 Precise positioning method for insulator sheds based on depth horizontal histogram

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ABSTRACT The insulator cleaning robot is essential to grid maintenance and personal safety, where the precise positioning of insulator sheds is the basis. However, due to the great differences in shape and color of the insulator, as well as the cluttered background in the substation, the traditional methods based on color and texture features can not achieve accurate positioning of the insulator shed. Aiming at the problem that the traditional features of insulator are easily submerged in the background, we propose a new depth horizontal histogram (DHH) feature and use it to achieve the accurate and fast positioning of insulator shed. In order to reduce the influence of complex background on insulator positioning, we directly bandpass filter the depth image of the insulator from the RGB-D (RGB and Depth) camera. To obtain the effective DHH feature, the filtered image is processed by rotation, horizontal projection, and morphology. Finally, we perform gradient detection on the DHH and achieve the precise positioning of the insulator sheds. The experiments show that, compared with traditional methods, our method can achieve precise positioning of the insulator shed and performs better in speed, accuracy, and adaptability.

INDEX TERMS Insulator cleaning robot, Insulator sheds positioning, The DHH feature, Gradient detection.

I. INTRODUCTION

The insulator is a device that plays an important role in supporting and insulating in substations and overhead transmission lines [1], [2]. It is often composed of a number of round insulator sheds, to achieve different voltage levels of insulation function. Due to long-time exposure to the harsh outdoor environment, the insulator usually accumulates dirt, ice or snow, resulting in reduced insulation performance. As a consequence, the insulators are susceptible to flashover accidents which cause large-scale power outages and result in huge economic losses [3]. Therefore, Many electrical companies conduct regular insulator inspection and cleaning to prevent the appearance of the aforementioned defects.

The traditional method of cleaning insulators is manual maintenance, as shown in Fig. 1(a). However, due to the increasing power grid scale, the manual maintenance requires more and more workers and physical strength. In addition, the workers need to climb on live insulators for cleaning, which presents lots of risks. In this case, some insulator cleaning robots have been extensively studied [4], [5]. A typical insulator cleaning task with a robot is shown in Fig. 1(b).

(a) The manual maintenance (b) The robot maintenance

FIGURE 1. Two ways of the insulator cleaning task

The insulator cleaning task with a robot mainly includes two steps: insulator positioning with the vision system, cleaning operation with the cleaning tool. In order to achieve efficient and high-quality cleaning operation, the robot vision system needs to measure the spacing between two insulator...
sheds and the diameter of each insulator shed before cleaning them layer by layer. Therefore, the vision system needs to complete the accurate spatial positioning of the key points of all insulator sheds in complex background.

However, there are many difficulties in positioning the insulator sheds in an open outdoor environment [6]. On one hand, due to different application scenarios and voltage levels, the insulators differ in size, shape (e.g., disc, needle and oval), color (e.g., red, green and white) and material (e.g., glass, ceramic, composite) [7]. On the other hand, the insulators are in a cluttered outdoor environment, including different brightness, different angles of sunlight and messy backgrounds (e.g., the pylon). Moreover, due to long-term exposure to the outside, the insulator sheds are easy to accumulate dirt, rust and other contaminants, which often result in color changes. In addition, the insulator images are often taken at different viewing angles and different distances, which drives to a huge variability of the appearance of the insulator in the image.

In recent years, many scholars have proposed various methods to identify and locate the insulator by processing the color, edge, or region of the insulator images. For example, Li et al. [8] proposed a method to locate the area of insulator sheds in the aerial image. Firstly, the aerial image is converted to HSV colour space model, then the components of H and S are filtered to segment the insulator sheds and background areas. This method requires large colour differences between the background and the insulators. Yu et al. [9] proposed a texture-and-shape-based active contour model, which can achieve insulator segmentation by evolving a curve iteratively by the texture features and shape priors. But Yu’s model is complex and the shape-driven curve evolution process is time-consuming. The above methods have many parameters that need to be adjusted artificially, which are difficult to adapt to the insulator objects with different shapes, sizes and backgrounds, or even mixed insulators.

Due to the significant difference in the infrared band [10] between the insulator and the complex background, some scholars consider using infrared image to identify insulator. For example, Liu et al. [11] proposed a method to complete the positioning of single insulator shed through temperature threshold and morphological processing. However, there are many temperature thresholds need to be set, so the method has a low accuracy and poor robustness [12].

