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Real-Time 3D Intelligent Detection System for Railway Fasteners

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Abstract

This study addresses the challenges of low efficiency in manual railway fastener inspection and susceptibility to lighting interference in image-based detection by proposing a line structured light-based 3D reconstruction and fault detection method, enabling precise identification of fastener anomalies and loosening. Key research contributions include: 3D Point Cloud Reconstruction Developed an improved region-growing algorithm for segmenting fastener component point clouds, constructing high-precision 3D models.For Type I resilient fasteners, a host computer software was implemented for scanning and reconstruction. Experimental results demonstrated 40% reduction in point cloud noise and 35% improvement in model completeness. Anomaly Detection Algorithm Proposed an ensemble classifier model to detect six categories of anomalies, including nut loss and resilient fastener missing.At a detection speed of 40 km/h, the system achieved 95% detection accuracy with only 3% false alarm rate. Loosening Detection Method Utilized resilient fastener registration algorithms to calculate gap distances and established a conversion relationship between nut loosening values and fastener displacement.Field tests confirmed <1 mm measurement error and RMS error of 0.32 mm, meeting high-speed railway maintenance standards.The developed detection system has been validated through experiments, showing 8× efficiency improvement over manual inspection, providing critical technical support for intelligent railway maintenance.

Keywords

fastener fault detection, Line Structured Light Measurement,Centerline Extraction, 3D Reconstruction.

1. Introduction

In order to solve the problems of lack of depth information and insufficient accuracy of three-dimensional detection of rail fasteners, an intelligent detection method based on three-dimensional point cloud of linear structured light is proposed. By constructing a linear structured light measurement system, the improved gray center of gravity method was used to realize the center extraction of sub-pixel light strips (root mean square error<0.32mm), and the precise positioning of fasteners and parts segmentation were completed by combining RANSAC bolt fitting and improved area growth algorithm. The innovative design of the combined classifier realizes anomaly detection (detection rate of 95%/false detection rate of 3%), and develops a spring strip gap detection model based on nut loosening value conversion (error <1mm). Experiments show that the system can simultaneously detect 6 types of anomalies such as nut loss and elastic strip fracture and 0.1mm level looseness, which improves the detection dimension and accuracy compared with traditional methods, and the supporting C host computer software supports three-dimensional visual analysis, providing efficient automation solutions for railway operation and maintenance, which is significantly better than manual inspection and two-dimensional visual inspection solutions.

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2. Background and implications

Rail transit is the core of the integrated transportation system, and by the end of 2024, China's total railway mileage will reach 162,000 kilometers, and the high-speed rail mileage will be 48,000 kilometers, ranking first in the world. With the rapid development of high-speed rail, the safety maintenance of rail facilities has become a key challenge, and it is necessary to improve the intelligent level of facility testing and promote the research and development of intelligent maintenance equipment. As the core component of the fixed rail, the looseness or abnormality of the rail fastener will cause the geometric deformation of the track and threaten the safety of driving. At present, fastener inspection relies on manual inspection, which has problems such as low efficiency, high missed detection rate, and high risk of night operation. The two-dimensional image-based detection technology is susceptible to light interference and cannot quantify the loosening state of the fastener, while the three-dimensional detection technology can break through this limitation and achieve accurate analysis of multiple parameters. Therefore, it is of great significance to study the three-dimensional detection method based on linear structured light to ensure the safe operation of railways.

3. Three-dimensional reconstruction of rail fasteners based on improved gray center of gravity method

3.1. Grayscale center of gravity method

The gray center of gravity method is a weighted average method based on the gray distribution of the image, which is used to locate the center or feature point of the target object. It determines the position of the center of gravity by calculating the weighted average of the gray values of the pixels in the image, which is suitable for the precise positioning of targets such as light spots, stars, and industrial parts. The grayscale value of each pixel in the image is used as a weight, and its weighted average position in the horizontal and vertical directions is calculated, and the result is the "gray center of gravity" of the target.

