



Error Correction Technology for Welding Robots Based on Three-Dimensional Visual Localization

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ABSTRACT

We have developed a novel welding robot through three-dimensional visual localization, which can promptly correct deviations in the welding seam's position and shape, thus improving the welding accuracy. This new welding robot can better meet customer demands and complete complex manufacturing processes faster. After multiple experiments, we found that the welding seam error correction technology based on three-dimensional visual localization significantly reduces welding errors, thereby substantially improving product quality and accuracy. Therefore, we recommend adopting this new error correction technology to enhance product quality. This research significantly benefits welding technology improvement, helping us better control welding seams and accurately predict future variations. As a result, we can ensure superior product quality, safety, and reliability.

Keywords: Three - Dimensional Visual Localization, Welding Robot, Welding Seam Error Correction Technology

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1. Introduction

In recent years, due to the rapid growth of industrial production, welding has become an essential technology in many fields. However, traditional welding methods are prone to defects, such as deviations or changes in the welding seam's shape, which affect the overall product performance. We can effectively address this issue by adopting advanced technology that can monitor and correct deviations occurring during the welding process in real-time. Over the past few decades, with technological advancements, welding robots have become increasingly widespread[1]. They offer outstanding performance in terms of speed, accuracy, and flexibility,

significantly enhancing production efficiency while ensuring product quality. Nevertheless, as they cannot promptly correct welding seam deviations, there is still a need for more advanced technology to improve this situation. Lack of reliable technical support makes it challenging for welding robots to achieve high efficiency [2]. In recent years, the emergence of three-dimensional visual localization technology has made it possible to effectively control welding seam error correction. It can capture details such as the position, size, and shape of the welding seam, enabling timely error correction [3], greatly improving welding seam accuracy. This advanced localization method not only effectively reduces errors but also greatly enhances welding seam quality, significantly improving welding seam accuracy. The purpose of this article is to explore how welding robots based on three-dimensional visual localization can correct welding seam misalignment. To better understand this work, we need to grasp its historical background, challenges, and advantages. Furthermore, a deep understanding of the fundamentals of three-dimensional visual localization is required, combined with practical case analysis. In this study, we first explore a welding seam error correction solution based on three-dimensional visual localization, providing a detailed description of its operational process and related technical requirements. Subsequently, after multiple experiments, we validate the effectiveness and operability of this novel error correction algorithm, and delve into the experimental results. In conclusion, this research aims to develop a novel technology capable of promptly detecting and correcting welding seam misalignments, thereby improving the working status and product quality of welding robots. Precise testing and control can help us better identify welding seam deviations, reducing or eliminating welding quality defects, while also increasing the rigidity and durability of welded components [4]. Additionally, it can promote continuous improvement in welding technology, significantly enhancing factory production efficiency and product quality.

2. Related Work

In recent years, the technology of error correction for welding robots based on three-dimensional visual localization has attracted extensive attention and research. Many scholars and researchers have conducted significant work in this field, proposing various methods and algorithms. One common approach is based on laser scanning three-dimensional visual localization [5]. Laser scanning technology sends laser beams and detects their reflection signals to obtain three-dimensional point cloud data of the welding seam. By processing and analyzing the point cloud data, geometric features of the welding seam, such as its position, shape, and size, can be obtained. The acquired welding seam information is then integrated with the robot's control system to achieve real-time error correction of the welding seam [6]. For example, researchers have proposed a laser scanning-based welding seam tracking method that collects real-time three-dimensional information of the welding seam and compares it with the predetermined welding path to achieve real-time error correction of the welding seam [7]. In addition to laser scanning technology, some studies have utilized structured light projection technology to achieve three-dimensional visual localization of the welding seam. Structured light projection technology projects specific light patterns or spots onto the welding seam's surface and captures them with a camera to obtain three-dimensional shape information of the welding seam. This method does not require contact measurement and enables non-contact, rapid, and accurate welding seam positioning [8]. Some researchers have realized real-time three-dimensional tracking and correction of the welding seam through structured light projection technology, thereby improving welding accuracy and quality.

Apart from the mentioned methods, some studies have applied machine vision and sensor fusion to welding seam error correction. For instance, combining cameras and laser rangefinders and other sensors allows for multimodal detection and measurement of the welding seam's position and shape [9]. By fusing and comprehensively analyzing data from multiple sensors, the accuracy and stability of welding seam localization

can be improved. Some researchers have proposed welding seam error correction methods based on multi-sensor fusion, which involve real-time acquisition of data from multiple sensors, followed by comprehensive analysis and processing for real-time error correction of the welding seam. Additionally, some research focuses on algorithm improvement and optimization. For example, using machine learning and deep learning techniques, automatic recognition and localization of the welding seam can be achieved. By training algorithms and models, the image features of the welding seam can be associated with its actual position, enabling automated welding seam error correction. Some researchers have proposed deep learning-based welding seam recognition and correction methods, constructing deep neural network models to accurately predict and correct the position and shape of the welding seam [10].

