

Dial Correction Method of Circular Instrument Based on Perspective and Affine Transformation

Tianyu Li*, Zirui Yang

School of Electrical and Electronic information Engineering, Sichuan University Jinjiang College, Meishan, 620000, China

* Corresponding author: Tianyu Li (Email: litianyu207@163.com)

Abstract: A dial correction method based on perspective and affine transformations for pointer instrument reading recognition using the angle method is proposed to address the error caused by image capture angles. Firstly, Hough circle detection is used to locate the circular instrument and remove background interference. Then, Canny edge detection and least squares method are applied to detect the contour of the instrument dial, and the inner contour is used to extract the dial area. Finally, to correct the distortion of the circular dial into an ellipse due to different shooting angles, projection transformation and affine transformation are utilized to correct the distorted instrument dial. The experimental results show that the dial correction method studied in this paper can achieve the goal of restoring the horizontal alignment of instrument dials captured at different angles.

Keywords: Canny operator, Least squares method, Projective transformation, Affine transformation.

1. Introduction

In power systems, substations serve as critical nodes for electricity transmission and distribution. The real-time monitoring and precise control of their operational status are invaluable for ensuring the safety and stability of the grid, as well as improving the quality and efficiency of power supply [1]. With the accelerated development of smart grids, the automation and intelligence levels of substations are increasingly enhanced. As an indispensable monitoring tool within substations, the automation and intelligent recognition of pointer instrument readings have become a current research hotspot and challenge.

Currently, the widely used method for recognizing the readings of pointer instruments in substations is based on the angle method. This method first obtains the included angle between the 0-degree mark and the pointer, then converts the angle to the corresponding scale value to get the final reading. However, often the image capture angle of the dial is not always perpendicular to the front of the dial, resulting in the recognized inner contour of the dial being an ellipse rather than a perfect circle. Therefore, using the angle method inevitably introduces significant errors. Thus, it is necessary to correct the dial captured by the camera to improve recognition accuracy [2].

To address this issue, literature [3-4] proposes using deep learning methods to locate the instrument, extract its contour features, correct the instrument contour to a circle, and finally use the angle method for reading recognition. Literature [5] matches ORB features between the detected instrument image and a predefined standard template, then calculates the homography matrix between them to achieve dial correction. Experiments show that the corrected images can improve the accuracy of reading recognition. Tong Weiyuan et al [6] establish a template library containing scale line recognition area information, first extract the scale feature subregion from the image to be recognized, then perform scale line extraction, and finally obtain features through clustering methods. This approach overcomes issues such as uneven lighting and background interference but is complex to apply and has low recognition accuracy. Literature [7] transforms the scale

region of the instrument dial into polar coordinates, converting the arc-arranged scale lines into vertically arranged ones, thereby solving the reading error caused by dial tilt. Literature [8] uses the SIFT algorithm for real-time matching to locate the instrument, but this method is time-consuming, requires high image quality, and is prone to incorrect matching with noisy images. Literature [9] adopts a method of extracting corner points from scale lines to determine their positions, but this method has low recognition accuracy and very complex corner points. Literature [10] addresses the inaccuracies in reading recognition due to shooting angles by approximating the camera's perspective projection as an affine projection, but the final results are still not precise. Therefore, since the scale plane of the dial and the pointer rotation plane are not coplanar, in cases of tilted instrument capture, the center of the image scale does not coincide with the axis center of the pointer, and the indicated scale in the image is not the actual scale [11].

Therefore, to address the recognition errors caused by camera shooting angles when using the angle method, this paper designs a circular instrument image correction method. First, Hough circle detection is used for circular instrument localization and Gaussian filtering for image denoising to remove background interference; then Canny edge detection and the least squares method are employed for instrument dial contour detection, and the inner contour is extracted to define the dial area; finally, to correct the dial distortion caused by different shooting angles, projective transformation and affine transformation are utilized to correct the tilted instrument.