Due to the problems of poor adaptability and low accuracy in traditional texture-based positioning methods, some scholars proposed some methods based on machine learning to recognize the insulator. In [13], a sliding window was used to extract the local orientation features of the insulator, and then support vector machine (SVM) was used to improve the detection accuracy of the insulator region. Tao et al. [14] proposed a novel deep convolutional neural network (CNN) cascading architecture for locating insulators and detecting defects. Although the above methods have a high comprehensive recognition rate of insulators under complex backgrounds, they failed to locate the key points (such as edge points) of insulator sheds accurately in the image, and the method requires a large number of insulator picture samples for model training, which is difficult to implement in small and dangerous substations.

It is easy to find that the above methods based on color-texture or CNN model didn’t comprehensively consider the accuracy, adaptability and speed of insulator positioning. What is more, the above methods failed to achieve the 3D (three dimensional) positioning of single insulator shed, and the results cannot be really used for robot cleaning operation. With the development of RGB-D (RGB and depth) camera technology [15], few scholars have begun to use depth information to position the insulators. In the methods of Sun et al. [16] and Gong et al. [17], a RGB-D camera was used to obtain depth information of the insulator, then the contour extraction and principal component analysis (PCA) were used to complete the central-axis 3D positioning of the insulator. However, Sun and Gong failed to detect all key points of the insulator sheds, and the low accuracy of their methods are difficult to ensure the effective cleaning of the robot.

In short, on one hand, due to the cluttered outdoor environment of insulators and uneven color of insulator surface, the existing methods based on color and texture features [18] are very complex, with low accuracy and poor robustness, and can only realize the overall 2D positioning of insulator, which cannot guide the robot operation. On the other hand, due to the interference of outdoor light on RGB-D camera, the information of insulator depth gradient is easy to be missing, thus the existing methods based on depth information have poor robustness, low accuracy and incomplete detection results. In this case, we propose the DHH feature, and use it to achieve the accurate and rapid positioning of insulator shed.

In our method, the band-pass filtering is used directly to complete the background filtering of the insulator depth image. Then the depth horizontal histogram is used to complete the segmentation of the insulator sheds. After detecting the key points of the insulator sheds according to the depth gradient, we complete the precise positioning of the insulator sheds effectively. The main contributions of this paper are as follows:

1) We propose a new DHH feature, which contains the geometric information of the target and is invariant to color, scale and rotation. The experimental results show that this feature is suitable for precise and rapid positioning of insulator shed under complex background.

2) We propose to use band-pass filtering based on prior information to process the target depth image directly, so as to achieve effective filtering of complex backgrounds and rapid extraction of short-range targets.

3) While many existing studies focus on the segmentation and location of insulators in 2D image, whose results are of little significance for guiding the robot to clean the insulators, we use the insulator sheds positioning method based on DHH to complete the substation insulator 3D
positioning and have applied it to the robot applications successfully.

The remainder of this paper is organized as follows. Section II introduces the engineering background and tasks. Section III introduces the precise positioning method for insulator sheds based on DHH. Later, some positioning experiments of insulator sheds are carried out in outdoor environment to prove the effectiveness of the proposed method in section IV. Finally, a brief conclusion and the future work are provided in section V.

II. INSULATORS POSITIONING WITHIN OUTDOOR ENVIRONMENT

In order to explain this method effectively, we use a porcelain insulator of the substation as the experimental object, which is shown as Fig. 2.

![The porcelain insulator in 110kV substation](image)

FIGURE 2. The porcelain insulator in 110kV substation

The characteristics of porcelain insulator sheds are as follows:

1) A porcelain insulator is of axisymmetric and hierarchical structure, which is composed of two iron caps and a series of insulators sheds, and the sheds have same radius and equal spacing, and the type is same.

2) With the rise of voltage level, the number of insulator sheds increases. For instance, the number of insulator sheds varies from 7 to 10 for 110kV voltage level, while the number varies from 14 to 20 for 220kV voltage level.

3) The insulator has obvious edge characteristics, weak texture and the surface color is uneven [19].

It can also be seen from Fig. 2 that the insulators are in an complex and open outdoor environment, including other insulators and strong light. The surface of the insulator is smooth and the central features are not obvious. What’s more, the insulators are located in outdoor substation all year round, which often accumulates various kinds of pollution, resulting in surface color changes. Considering the practical application requirements, in order to ensure that the charged insulator will not release an arc to the vision system at a close range, the robot vision system should try to detect the target at about 1000 mm. On the other hand, in order to realize the high-quality cleaning operation of shed layer by layer, the cleaning tooling at the end of the robot should be close enough to the insulator shed, but not touch the insulator to damage the insulator, so the measurement error of shed spacing should be as small as possible.