In summary, error correction technology for welding robots based on three-dimensional visual localization is a popular research area. By employing various methods and techniques, real-time detection and correction of welding seam errors can be achieved, enhancing the adaptability and welding quality of welding robots [11,12]. Future research can further explore more precise and efficient three-dimensional visual localization methods, as well as their combination with machine learning and deep learning technologies, to advance the development of welding robot technology.

3. Machine Learning Algorithm Design

In the process of welding seam error correction, it is necessary to classify the obtained three-dimensional point cloud data to accurately identify the position and shape of the welding seam for error correction. The following are several common algorithm design methods. In this paper, machine learning algorithms combined with geometric features are used to effectively classify different parts of the weld joint [13-15]. For example, we can use information such as curvature, normal vectors, and angles to distinguish different joints. One commonly used machine learning algorithm is Support Vector Machine (SVM), which can identify various shapes of welding points and optimize their shapes. This method helps to better identify various shapes of welding points and correct their misalignment [16,17]. In the vicinity of X , the covariance matrix of the point cloud exhibits significant variations.

$$M = \frac{1}{k} \sum_{m=1}^k (p_m - \bar{p}) \cdot (p_m - \bar{p})^T \quad (1)$$

The elevation value in the remote sensing point cloud has actual geographical significance. Therefore, the elevation information of points around the point cloud can be statistically analyzed to assist in determining the point cloud category. Through statistical analysis, the elevation value h of the query point, the maximum height difference A_h among neighboring points around the point cloud, and the standard deviation of elevation values of neighboring points are obtained. In addition to statistics related to elevation values, there is also the neighborhood radius. The neighborhood radius with a definition of 1 cm represents the distance between the query point and its farthest neighboring point. The spatial density d_{2D} of the three-dimensional point cloud within the neighborhood. Verticality V . Based on the translation and rotation characteristics of lines, to increase the distinction between different features, the three-dimensional point cloud is projected onto a two-dimensional horizontal plane. The two-dimensional covariance matrix of the query point is obtained on the two-dimensional horizontal plane, and the eigenvalue decomposition of the two-dimensional covariance matrix is conducted. The projection of parallel rays can be achieved by a set of parallel line models, while the projection along the ray $x\cos\theta + y\sin\theta = \rho$ can obtain any point in the projection data. After detecting lines in the insulator image, horizontal rotation of the insulator edge detection image is needed. The average of several line slopes

in the line detection results is taken as the horizontal rotation angle. The definition of the feature is as follows:

$$d_{2D} = \frac{k+1}{\pi r_{km, 2D}^2} \quad (2)$$

Deep learning has become an important technology in the field of computer vision, effectively helping to address the welding seam error correction problem. By constructing deep neural network models, automatic recognition and classification of welding seams can be achieved, thereby improving work efficiency. Convolutional neural networks can effectively extract and classify features in three-dimensional point cloud data, thus accurately identifying various types of welding seams [18]. Additionally, deep neural networks can help process complex data and transform it into a simple and understandable form, making it more applicable in image processing and computer vision. By utilizing feature descriptors, the accuracy of three-dimensional point cloud data can be improved, better identifying and correcting welding seam errors. These feature descriptors can be scale-invariant and robust, or they can take other forms [19-21]. With the projection technology of three-dimensional point cloud data, we can accurately identify the position information of welding seams and other related information. Moreover, edge detection algorithms and corner detection algorithms can be utilized to more accurately identify the position information of welding seams, thereby better correcting the misalignment of welding seams. Canny and Harris are commonly used image processing algorithms. Their common features are: 1) accurate recognition of edges without false positives or omissions; 2) strict control over the accuracy of edges; 3) detailed description and analysis of features for each pixel during processing. Cartesian coordinates allow us to express a straight line in slope-intercept form. By using the motion deformation of lines, we can construct a set of parallel ray arrays to obtain the position information of each ray $x \cos \theta + y \sin \theta = \tilde{n}$. After completing the direct observation of the insulator, we must also rotate its edge observation results horizontally to obtain more information. By unifying the analysis of the slopes of several lines, their average value can be determined to determine their horizontal rotation angle. The general calculation method is:

$$g_{\theta} = \arctan \left[\left(\sum_{i=1}^n h_i \right) / n \right] \quad (3)$$

In this equation, h_i represents the slope of the line, while n indicates the number of detected lines. Through three-dimensional visual positioning technology, the design of classification algorithms plays a crucial role in the welding seam error correction of welding robots. By adopting appropriate algorithms and methods, welding seams can be accurately identified, effectively reducing welding seam errors. Future research will delve into more efficient and precise classification algorithms and integrate them with other advanced technologies to enhance the flexibility and welding quality of welding robots.