The grayscale center of gravity method can achieve sub-pixel level accuracy when extracting the centerline of the light bar, especially for objects with relatively flat surfaces, but in a noisy environment, it is easy to be interfered by noise, which may lead to large positioning errors, so it is more suitable for the situation with good image quality. In practical application, considering that there may be complex curvature changes and irregular shapes on the surface of the measured object, the light stripes projected onto the surface of the object may form a curved and changeable curvature shape. In this case, when there is a significant deviation between the actual normal direction of the center of the light stripe and the direction of the image column or row, the position of the center point of the light strip extracted by the traditional gray center of gravity method may be far from the position of the real center point, which introduces measurement errors, and then affects the overall extraction effect and accuracy.

In this paper, a detection system based on line structured light sensor is constructed to realize the 3D reconstruction of fasteners and automatic fault detection, as follows:

(1) System calibration and modeling: Establish the mathematical model of the camera and line structured light, complete the calibration of the camera, light plane and displacement, and verify the accuracy of the system.

(2) Three-dimensional reconstruction optimization: An improved gray center of gravity method is proposed to extract the centerline of the optical strip, combined with voxel downsampling and outlier filtering, to generate a high-precision fastener point cloud model.

(3) Anomaly detection: Based on the random sampling consistency algorithm to locate fasteners, improve the regional growth method to segment parts, and build a combined

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classifier to detect anomalies such as nut loss and elastic strip breakage, the detection rate is 95%, and the false detection rate is 3%.

(4) Looseness detection: Through the point cloud registration of elastic strips and the plane analysis of nuts, the conversion model of looseness value and gap distance was established, and the experiment showed that the measurement error of gap separation was less than 1mm, and the root mean square error was less than 0.32mm.

System development: Design the host computer software based on the MFC framework, and build an experimental platform to verify the feasibility.

3.2. Centerline extraction based on improved gray center of gravity method

After calibrating the linear structured light measurement system, the world coordinates of the center of the light fringe can be calculated according to the mathematical model of the measurement system, and the point cloud model of the fastener can be constructed by splicing the center lines at different positions according to the displacement information generated by the detection system with the change of spatial position. The improved gray center of gravity method was used to reconstruct the fasteners in three dimensions, then the KD-tree was established on the point cloud data, the voxel downsampling method and outlier filtering algorithm were used to simplify and filter the outliers, and finally the point cloud was rendered according to the three-dimensional height information.

3.3. Anomaly detection

Rail fastener anomaly detection: mainly for the spring bar I type split fastener anomaly detection, this type of fastener is widely used in the railway, and the overall structure is similar to other types of fastener structure, the spring bar I type split fastener is composed of a number of key components, including nuts, bolts, spring bars, gauge baffles, flat washers and baffle seats.

Construction of fastener detection coordinate system: Based on the principle of RANSAC method, random sampling is carried out when the initial point is found, and the point cloud on the upper surface of the bolt is fitted by estimating the optimal circular parameters for accurate positioning of the fastener.

Set the fastener detection coordinate system: select the center of the fitting circle as the origin of the construction coordinate system; The x-axis of the detection coordinate system is parallel to the direction of the rail, and its direction is the same as that of the detection movement; The y-axis of the coordinate system is perpendicular to the rail, and the direction points to the inside of the rail; The z-axis extends along the height direction to form a three-dimensional right-angle fastener detection coordinate system, which allows for accurate description of the fastener's position and orientation information relative to the rail. Four detection areas of interest, A, B, C, and D were set, and the point cloud of the detection area was extracted for fastener fault detection.

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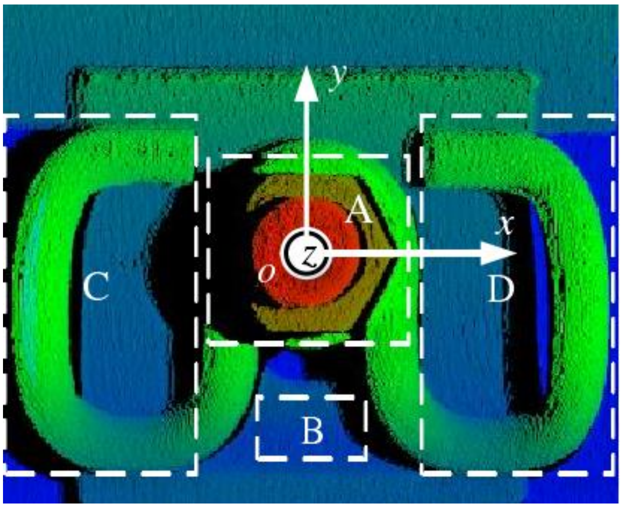

