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Research on the Calibration Method of Welding Inspection Robot's Binocular Vision

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Abstract

In the context of intelligent manufacturing, the automation and intelligent upgrading of welding inspection have become core requirements in industrial fields. Traditional manual inspection faces challenges such as low accuracy, poor efficiency, and difficulties in adapting to hazardous environments. The integration of machine vision and welding robots provides a key solution to these issues, with precise calibration of binocular vision systems serving as the core prerequisite for this integration. This study systematically investigates the calibration of binocular vision systems in welding inspection robots: it completes the resolution of camera internal and external parameters; experimental verification using MATLAB calibration tools demonstrates a reprojected error of 0.06 pixels, with actual measurement errors ≤0.02mm and a standard deviation of 0.0073mm, indicating high calibration accuracy. The research provides a complete and feasible calibration technical solution that enables precise 3D positioning of welds, enhances the automation and intelligence of welding inspection, and can be extended to various industrial inspection scenarios, demonstrating strong engineering application value.

Keywords

Welding Inspection Robot; Binocular Vision System; System Calibration; Image Preprocessing; Coordinate System Transformation.

1. Introduction

Machine vision, as the core technology of intelligent manufacturing, is widely applied in industrial scenarios due to its multiple advantages and serves as the key support for intelligent perception and operations in industrial robots. Its deep integration with industrial robots represents an industry upgrade trend, enabling unmanned operations in welding inspection to enhance efficiency and safety. As a 3D perception technology, binocular vision outperforms monocular vision in 3D information acquisition, making it the core technical support for high-precision operations in welding inspection robots. System calibration is the prerequisite for their integrated application, as calibration accuracy directly impacts operational effectiveness. Researching calibration methods suitable for welding inspection scenarios is of great significance for improving operational precision and advancing industry automation upgrades.

Bimanual vision, with its 3D perception capability, has been widely applied in industrial inspection, robotics, and smart manufacturing. Scholars worldwide have conducted extensive research on calibration methods and system integration, laying the technical foundation for welding inspection robots. Yin Wenqian improved barcode recognition efficiency by enhancing calibration accuracy [1]; Chen Hong validated the application potential of bimanual vision in high-precision measurement using OpenCV and VS2017 [2]; Han Bo integrated neural networks with bimanual vision to improve the accuracy and efficiency of complex workpiece

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recognition [3]. Additionally, hand-eye calibration studies enhanced system calibration precision through error analysis and parameter optimization. Current research focuses more on multi-sensor fusion and robot system integration. Haikuo Shen et al. proposed an adaptive optimization calibration algorithm by integrating laser and bimanual vision, improving measurement efficiency and accuracy [4]; NAO robots utilize bimanual vision for object positioning and grasping; foreign scholars have advanced calibration technology in areas such as coordinate system transformation [5]. Although bimanual vision calibration has achieved results in industrial fields, research on specialized welding inspection scenarios remains insufficient. Developing high-precision and high-reliability solutions tailored for welding robots remains a key focus of this study.

This study focuses on the calibration of the binocular vision system for welding inspection robots, completing the camera's intrinsic and extrinsic parameter calibration and solving the parameter matrix. Using MATLAB for calibration experiments, the feasibility of the proposed scheme is verified, and the accuracy and reliability are analyzed to provide support for practical applications.

2. Key Technology of Binocular Vision System Calibration

2.1. Calibration Principle

Figure 1 illustrates the camera calibration coordinate system. The core of camera calibration lies in establishing mutual transformations among the world coordinate system, camera coordinate system, image coordinate system, and pixel coordinate system. By solving the transformation equations from the world coordinate system to the pixel coordinate system, the camera's intrinsic and extrinsic parameter matrices are calculated. Only after calibration parameter correction can the camera be deployed in practical applications.