4. Experimental Design and Analysis

Experimental design and analysis are crucial steps in the three-dimensional visual positioning-based welding seam error correction technology for welding robots. Below is a basic experimental design framework, along with some discussion on experimental analysis. The specific process of the experiment is as follows. To conduct effective experiments, careful adjustments of various parameters are required, including adjustments to the classification algorithm, selection of training and testing datasets, to improve the effectiveness of the classification model.

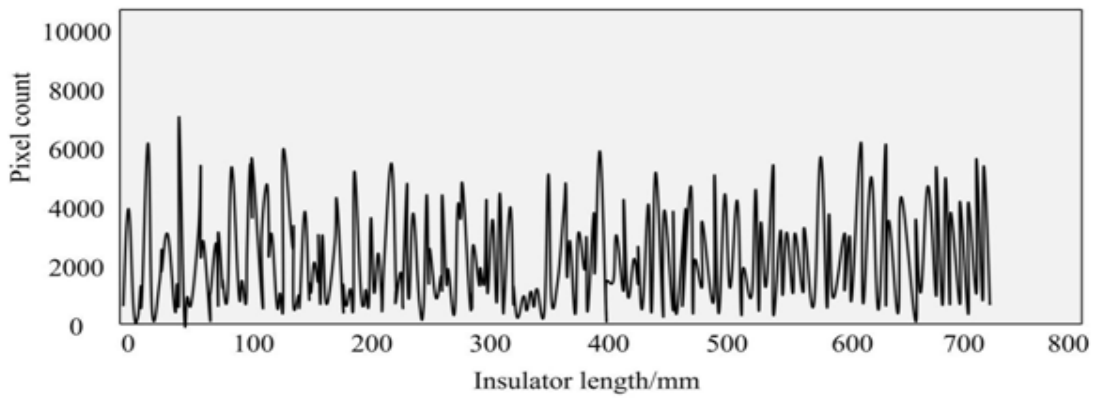


Figure 1. Vertical Projection of the Novel Canny Edge Detection Algorithm

Based on Figure 1, we observed that when the length of the insulator is between 370mm and 400mm, the amplitude of its vertical projection image undergoes significant changes, indicating the possibility of insulator self-explosion, which has also been verified. By comparing different training sets, we conducted detailed training of the classification algorithm and further tested its generalization ability effectively. Additionally, we validated the effectiveness of this algorithm through various interactive verifications. Through comparison, the machine vision measurement system accurately measured the distance between two points of the weld seam. The visual measurement result showed a distance of 889.31mm, while the actual measurement result showed a distance of 885.97mm, with a relative error of only 0.38%. This indicates that the system's precision is very high and meets the requirements for measuring the weld seam position. Through precise visual recognition and positioning techniques, we detected the weld seams inside the eight main beams of the crane, as shown in Figure 2, demonstrating the accuracy of our approach.