2. The Process of Circular Instrument Dial Correction Method

Most pointer instrument reading recognition methods utilize the angle method, which first obtains the included angle between the 0-degree mark and the pointer, then converts the angle to the corresponding scale value to get the final reading. However, the shooting angle of the instrument image is not always perpendicular to the front of the dial, so the recognized inner contour of the dial is an ellipse rather than a perfect circle. Therefore, using the angle method

inevitably introduces significant errors. Thus, it is necessary to correct the dial captured by the camera to improve recognition accuracy.

To address the error issues brought by image shooting angles when using the angle method for pointer instrument reading recognition, a dial correction method based on perspective transformation and affine transformation has been studied. This method first uses Hough circle detection for circular instrument localization and Gaussian filtering for image denoising to remove background interference; then, Canny edge detection and the least squares method are employed for instrument dial contour detection to achieve dial image extraction; finally, to correct the dial distortion caused by different shooting angles, projective transformation and affine transformation are utilized to correct the tilted instrument. The flowchart of the circular instrument correction method is shown in Figure 1.

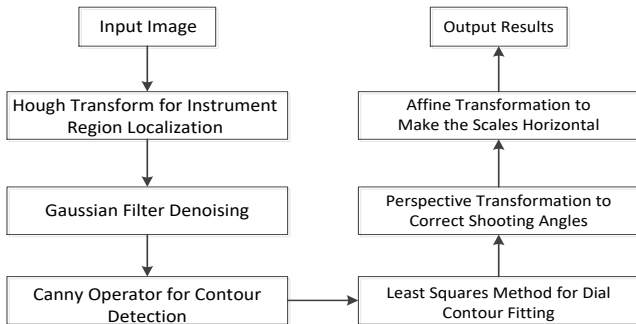


Figure 1. Flowchart of the Circular Instrument Correction Method

3. Extraction of Dial Area

In camera-captured instrument images, there is often a lot of background noise that can interfere with subsequent dial correction. Therefore, this paper first performs preliminary positioning and denoising of the instrument image through Hough circle detection and Gaussian filtering. Then, it utilizes the Canny algorithm to detect the instrument contour. Finally, it fits the instrument contour using the least squares method to complete the extraction of the dial area.

3.1. Detection of Instrument Images

The basic idea of the Hough Transform [12] is to consider that every non-zero pixel point in an image has the potential to lie on a circle. Through coordinate transformation, the original two-dimensional coordinate points are converted into three-dimensional coordinate points and counted by voting. Finally, the votes are compared with a set threshold to locate the circles in the image.

In the Cartesian two-dimensional coordinate system, the equation for the coordinates of a circle is:

$$(x-a)^2 + (y-b)^2 = r^2 \quad (1)$$

In equation (1): (a, b) represents the coordinates of the center of a circle in two-dimensional space, and r is the radius of that circle. From the above equation, it can be seen that in the two-dimensional parameter space, knowing the coordinates of the circle center (a, b) and the radius r allows for the determination of a specific circle in space. Each point in the three-dimensional parameter space represented by a, b, and r corresponds to a specific circle in the two-dimensional parameter space. By iterating through the image pixel coordinates and substituting into equation (1), the corresponding r value for the above equation can be solved.

For each calculated (a, b, r) value, an accumulator corresponding to it is incremented by 1. After the iteration ends, when the accumulator value for a coordinate point exceeds a set threshold, it can be considered that a circle has been detected at the corresponding coordinate point [13].



(a) Original detection image (b) Hough Transform localization result

Figure 2. Instrument Localization Results

The preliminary positioning result of the instrument image is shown in Figure 2. As can be seen from the figure, Hough Transform can preliminarily achieve the positioning of the instrument image and remove background interference.

3.2. Gaussian Noise Reduction

In the power system of substations, images are captured by cameras and then transmitted wirelessly to a computer for image processing [14]. Due to the uncertainties of the external environment, the collected images may contain a significant amount of noise. Therefore, it is necessary to preprocess the collected images to highlight the instrument features and prevent errors in subsequent reading recognition.