Figure 3.1: Coordinate system for fastener detection

Fastener point cloud component segmentation: The traditional regional growth segmentation method has intuitive principles and relatively simple algorithm implementation, but in practical applications, due to the existence of noise and uneven curvature distribution, it is easy to lead to problems such as voiding, excessive segmentation or insufficient segmentation in the segmentation results. In addition, the traditional method usually requires manual intervention when selecting seed points, and the operation process is complex and cumbersome, and the segmentation effect is difficult to achieve the ideal state. In order to solve the above problems, the team improved and optimized the traditional regional growth segmentation technology.

Firstly, the specific position information of the fastener parts in the detection area was used to automatically select the appropriate seed point, which avoided the cumbersome steps of manual participation. Secondly, according to the local density characteristics of the fastener point cloud data, the number of point cloud clusters, the normal vector direction and curvature of a single point, more accurate seed point growth rules were set to achieve accurate segmentation of the fastener parts point cloud data. Finally, by comparing and analyzing the segmentation results with the preset segmentation results, if the ideal segmentation effect is not achieved, the segmentation and adjustment will be re-performed according to the new rules. The improved region growth segmentation algorithm is used to segment the fastener point cloud data in different states, including the fastener point cloud in the normal state, the fastener point cloud with abnormal nut loss, and the fastener point cloud with the wrong elastic bar installation. From the segmentation results, it can be seen that the improved algorithm can achieve ideal segmentation effect when dealing with various abnormal types of fastener point clouds, so as to provide more accurate component point cloud data for subsequent fastener anomaly detection and tightness detection.

Euclidean cluster segmentation: An efficient segmentation method based on the geometric features of point clouds, which realizes data division by calculating the three-dimensional Euclidean distance, surface normal vector direction and local curvature changes between points. The core of the project lies in the use of Euclidean distance to determine spatial proximity, normal vector to reflect the local geometric direction, and curvature to quantify the degree of surface curvature, which can accurately identify the contour and structural characteristics of objects. The algorithm has low computational complexity, is suitable for complex scenarios, and is widely used in industrial detection, autonomous driving and other fields. However, it is sensitive to noise and data discontinuity, and needs to be improved by preprocessing such as filtering and smoothing. In the face of highly complex structures, a single cluster may not be able to capture the details, and hybrid methods such as graph theory

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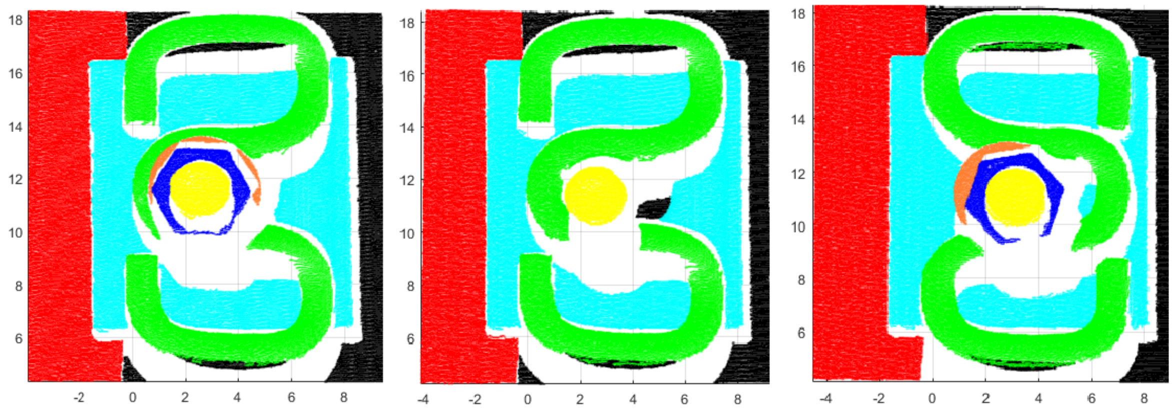
segmentation or shape feature analysis need to be used to optimize boundary recognition. In general, Euclidean clustering has significant advantages in balancing accuracy and efficiency, but it needs to be combined with other technologies to enhance adaptability in extreme scenarios.