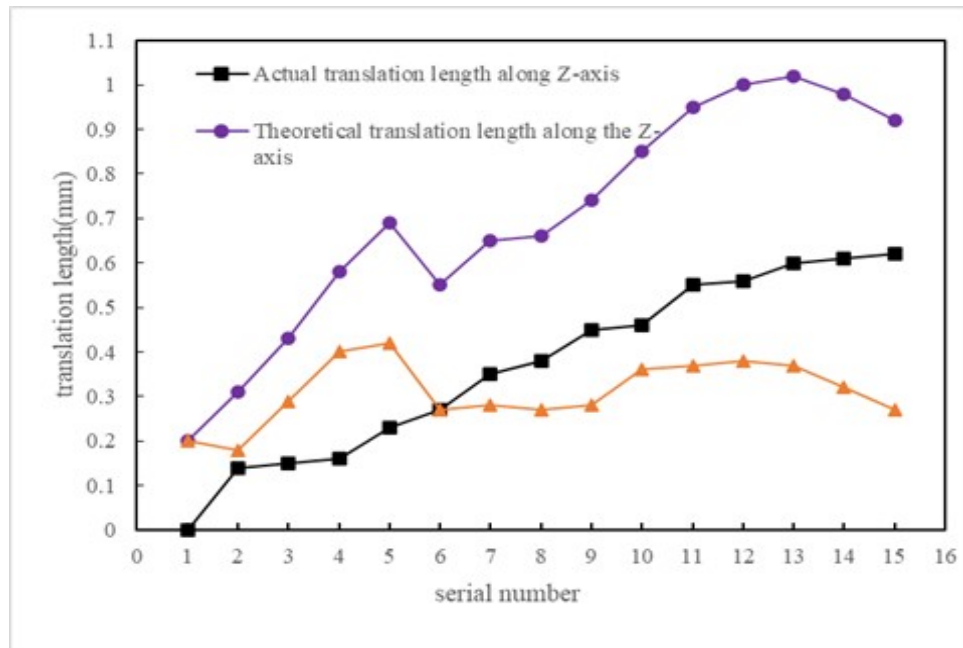


Figure 2. Weld Seam Recognition and Positioning Distance Error Analysis

The measurement of the positioning distance error for the 16 endpoints of the 8 weld seams shown in Figure 2 indicates that their precision ranges from 2.5mm to 4mm, fully complying with the process requirements for weld seams inside the main beams of the crane. Therefore, we can conduct more accurate testing of the precision of these weld seams to ensure their quality. The spatial coordinates of the weld seam endpoints obtained through machine vision are input into the welding robot's program to facilitate welding tasks in actual production. To ensure safety, CO₂ shielded welding is employed, and the robot controls the welding wire to start from one end of the weld seam and accurately connect to the spatial coordinates of the other end in a straight line.

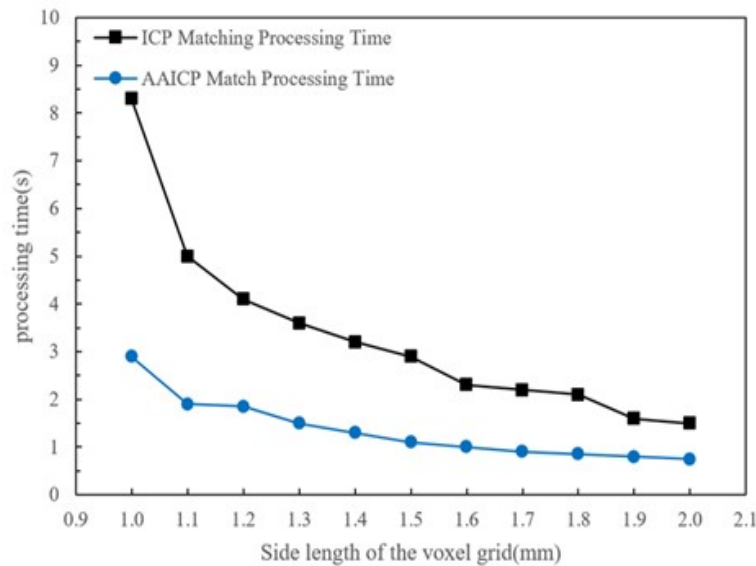


Figure 3. Depth Information of a Row in the Weld Seam Image

According to Figure 3, when there is a significant offset in the depth measurement results between adjacent pixels in the same row, it indicates that their three-dimensional relationships are not entirely consistent and exhibit noticeable vertical variations. Therefore, we adopted the dual-pixel scanning technique to inspect and extract the two-dimensional boundaries on the left and right sides of the welding area to ensure their vertical variations. Through careful design and detailed analysis, the weld seam error correction technology based on three-dimensional visual positioning for welding robots has achieved significant results. By evaluating the classification algorithm, we can better understand its performance and make targeted improvements to its error correction methods, thus providing strong support for the technology's development.

5. Conclusions

The use of three-dimensional visual positioning for welding robots allows for more accurate correction of weld seam deviations, greatly improving the overall welding quality. Through systematic experimental testing, we found that data collection and preprocessing are essential for the accuracy of the positioning process. To obtain more accurate and comprehensive three-dimensional point cloud data, we must perform denoising, filtering, and calibration operations. Additionally, correct feature extraction and classification techniques are essential for correcting weld seam errors. Therefore, in weld seam positioning, practical considerations must be taken into account from various perspectives to achieve better results. After multiple practical applications, the weld seam error correction technology based on three-dimensional visual positioning has achieved satisfactory results.

It not only significantly reduces welding defects but also greatly improves inspection accuracy, thereby enhancing product quality. The welding quality can be significantly improved through the three-dimensional visual positioning technology for welding robots. Through careful design and detailed analysis, this technology will bring more possibilities for the development and application of the welding industry.

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