In the proposed method, we need to obtain high-quality insulator depth information as much as possible to achieve the precise positioning of the insulator sheds. Among the current RGB-D camera techniques for obtaining target depth information, only binocular camera works well outdoors, but it still performs poorly for the insulator which has weak texture [20]. Therefore, according to our previous outdoor 3D reconstruction method based on multi-line laser and binocular vision [21], we make the improved RGB-D camera system to obtain the color and depth images of the insulator.

The actual system is shown in Fig. 3(a).

![Experiment environment](image)

FIGURE 3. Experiment equipment and the environment

In Fig. 3(a), the RGB camera is used to obtain the color image, the line-laser generator is used to create manual features on the insulator, which has 75° viewing angle, 810 nm wavelength and 300 mW power. The binocular camera is used to capture laser characteristics and calculate the depth image, whose key parameters are shown in Table 1.

| Parameters       | Parameter Values |
|------------------|------------------|
| Resolution (pixel)| 1280 x 720       |
| Baseline         | 50 mm            |
| Focal length     | 1.93 mm          |
| Pixel size       | 2.04 um          |
| Camera FOV       | H 91.2°; V 65.5°; D 100.6° |

Then we put the camera system in the outdoor environment as shown in Fig. 3(b). Since the actual insulator cleaning robot works near the insulator, we set the distance between the camera system and the target insulator at about 1000 mm. To simulate the complex environment of the substation, we set up the experiment background of insulator with white wall, red floor and gray iron plate. When the camera system works, the insulator gray image with line lasers and the RGB image are obtained, as shown in Fig. 4(a) and (b), then the insulator depth image is calculated through laser extraction and stereo matching, as shown in Fig. 4(c).

It can be found from Fig. 4 that in the color image, the insulator has smooth surface, few texture features and the edge of the insulator is mixed with the complex background. In the depth image, the spatial characteristics of the insulator is very obvious and the single insulator shed is distributed
horizontally. What’s more, the gray value of insulator is different from the background objects in the depth image. Obviously, the depth image of the insulator is more suitable for the accurate positioning of the insulator sheds.

III. THE INSULATOR SHEDS POSITIONING METHOD BASED ON DHH FEATURE

The main purpose of this method is to accurately and efficiently obtain the 3D coordinates of the insulator sheds, which are used to guide the operation of insulator cleaning robot. The procedure of the precise positioning method of the insulator sheds is shown in Fig. 5, and the difficulties and purposes of each step are as follows:

**Step 1:** The high-quality RGB-D images of the insulator will be obtained. Specifically, the robot will be placed near the insulator artificially before the actual insulator cleaning operation. Thus we can use the camera system in Fig. 3(a) to get the RGB-D images, where the target insulator is basically located in the central area of the image.

**Step 2:** In order to reduce the interference of background objects in the RGB-D image to the target insulator, the band-pass filtering method is used to remove the complex background and achieve the insulator rough positioning.

**Step 3:** To obtain the DHH feature of the insulators effectively and extract the radial features of the insulator sheds as much as possible, the principal component analysis (PCA) is used to calculate the inclination of the insulator and achieve the inclination correction.

**Step 4:** The DHH feature is to be obtained through pixel level integration and preprocessed through corrosion. The step 4 is the key to obtain high-quality DHH features, which can solve the problem of incorrect segmentation of insulator shed due to lack of depth information.

**Step 5:** The DHH feature contains the spatial structure information of the insulator shed. Therefore, by performing gradient detection on the DHH feature, the segmentation of each insulator shed and the final key points positioning can be realized.

This method is based on the obtained RGB-D image from the camera system, so the following part will introduce the details involved in step 2 to step 5.
A. THE ROUGH POSITIONING OF THE INSULATOR

In actual scene, the distance between the camera system on the robot and the insulator is usually between 800 mm and 1100 mm. Based on this range, the complex background of insulator can be filtered easily. Next, we can complete the initial positioning by detecting the continuous depth (the yellow box area) and get the main region of the insulator (the green box), as shown in Fig. 6(a). Then we can get the insulator depth image of the corresponding area, as shown in Fig. 6(b).