Image filtering uses Gaussian filtering, which is a linear smoothing filter based on the normal distribution (or Gaussian distribution) function for image processing [15]. It can eliminate Gaussian noise and is widely used in the noise reduction process of image processing. Gaussian filtering performs weighted average calculations on an image, where the target pixel and its surrounding adjacent pixels together form a Gaussian filter template. The weighted mean of all pixels in the template is the Gaussian-filtered value of the target pixel. One implementation method of Gaussian filtering involves discrete window sliding convolution; the main parameter of this method is the Gaussian kernel. This paper selects a 5x5 Gaussian kernel. The Gaussian template is calculated through the Gaussian function, with the formula as follows:

$$G(x, y) = \frac{1}{2\pi\sigma} \exp\left\{-\frac{x^2 + y^2}{2\sigma^2}\right\} \quad (2)$$

In equation (2), (x, y) represents the relative coordinates of a pixel, indicating the distance from that point to the center. σ is the standard deviation of the Gaussian distribution, which determines the width of the Gaussian function (i.e., the extent of pixel distribution near the center point). The larger this value, the more blurred the filter becomes, enhancing noise removal capabilities but potentially sacrificing more image details. This formula describes that in two-dimensional space, pixels farther from the center pixel have lower weights. When the surrounding pixels participate in the calculation, those closer to the center have higher weights, and those farther away have lower weights. The result of Gaussian filtering is shown in Figure 3.



Figure 3. Gaussian Filtering Denoising Results

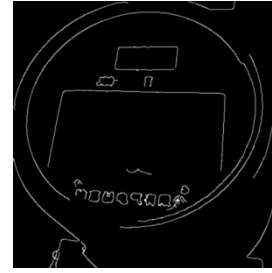


Figure 4. Canny Edge Detection Results

3.3. Acknowledgment

Image edges [16] refer to parts of an image where there is a significant change in local area brightness. The grayscale profile of this region can be seen as a step, meaning that the grayscale value changes abruptly from one value to another with significantly different grayscale values within a small buffer region. Determining and extracting the edges of instrument images is very important for extracting the instrument region and also serves as an important feature relied upon for instrument readings.

Canny [17] edge detection is one of the most commonly used methods for detecting edges using a multi-stage edge detection algorithm. It mainly includes the following four steps:

(1) Image filtering and noise reduction. Since Canny edge detection needs to use gradient operators to enhance the edge contour information of the image, but gradient operators are greatly affected by noise, it is necessary to first reduce the noise, usually through Gaussian filtering.

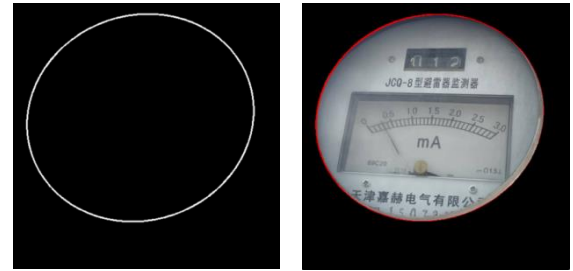
(2) Calculate the gradient value G and the direction of the gradient. Since edges are collections of pixel points where the grayscale values change significantly, edges can be found based on the gradient. The formulas for calculating the gradient and direction are shown in equation (3).

$$\begin{cases} G = \sqrt{G_x^2 + G_y^2} \\ \theta = \arctan(G_x, G_y) \end{cases} \quad (3)$$

(3) Non-maximum suppression. Since edges are amplified during the filtering process, only the edges with the greatest grayscale change are retained in the local range of gradient directions, thereby filtering out the true edge information.

(4) Detect edges using double thresholds. By setting upper and lower thresholds, pixel points above the upper threshold are designated as strong edge pixels, while those below the lower threshold are eliminated.

The entire circular pointer instrument is divided into inner and outer contours, and the inner contour belongs to the instrument dial area. This area's image contains the pointer and scale, which are key features for subsequent instrument recognition. Therefore, this paper adopts the Canny operator to perform edge detection on the instrument, finding the inner and outer contours of the instrument to provide a basis for subsequent dial extraction. The contour detection results of the Canny operator on the instrument are shown in Figure 4, where it can be seen that the Canny operator has essentially extracted both the inner and outer contours of the instrument.



