{det}} \) is the position of corresponding feature pixel points in the equipment image detected by equipment inspection robot in real time.

3.2. PTZ offset angle calculation and control
The calculation method of converting the image pixel deviation result to PTZ offset angle is as follows.

3.2.1. Calculation of PTZ offset angle
According to the distance and focal length, the corresponding tangent angle is calculated, and the PTZ offset angle is calculated based on the image deviation;

3.2.2. PTZ rotation control value transformation;
The PTZ rotation angle corresponding to the image error offset is calculated;

3.2.3. PTZ rotation offset control.
The PTZ moving target position obtained by PTZ current coordinate plus rotation offset.

4. EXPERIMENTAL VERIFICATION
In order to verify the effectiveness of the proposed algorithm, the inspection robot is tested in the case of no visual servo and the application of visual servo system based on AVS algorithm in the substation.
We set the inspection distance of the inspection robot to 10 meters, align the camera with the equipment to be inspected, and test 50 different equipment in a test task.

Figure 2 shows the test results of the inspection robot without visual servo and the visual servo system with adaptive visual servo algorithm. “•” indicates the deviation of the image captured by the inspection robot without visual servo system, “*” indicates the deviation of the image captured by the inspection robot without adaptive visual servo algorithm, and “+” indicates the deviation of the image captured by the inspection robot with adaptive visual servo algorithm. It can be seen clearly that after applying the AVS algorithm proposed in this paper, the average error deviation of the image pixels collected by the inspection robot through the visual servo system is less than 5%. Compared with the situation without visual servo and the situation without adaptive visual servo algorithm, the accuracy of the image captured by the inspection robot is significantly higher.

In order to further verify the superiority of the algorithm proposed in this paper, the average detection time of single equipment and the accuracy of equipment state recognition in three cases are counted. C, Band A are used to represent the situation of no visual servo, the situation of visual servo without adaptive visual servo algorithm and the situation of visual servo system with adaptive visual servo algorithm respectively, and the statistical results are obtained, as shown in Table 1.

| Status | Average detection time of single equipment and | Accuracy rate of equipment status identification |
|--------|-----------------------------------------------|--------------------------------------------------|
| A      | 1.92s                                         | 99.52%                                           |
| B      | 4.67s                                         | 87.43%                                           |
| C      | 8.35s                                         | 80.16%                                           |

It can be seen from table 1 that after the inspection robot applies AVS algorithm to optimize the visual servo system, the average detection time of a single device is greatly reduced compared with the detection time of vision servo system without or without AVS algorithm, and the accuracy of equipment status recognition is significantly improved, which shows that the inspection robot can be more accurate through the optimized visual servo system. The detection image of all substation equipment is captured and its working state is accurately identified.

5. CONCLUSION
Through the experimental verification, the control optimization method of substation equipment inspection machine based on AVS algorithm proposed in this paper greatly improves the accuracy of
image acquisition of robot equipment. After the improved control operation of visual servo system, the accuracy of image acquisition of inspection robot is more than 95%, and the detection speed is greatly improved, and the accuracy of equipment status recognition is increased to more than 99%. After the implementation of this method, the inspection robot can perform the inspection task of power equipment 24 hours in the substation, which ensures the safe operation of substation equipment and effectively improves the stability of power system operation.

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