It can be seen that bandpass filtering can filter the background of the insulator depth image effectively, thereby achieving rough positioning of the insulator. The rough positioning will improve the image processing speed effectively while removing complex background interference.

B. CALCULATION AND CORRECTION OF INSULATOR INCLINATION

In general, the camera system is not facing the insulator strictly. To extract the radial feature information of insulator shed as much as possible, we need to detect the insulator inclination in the depth image and complete the tilt correction. Here we use PCA to calculate the inclination of the insulator, and rotate the depth image of Fig. 6(b) around the image center to complete the correction of insulator. The process of insulator inclination correction is shown in Fig. 7.

C. DHH ACQUISITION AND PREPROCESSING

The DHH contains insulator spatial structure information, which can be used to segment each insulator shed effectively. We first complete the binarization of the correction depth image, and then get the DHH by accumulating the black pixels of each row of the binary image, as shown in the black area from Fig. 8(a). It can be found that there are many defects in the crests and troughs of the histogram, which affects the gradient detection and the segmentation accuracy of single insulator shed greatly. Here, the median filtering is used to smooth the edges of the histogram, and erosion processing [22] is used to make the crests and troughs of the DHH more obvious. For the original DHH image, assumed that \( X \) is the part to be processed (black pixel) and the \( S \) is the structural element (white pixel, generally 5 * 5 pixels), then the erosion processing is as follows: \( S \) convolutes along the inner edge-side of \( X \) once, and the result is the \( x \), which can be expressed as Eq. 1:

\[
X \Theta S = \{ x | S + x \subseteq X \} 
\]  

With the median filtering and erosion processing, we can get the preprocessing result of DHH, as shown in Fig. 8(b).

D. INSULATOR SHEDS SEGMENTATION AND KEY POINTS DETECTION

In general, the key points of single insulator shed include the points on both sides and the middle convex point, as shown in Fig. 9.

It can be found from Fig. 7(b) that in the corrected insulator depth image, the insulator sheds are horizontally distributed, which helps to generate the DHH.

Compared with the crest and trough in Fig. 8(a) and (b), it can be found that the crests and troughs in DHH are smoothed effectively, and the gradient information is more accurate.
insulator sheds based on the gradient information of the DHH firstly. Then, the gradient detection is performed on the depth image of each shed to complete key points detection.

Assumed that \( f(y) \) is the accumulated value of the black pixels in the \( y \) row on the depth histogram, \( f'(y) \) is the first derivative of \( y \) in the neighborhood, and \( f''(y) \) is the second derivative. The gradient detection algorithm of DHH feature is shown in Algorithm 1:

**Algorithm 1** The gradient detection of DHH feature

Require: The preprocessed DHH that contains \( R \) rows pixels;

Ensure: The row number of insulator shed trough: \( N_t = \{t_0, t_1, ..., t_{n-1}\} \); The row number of insulator shed crest: \( N_c = \{c_0, c_1, ..., c_{n-1}\} \);

1: Counting the number of black pixels in each row on the depth histogram to get \( f(y) \) \( (y = 0, 1, ..., R - 1) \);
2: for \( y = 0 \) to \( R - 1 \) do
3: \hspace{1em} Calculating the first derivative of \( f(y) \) to get \( f'(y) \), and calculating the second derivative of \( f(y) \) to get \( f''(y) \);
4: \hspace{1em} if \( f'(y) = 0 \) and \( f''(y) > 0 \) then
5: \hspace{2em} \( t_{i+j} \leftarrow y \) (the \( y \) row pixels pass through the trough between the two sheds);
6: \hspace{1em} end if
7: \hspace{1em} if \( f'(y) = 0 \) and \( f''(y) < 0 \) then
8: \hspace{2em} \( c_{j+i} \leftarrow y \) (the \( y \) row pixels pass through the crest of single shed);
9: \hspace{1em} end if
10: end for

The above processing can complete the trough positioning of the DHH effectively, as shown in Fig. 10(a). Then we can complete the segmentation of each insulator shed easily according to the line data of the trough, as shown in Fig. 10(b).

It can be seen from Fig. 10(b) that the insulator sheds are segmented one by one. After that, the key points of single insulator shed can be detected with the follow steps:

1. With the row data (Fig. 11(a)) where the DHH crest is located based on the Algorithm 1, the corresponding row of the depth image is traversed to find the depth mutation point, as shown in \( L_1 \) of Fig. 11(b). Then the two key points \( P_L \) and \( P_R \) on both sides of the insulator shed can be detected;

2. Based on the two edge points, the central axis of the insulator shed can be positioned, as shown in \( L_2 \) of Fig. 11(b). By search the minimum depth, the central convex point \( P_M \) of the insulator shed can be detected.