(a) Instrument Inner Contour Fitting Results (b) Dial Region Extraction Results

Figure 5. Dial Region Extraction Results

After Canny edge detection and morphological operations, the inner contour of the dial is preserved while irrelevant details are minimized as much as possible, laying the foundation for subsequently finding the elliptical inner contour of the dial through an ellipse fitting algorithm. Therefore, to further complete the extraction of the dial image, this paper chooses the least squares method to fit the ellipse. Then, using the approximate range of the instrument obtained from preliminary instrument positioning, multiple fitted ellipses are conditionally screened to accurately determine the position of the elliptical inner contour of the dial, thereby extracting the dial image. The results of the dial extraction are shown in Figure 5(a) and (b).

4. Dial Correction Method for Round Instruments Based on Projective and Affine Transformations

The shooting angle of the instrument image is not always perpendicular to the front of the dial, so the identified inner contour of the dial appears as an ellipse rather than a perfect circle. Therefore, using angle-based recognition inevitably leads to significant errors. Thus, it is necessary to correct the dial captured by the camera during dial recognition to improve accuracy. This paper utilizes perspective transformation and affine transformation to achieve the correction of tilted instrument dials.

4.1. Perspective Transformation

It is well known that the Earth's surface is a non-developable sphere, while a map is a plane. Therefore, if one wants to mark objects on the Earth's surface onto a planar coordinate map, it is necessary to establish some kind of correspondence from the spherical surface to the plane. This type of correspondence is called map projection. The purpose of map projection is to represent the intersection points of longitude and latitude lines on the Earth's ellipsoid in a planar coordinate system, and to calculate the distances and directions between these points within the planar coordinate system.

Therefore, utilizing perspective transformation in instrument images refers to the central projection transformation between two planes. According to the law of perspective rotation, the image plane (perspective plane) rotates around the trace line (perspective axis) by a certain angle, breaking the original bundle of projection rays, yet maintaining the geometric figures projected on the image plane unchanged [17]. The general formula for perspective transformation is:

$$\begin{bmatrix} x' & y' & w' \end{bmatrix} = \begin{bmatrix} u & v & w \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad (4)$$

In Formula (4), (u, v) represents the original image pixel coordinates, and $(x = \frac{x'}{w'}, y = \frac{y'}{w'})$ represents the transformed image pixel coordinates. This paper corrects the shooting angle based on perspective transformation, achieving central projection transformation between two planes to correct the shooting angle and reduce the roundness error of the dial.

4.2. Affine Transformation

Although perspective transformation has achieved the projection from an elliptical dial to a circular one, reducing the angular error of the scale disk, it has also caused the image to rotate by a certain angle, making the instrument scale no longer horizontal. Therefore, after the projection transformation, an affine transformation is used to complete the rotation of the instrument to a horizontal position. Affine transformation is a mathematical model for coordinate transformation based on the affine coordinate system, obtained through composite transformations such as translation, scaling, rotation, symmetry, and shearing. When the number of coincident points is greater than or equal to 3, affine transformation can be applied.

$$\begin{cases} X'_i = a_0 + a_1 X_i + a_2 Y_i \\ Y'_i = b_0 - b_1 X_i + b_2 Y_i \end{cases} \quad (5)$$

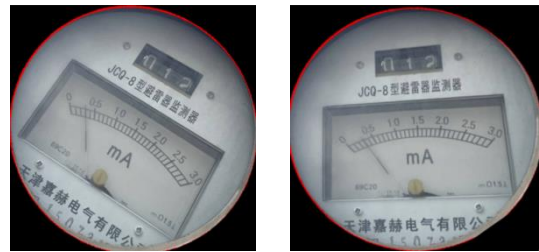
In the above formula (5), a_0 to b_2 are affine transformation parameters, totaling 6. Only three control points are needed to uniquely determine the conversion coefficients. When the number of control points exceeds three, the least squares method can be used for determination, which helps improve the accuracy of the conversion parameters. Once the conversion parameters are determined, they apply to all transformed points of the graphic. In practical applications, it is common to use more than four corresponding point coordinates and the least squares method to solve for the transformation coefficients to improve transformation accuracy [18].