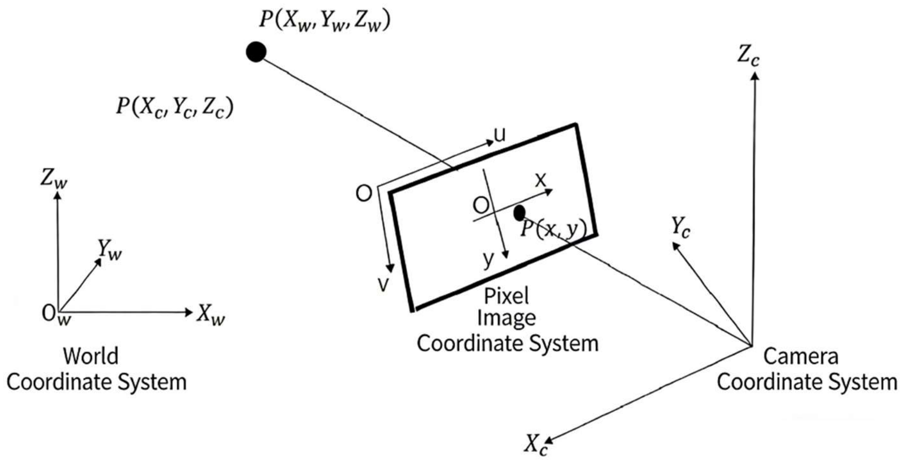

Figure 1. Coordinate System

The camera's internal parameter matrix, determined by its focal length, pixel dimensions, and principal point coordinates, remains independent of its placement and orientation. The external parameter matrix, composed of a rotation matrix and a translation vector, defines the camera's spatial position and orientation in the world coordinate system. The calibration of binocular cameras $P_l P_r R_{12} = R_r \cdot R_l^{-1} T_{12} = T_r - R_r \cdot R_l^{-1} \cdot T_l$ involves not only solving the internal and external parameter matrices for the left and right monocular cameras but also determining their relative positional relationship. Given the coordinates of a point in the world coordinate system for both cameras, the rotation matrix and translation vector can be derived through the formula after eliminating the world coordinate system's correlation parameters. This completes the internal and external parameter calibration of the binocular camera, establishing a comprehensive binocular vision projection model.

2.2. Calibration Process

The specific method involves using a standard film calibration board to capture calibration images. By continuously changing the position and orientation of the calibration board to traverse the entire field of view of the camera, a total of 21 pairs of binocular images were acquired (meeting the requirement of ≥15 pairs for calibration), with one pair shown in Figure 2.

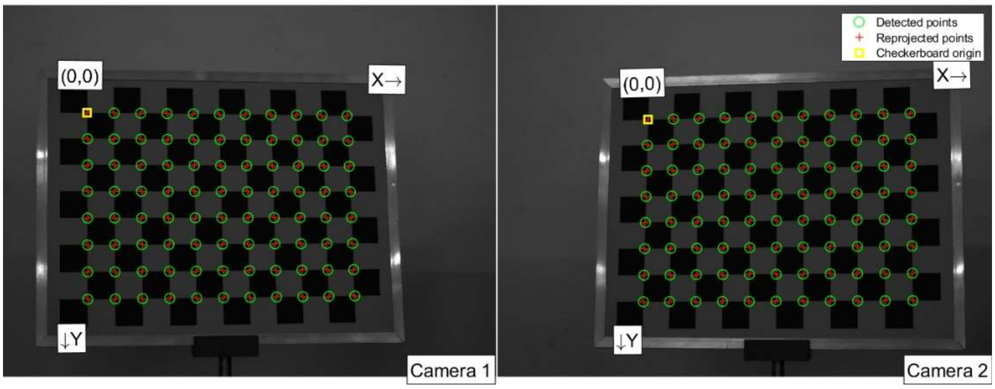

Figure 2. Calibration Process

Launch MATLAB and activate the stereo camera calibration toolbox via the `stereoCameraCalibrator` command. Import the 21 calibration images and set the checkerboard grid size to 5mm. The toolbox automatically filters the imported images, removing blurry or poorly defined ones, then performs corner detection and extraction on qualified images. Click the "Calibration" button to calculate the camera's intrinsic and extrinsic parameters, distortion coefficients, and relative position between the left and right cameras. The experiment achieved a reprojected error of only 0.06 pixels with no outliers, meeting the required calibration accuracy as shown in Figure 3.

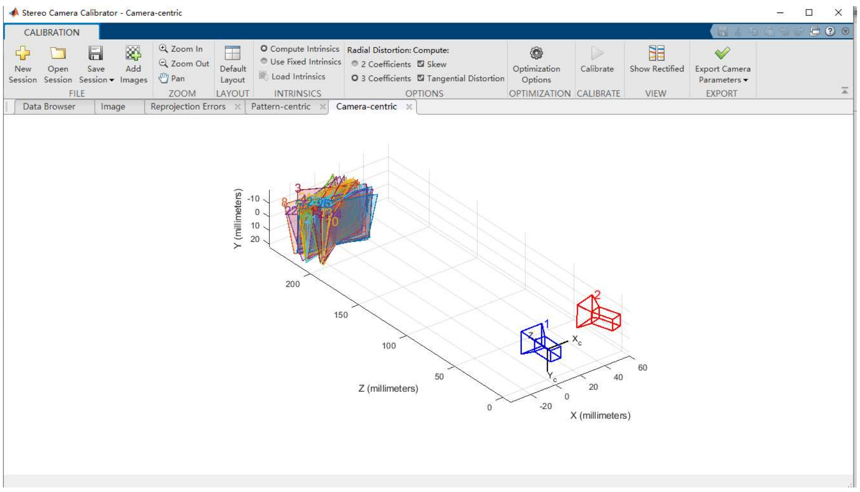

Figure 3. Camera-centered calibration view

The internal parameter matrix R_1 of the left CCD camera is:

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$$R_1 = \begin{bmatrix} 7946.86867 & 0 & 1275.51732 \\ 0 & 7947.94504 & 1024.86205 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The internal parameter matrix $R_2$of the right CCD camera is:

$$R_2 = \begin{bmatrix} 7946.35324 & 0 & 1240.28645 \\ 0 & 7945.42565 & 1015.73696 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

The relative rotation matrix and translation $R_{12}T_{12}$matrix of binocular stereo vision system are:

$$R_{12} = \begin{bmatrix} 0.9571 & -0.0162 & -0.2893 \\ 0.0169 & 0.9999 & 0.0096 \\ 0.2892 & -0.0049 & 0.9573 \end{bmatrix} \quad (3)$$

$$T_{12} = \begin{bmatrix} -53.7707 \\ 0.3287 \\ 7.7224 \end{bmatrix} \quad (4)$$

2.3. Verification of Calibration Results

The Matlab calibration toolbox initiates the calibration process for the input image data, yielding a re-projection error as depicted in Figure 4. The figure reveals that the re-projection error in this calibration process is merely 0.06 pixels, demonstrating that the precision has met the required standards.

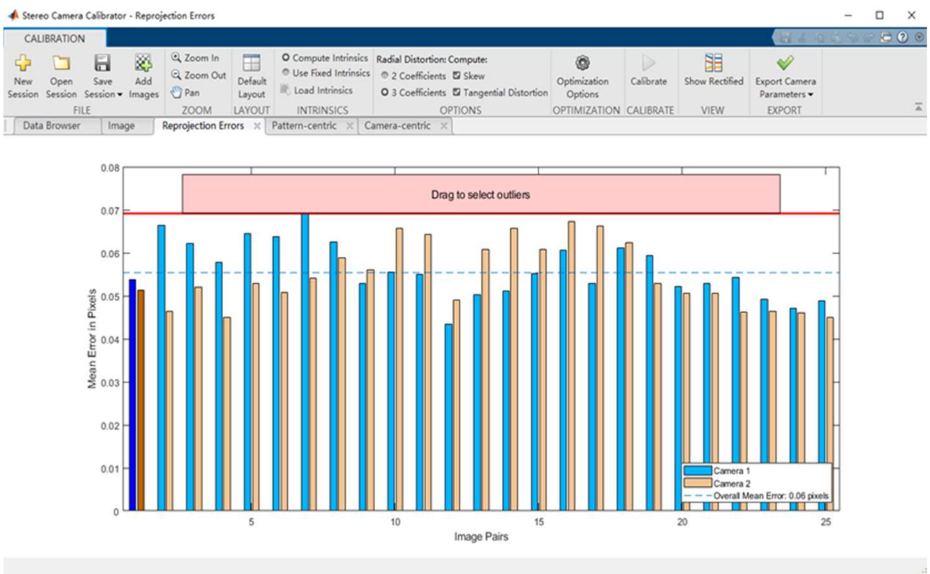

Figure 4. Dual-target calibration results

To further quantify the reliability of the calibration results, calculate $\bar{d}\sigma(d)$ the mean and standard deviation of the distance between adjacent corner points, using the following formula:

$$\bar{d} = \frac{1}{n}\sum_{i=1}^{n} d_i \quad (5)$$

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$$\sigma(d) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(d_i - \bar{d}\right)^2} \quad (6)$$

Here, is nd_iithe number of measurement samples, and is the measurement distance of the group. The mean value of the distance between adjacent corner points is 4.9914mm, which is in good agreement with the standard distance height. The standard deviation is only 0.0073mm, indicating that the dispersion of the calibration results is extremely low, and the accuracy and reliability meet the requirements of the binocular vision of the welding inspection robot.

3. Conclusion

This study systematically investigates the core issue of binocular vision system calibration for welding inspection robots, covering theoretical modeling to experimental validation. We propose a binocular vision calibration scheme tailored for welding inspection scenarios, with the following key findings:

(1) The complete transformation model from world coordinate system to pixel coordinate system is established, the theoretical basis of camera calibration is defined, and the clear calculation path for solving the camera internal and external parameters is provided.

(2) The camera's internal and external parameters are solved, and the relative position between the left and right cameras is determined, which provides a precise parameter basis for the 3D measurement of the binocular vision system.

(3) The experiment of binocular camera calibration using MATLAB calibration toolbox has obtained the re-projection error of 0.06 pixels. The measurement error of the distance between adjacent corner points is less than or equal to 0.02mm, and the standard deviation is only 0.0073mm. The accuracy and reliability of the calibration results are excellent, which can meet the requirements of welding inspection robot.

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