With the above two steps, the three key points on the insulator shed can be detected well, as shown in Fig. 11(c).

According to the binocular vision model [21], the 3D coordinates of each key point on the insulator shed can be obtained under the camera coordinate system. Finally, we can achieve precise positioning of the insulator sheds.

**IV. EXPERIMENTS AND RESULTS ANALYSIS**

To illustrate the effectiveness of this method, we carry out insulator comprehensive positioning experiments under different background, different distance and different inclinations in outdoor open environment, and compared and analyzed different methods in detail.

**A. INSULATOR SHEDS POSITIONING EFFECT**

We first use the RGB-D images of the insulator to conduct the comprehensive positioning experiment of insulator in six different backgrounds, which can be shown in Fig. 12.

It can be found that whether the background contains iron bars, walls, wood, red ground or clouds, this method can complete the segmentation of each insulator shed easily in different backgrounds, which can be shown in Fig. 12.

Specifically, we analyze the positioning effect of the insulator sheds in scene 1 in detail, as shown in Fig. 13.
It can be seen from the red points in Fig. 13 that, the proposed method can locate the key points of all insulator sheds well, and the results are not affected by the complex background and the position of the insulator sheds. Considering that the insulator shed at the edge of the image is often incomplete and the depth accuracy of the image edge becomes lower, the last insulator shed is not marked.

By obtaining the 3D coordinates of the key points of the insulator sheds, and calculate the spacing of the left, center, and right key points respectively in the six scenes, the insulator positioning accuracy in this method can be analyzed. Firstly, we calculate the average spacing between three groups of key points on the insulator sheds in six scenes and get the average error rate, whose results are shown in Table 2.

As shown in Table 2, the average spacing error of three groups of key points on insulator shed is within ±1 mm, which effectively meets the actual robot operation requirements. Due to the axial symmetry of the insulator, the three groups of spacing errors are similar. While the middle spacing error is the smallest, the left error is less than the right side. The reason can be explained as follows:

1) The insulator surface is smooth and the shape is disc-shaped. The laser projected by the RGB-D camera system can create obvious texture on the middle part of the insulator shed effectively. However, the texture created on both sides of the insulator shed is easy to be reflected totally, which makes the laser texture information on both sides of the shed unable to be captured by the camera. Therefore, the quality of depth image on both sides of insulator is a little poor, even a little missing.

2) Generally, the optical center of left camera in the binocular camera is regarded as the reference coordinate system, so the depth information on left side of the insulator is easier to be obtained and the depth quality is higher. Thus, the positioning accuracy of the left side of the insulator shed is higher than the right side’s.

Considering the selection and use of visual data in actual robot operation, The measurement error rate of 0.93% was selected as the measurement error of the insulator shed spacing in this method. Thus, we can get the conclusion that this method can complete the accurate positioning of insulator shed under complex background effectively, and the error rate is less than 1%.

The reasons can be explained as follows: firstly, the improved RGB-D camera system is used to obtain the target depth image, whose image quality is not affected by the weak texture characteristics of insulator surface and the ambient light; secondly, the band-pass filtering of the target depth image can effectively filter the complex background, so this method has strong adaptability to the complex background; finally, the DHH feature proposed by this method has obvious gradient characteristics, which can be used to the segment all levels of the insulator shed, and finally realize the accurate positioning of the insulator shed.

### Table 2. The results of sheds spacing

| Group | Average point spacing in different regions |
|-------|-------------------------------------------|
|       | left points | middle points | right points |
| Scene 1 | 62.63 mm | 60.45 mm | 62.16 mm |
| Scene 2 | 61.86 mm | 60.20 mm | 62.79 mm |
| Scene 3 | 60.78 mm | 61.41 mm | 60.35 mm |
| Scene 4 | 61.64 mm | 61.58 mm | 62.59 mm |
| Scene 5 | 64.57 mm | 61.39 mm | 63.93 mm |
| Scene 6 | 60.96 mm | 60.87 mm | 60.78 mm |
| Average spacing | 62.07 mm | 60.98 mm | 62.10 mm |
| Real spacing | 61.5 mm | 61.5 mm | 61.5 mm |
| Error | 0.57 mm | 0.52 mm | 0.60 mm |
| Error rate | 0.93% | 0.85% | 0.98% |

### B. Comparison of Related Methods

Firstly, this section analyzes the insulator detection methods based on the traditional corner feature [23], texture feature...
[24] and color feature [25], and explains the reason why they are not suitable for accurate positioning of insulator sheds. Secondly, we extract the insulator DHH feature in the same scene and detect gradient information to explain the reason why the DHH is suitable for accurate positioning of insulator sheds.