The characteristics of affine transformation are: (1) a line remains a line after transformation; (2) parallel lines remain parallel after transformation, maintaining simple length ratios; (3) length ratios in different directions change. Affine transformation is a linear transformation between two-dimensional coordinates, preserving the "collinearity" (straight lines remain straight after transformation) and "parallelism" (the relative positional relationships between two-dimensional graphics remain unchanged, parallel lines

remain parallel, and the order of points on a line remains unchanged). Using affine transformation, the horizontal rotation results caused by perspective transformation can be further corrected to obtain the final dial image.

4.3. Dial Correction Method Based on Perspective and Affine Transformations

The specific steps for correcting the shooting angle based on perspective and affine transformations in this article are as follows: (1) Find the coordinates of the endpoints of the long and short axes of the elliptical dial contour; (2) Project the endpoints of the long and short axes of the four inner contour ellipses onto a circle through perspective transformation; (3) Rotate the projected transformation results using affine transformation to obtain the final horizontal frontal view of the instrument dial image. The table correction results based on perspective and affine transformations are shown in Figures 6(a) and (b). As can be seen from Figure 6(a), the projection transformation completes the projection of the dial ellipse to a circle, while Figure 6(b) achieves the rotation of the scale to a horizontal position.



(a) Projection transformation result (b) Affine transformation result

Figure 6. Dial Image Correction Results

5. Analysis of Experimental Results

To further verify the practicality of the dial correction method presented in this article, experiments were conducted using instrument images taken from different angles. The results are as follows:

(1) Circular Instrument Image Localization and Denoising



(a) Hough Transform Localization Result (b) Gaussian Denoising Result

Figure 7. Preliminary Processing Results of Instrument Image

This section mainly uses a single tilted instrument image for verification. Figure 7 shows the results of localizing the instrument using the Hough transform and Gaussian denoising. As can be seen in Figure 7(a), the Hough transform can achieve precise instrument localization and remove background interference. Meanwhile, Figure 7(b) indicates that Gaussian denoising can remove redundant feature information from the instrument image, emphasizing edge parts, which is beneficial for subsequent contour detection.

(2) Dial Region Extraction

After completing the preliminary processing of the

instrument image, it is necessary to extract the instrument dial to lay the foundation for subsequent dial correction. Figure 8 shows the edge detection results and the extracted dial region. As can be seen in Figure 8(a), the Canny operator detects all edges in the instrument, but there are too many detected edges to determine the specific position of the inner contour of the instrument. Therefore, based on this, the least squares method is used to fit the edges, ultimately obtaining the inner contour edge line of the instrument as shown in Figure 8(b).



(a) Edge Detection Results (b) Inner Contour Fitting Results

Figure 8. Dial Region Extraction Results

(3) Dial Region Correction

For the extracted dial region, due to shooting angle issues, the dial inevitably deforms from circular to elliptical, which can cause errors in subsequent instrument recognition. Therefore, for the extracted dial region, projection transformation is first used to transform the distorted ellipse into a circle, as shown in Figure 9(a). From the figure, it can be seen that although the ellipse is restored to a circle, the scale has rotated and is no longer horizontal. Therefore, the next step is to use affine transformation to restore the rotated instrument to a horizontal position, as shown in Figure 9(b).



(a) Perspective Transformation Correction Result (b) Affine Transformation Correction Result

Figure 9. Dial Correction Results

From the experimental results, it can be concluded that the dial correction algorithm studied in this article, based on perspective and affine transformations, can restore a distorted elliptical dial caused by shooting issues to a circle to some extent. The restored dial image is conducive to subsequent angle-based recognition of readings, which can further improve the accuracy of instrument recognition.

6. Conclusion

This article studies a meter image correction method based on projection transformation and affine transformation, which can improve the accuracy of angle-based recognition of instrument readings to some extent. This is conducive to promoting the development of unmanned substations, reducing social costs, and avoiding wastage of human resources. The method first uses Hough circle detection for circular instrument localization and background interference removal; then it employs Canny edge detection and the least

squares method for instrument dial contour detection and inner contour extraction to isolate the dial region. Finally, for different shooting angles, it utilizes projection transformation and affine transformation to correct the tilted instrument. While this method can improve the accuracy of instrument reading recognition to some extent, there is still considerable room for improvement.

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