By extracting the corner, texture and color features of insulators and marking them in red, the below Fig. 14(a), (b) and (c) can be obtained.

![Figure 14](image)

**FIGURE 14.** The insulator’s traditional features (red parts)

In [23], Guo extracted the Harris corner feature and used the sequential similarity detection algorithm (SSDA) to achieve the fault detection of insulators. However, Fig. 14(a) shows that the edge of insulator shed is very smooth, so the detected Harris corners are rare and uneven. In addition, some Harris corners are detected in the reflective area of insulator, which means the corner feature is affected by light greatly.

In [24], Wu used semi-global operator to extract the texture features of insulators, and used convex energy function to complete the effective segmentation and location of insulators. However, the Fig. 14(b) shows that the insulator textures (red parts) include many parts and are connected to other objects, so it is difficult to extract the insulator texture from the background texture.

In [25], Huang used the improved k-means algorithm to calculate the red and blue difference value in the color image, and used morphological filtering to compensate the result of insulator segmentation. However, the Fig. 14(c) shows that when the background is complex, the color of insulator is easy to fuse with the background. Thus it is difficult to locate the insulator by color information effectively.

We can draw the following conclusion from the above analysis: because the traditional corner, texture and color features of insulators are submerged in the background, the methods in [23–25] are difficult to complete the effective extraction of insulator features in complex scenes, and can not obtain 3D coordinate information of insulator, which has no practical significance for robot cleaning insulators.

To illustrate the effectiveness of DHH feature in experiments, the insulator depth image from the scene in Fig. 14(a) is processed and performed the gradient detection from Algorithm 1 to get Fig. 15(a). According to the gradient detection results, all levels of insulator sheds are segmented, as shown in Fig. 15(b). Finally, the key points of each insulator shed are detected, as shown in Fig. 15(c).

![Figure 15](image)

**FIGURE 15.** The key points positioning of insulator sheds based on DHH

It can be seen from the serial numbers 1–9 in Fig. 15(a) that all the troughs of insulator DHH are marked well. Then, using the line information of each two adjacent troughs, the depth image of the insulator can be segmented to obtain all levels of insulators, as shown in boxes 1–8 of Fig. 15(b). Finally, the key points detection method from Fig. 11 is used to locate the key points of each stage of the insulator sheds, as shown in Fig. 15(c). From the above analysis, it can be found that DHH feature is an important basis for the realization of all levels of insulator sheds segmentation, so as to get each insulator shed easily and achieve the final key points positioning. Therefore, compared with traditional features, the DHH feature of insulator is more suitable for accurate positioning of key points of insulator shed.

In order to illustrate the accuracy of this method, this method is compared with Gong’s depth traversal method [18], which directly used the traditional binocular camera to obtain the depth image, and extracted the central key point of each insulator shed by traversing the depth information of the insulator shaft. The comparison of these two methods are shown in Table 3:

| Method    | Real spacing | Measured spacing | Error rate |
|-----------|--------------|------------------|------------|
| Our method | 61.5 mm      | 62.07 mm         | 0.93%      |
| Gong      | 63.0 mm      | 65.59 mm         | 4.11%      |

It can be found that compared with Gong’s method, the proposed method has a high accuracy for the positioning of the insulator sheds. And more, when Gong’s method can only locate the middle key points of the insulator sheds, this method can locate all key points of the insulator sheds effectively. We think it can be explained from the following aspects:

1) Compared with Gong’s method, this paper uses the improved RGB-D camera system to obtain the depth im-
age, which has higher depth accuracy and more obvious insulator edges.

2) The DHH reflects the weight of the spatial distribution of the insulator sheds. By processing it, this method can complete the effective segmentation of all insulator sheds, and then complete the key points detection according to the gray gradient.

In order to demonstrate the effectiveness of the proposed method fully, the insulator positioning time measurement experiment is carried out. The computer configuration is as follows: graphics card GTX1050, running memory 8G, CPU 2.5GHz, and the resolution of single insulator image is 1280*720. By calculating the average measurement time of insulator shed in the six scenes in Fig. 13 and compared it with Zhang [20], Yu [9] and Wang [26], we can obtain the following Table 4.

| Method       | this method | Zhang [20] | Yu [9] | Wang [26] |
|--------------|-------------|------------|--------|-----------|
| Time (s)     | 0.202       | 1.62       | 10.99  | 11.87     |

In above methods, the [20] introduced the edge-based scale invariant feature to describe insulators and used edge-based tracker for insulator localization, the [9] introduces shape-driven curve evolution process for background suppression, and the [26] extracted the Gabor feature of insulator and used the SVM (support vector machine) for the localization. All the above methods have the problems of many parameters, complex model and long recognition time. On the contrary, this method removes a large amount of interference information in the image through band-pass filtering of the depth image, and reduces the image processing area through coarse positioning, so that the amount of image processing data is less. In addition, the steps such as calculation and correction of inclination, DHH feature acquisition and gradient detection are only include convolution and integral, so this method is a simple model, and has the advantages of fewer parameters and high efficiency.

C. COMPREHENSIVE POSITIONING EXPERIMENT

Considering that there are different positions, inclinations and different types of insulators in the substation, we carry out positioning experiments on different types of insulators under different distances and inclinations in this section. Taking the recommended working distance of 1000 mm as a reference, we control the distance between the camera and the insulator at 700-1200 mm, so that the insulator has a scale of 0.7-1.2 times. And the results are shown in Fig. 16.

It can be found that the insulator sheds can also be effectively positioned at different distances. Because the D-HH feature reflects the spatial distribution of the target, the gradient feature of the DHH still exists when the distance of the target becomes larger or smaller, so the DHH feature has scale invariance. Therefore, this method can complete the accurate positioning of insulators with different distances.

Similarly, we calculate the average spacing between three groups of key points on the insulator sheds in six distances and get the average error rate, as shown in Table 5.

| Group | The median value | Relative Error | Error rate |
|-------|------------------|----------------|------------|
| 700 mm | 62.23 mm | 0.73 mm | 1.18% |
| 800 mm | 62.19 mm | 0.69 mm | 1.12% |
| 900 mm | 62.26 mm | 0.76 mm | 1.24% |
| 1000 mm | 62.53 mm | 1.03 mm | 1.67% |
| 1100 mm | 62.55 mm | 1.05 mm | 1.71% |
| 1200 mm | 63.67 mm | 1.17 mm | 1.90% |

The Table 5 shows that, when the distance increases from 700 mm to 1200 mm, the measurement error increases from 1.18% to 1.9%. It can be explained as follows: according to the trigonometric ranging model in binocular vision, when the working distance of the camera is farther, the depth image acquisition accuracy is lower, so the positioning error is larger.

Considering that there are inclined insulators in the actual substation, To prove that the DHH feature is not affected by the target inclination angle, the positioning experiment of insulator under different inclination angles is carried out by adjusting the relative inclination angle between the insulator and the camera. And the results are shown in Fig. 17.

It can be seen from Fig. 17 that this method can be used to accurately locate the insulator shed for a range of inclination angles. It can be explained as follows: since the inclination angle of the insulator has been calculated by PCA and the rotation correction has been carried out, the gradient information of DHH still retained. After the shed segmentation and depth detection, the key points on the shed can be located effectively.

Before an insulator cleaning robot performs cleaning operations, the robot needs to select a cleaning tool of a corresponding size according to the diameter of the insulator shed. So it is necessary to accomplish the measurement of the insulator shed diameter. By measuring the space distance between the left and right key points of each shed with the results from Fig. 17, we can obtain the average diameter of all sheds in single insulator. And the results are as shown in Table 6.

| Angle | Real diameter | Measurements | Error | Error rate |
|-------|---------------|--------------|-------|------------|
| 84.6° | 185.0 mm | 179.34 mm | -5.66 mm | 3.06% |
| 87.2° | 185.0 mm | 180.42 mm | -4.58 mm | 2.48% |
| 90.7° | 185.0 mm | 178.68 mm | -6.32 mm | 3.42% |
| 91.3° | 185.0 mm | 179.33 mm | -5.67 mm | 3.06% |
| 93.2° | 185.0 mm | 180.91 mm | -4.09 mm | 2.21% |
| 96.3° | 185.0 mm | 182.90 mm | -2.10 mm | 1.14% |

According to Table 6, the measurement error rate of insulator shed diameter under different inclination angles is less
than 3.42%, which also proved that this method can complete the accurate positioning of insulator shed under different inclination angles and the DHH feature is not affected by the target pose. It can be found that, the measurement error of insulator shed diameter is larger than that of insulator shed spacing, which can be explained as follows: because the edge of the insulator shed is easy to reflect the laser texture, it is difficult for the 3D camera to obtain the depth information of the shed edge. Therefore, all measured values of insulator sheds diameter are smaller than the true value, and the error rate is larger than the shed spacing.

Finally, we choose a composite insulator which consists of two diameters, uniformly spaced sheds to carry out the comprehensive positioning experiment, and the insulator D-HH and positioning results are shown in Fig. 18.

It can be seen from Fig. 18(a) and (c) that although the insulator includes two sizes of sheds and the crests of the DHH are unevenly distributed, the gradient information of the DHH is still very obvious. Through the gradient detection from Algorithm 1, the segmentation of all levels of insulator sheds can be completed effectively, and the key points positioning is finally realized, as shown in Fig. 18(b) and (d). By counting the average spacing between the insulator sheds in two scenes, and the average diameter of the large sheds and the small sheds separately, we can get the Table 7.

From the Fig. 18 and Table 7, we can draw the conclusion that the proposed method is not affected by complex background, the insulator material, color, inclination angle, scale and other factors, and can effectively complete the precise positioning of insulator shed.

In addition, this method has been verified in the insulator cleaning robot of Huangshi 110kV substation in China, whose working environment is shown in the Fig. 19. The Fig. 19 was taken at one afternoon on summer, when the robot was in a temperature of 34 °C and the ambient light intensity was about 30,000 Lux. The operation process of the above robot is as follows: firstly, the camera system at the end of the six-dof manipulator obtains the RGB-D...
images of the insulator; Secondly, the computer calculate the DHH and extracts all key points on the insulator shed, and transmits the 3D coordinates of all key points to the robot coordinate system. Lastly, the six-dof manipulator carries out path planning and grasps the cleaning tools to complete the cleaning operation of each insulator shed. This is the first time that this method has been applied to the insulator cleaning robot, which is of great significance to the live working technology of the robot.

V. CONCLUSION
In the field of electric robot, the background of substation insulator is complex, the surface color is uneven, and the shape of insulator shed in the image is constantly changing. The traditional insulator positioning methods has the problem of complex model, poor adaptability and low accuracy. In this case, we propose a new DHH feature, which is invariant to color, scale and rotation, and use it to achieve the precise positioning method of insulator shed effectively. Specifically, the proposed method includes the following steps: (1) we directly use the improved RGB-D camera to obtain the high-quality depth information of the insulator, and complete the effective filtering of complex background by band-pass filtering; (2) the DHH feature that contains the gradient information of the target space is calculated and used to complete the segmentation of each insulator shed; (3) the gradient detection is carried out to achieve the precise positioning of the insulator sheds. The experimental results show that the method can accurately and efficiently realize the accurate positioning of insulator sheds. And the relative spacing error rate of equal-diameter shed is less than 0.93%, the error rate of diameter measurement is less than 3.42%, and the processing time of a single image with 1280*720 resolution is only about 0.2 s.

The future work mainly includes two aspects: on one hand, we will improve the DHH feature and use it to locate other objects with obvious spatial features, but unknown color and complex background, such as cube and spirochete in 3D space; on the other hand, when we apply the robot for substation insulator cleaning, we will collect the RGB-D images of substation insulator to create a data set synchronously, and build a new neural network model to complete the accurate positioning of insulator.

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### TABLE 7. Positioning results of the composite insulator in two scenes

| Data | Scene 1 (distance: 850 mm, angle: 86.17°) | Scene 2 (distance: 1050 mm, angle: 90.08°) |
|------|-----------------------------------------|------------------------------------------|
|      | spacing diameter of small shed diameter of large shed | spacing diameter of small shed diameter of large shed |
| True value | 54.0 mm 190.0 mm 225.0 mm | 54.0 mm 190.0 mm 225.0 mm |
| Average value | 54.99 mm 184.81 mm 222.69 mm | 55.25 mm 184.19 mm 221.60 mm |
| Error | 0.99 mm 5.19 mm 2.31 mm | 1.25 mm 5.82 mm 3.40 mm |
| Error rate | 1.83% 2.73% 1.02% | 2.31% 3.06% 1.51% |
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