（a）Normal fasteners （b）The nut is missing （c）The fastener is reversed

Figure 3.2: Segmentation result of the improved algorithm

Detection threshold determination: After locating the fastener and establishing the fastener detection coordinate system, setting the detection area, the fastener point cloud model is segmented by the improved point cloud segmentation algorithm, and the point cloud point number statistics are carried out in combination with the location information of the detection area and the segmentation results, and the detection thresholds of nut loss, fastener reverse, and fastener skew are set respectively.

3.4. Loose fasteners

In railway track systems, the rails are tightly fixed to the concrete sleepers by means of elastic deformation forces generated by fastener springs. When the elastic bar is loose, its pressure on the baffle is reduced, and the firm connection between the rail and the sleeper cannot be effectively guaranteed. Insufficient pressure of the elastic bar buckle will cause many hazards, such as lateral or longitudinal displacement of the rail, twisting deformation and horizontal irregularity, etc., which will pose a serious threat to the safety of train driving. According to Articles 3.7.5 and 3.7.6 of the "High-speed Railway Line Maintenance Rules" issued by the National Railway Administration in June 2023, it is pointed out that the lower part of the middle and front end of the elastic strip should be in contact with the gauge baffle, and the gap should not be greater than 2mm, and it needs to be repaired or replaced in a planned manner when it exceeds 2mm. Therefore, based on the fastener point cloud model and the results of component point cloud segmentation, the team conducted research and experiments on fastener loosening detection.

Strip Gap Detection Based on ICP Point Cloud Registration Algorithm: Based on the improved regional growth segmentation method, the loose fastener point cloud and the fastened fastener point cloud were extracted respectively, and the fastener snap point cloud in compression and the fastener in relaxation were registered through the ICP point cloud registration algorithm, and the height difference between the two was statistically compared, and whether the fastener was in a loose state was judged according to the height difference.

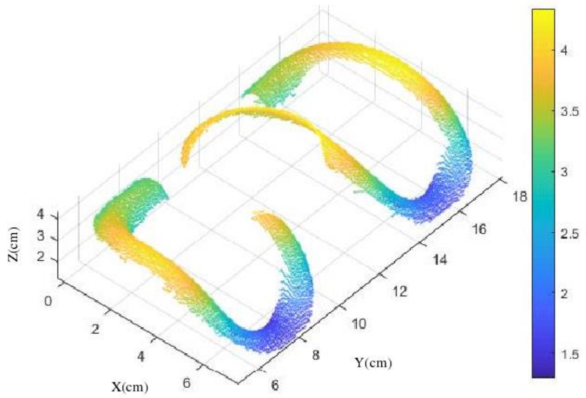


Figure 3.3: point cloud of bullet bars

Calculation of nut loosening value: the nut is loosened due to the longitudinal displacement along the bolt upward, and the plane where the upper surface of the nut is located is plane s, the distance from the surface of the baffle is H, and the distance from the surface of the baffle is H0 when it is fully tightened.

The distance H from the upper surface of the nut to the baffle is calculated as:

$$\begin{cases} H_x = \dfrac{Ax_0 + By_0 + Cz_0 + D}{\sqrt{A^2 + B^2 + C^2}} \\ H = \dfrac{H_E + H_F}{2} \end{cases} \quad (3.1)$$

where H - the distance from the feature point to the plane s (mm, take HE, HF (local point fitting); x0 , y0 , z0 - the 3D coordinate value of the detection datum point.

Then the nut looseness value L is calculated as follows:

$$L = (H - H_0) \quad (3.2)$$

4. Conclusion

In this study, a fault detection method for rail fasteners based on three-dimensional point clouds of linear structured light is proposed, which solves the problems of missing depth information and insufficient accuracy of traditional two-dimensional detection through multi-module collaborative optimization. Firstly, the Zhang Zhengyou calibration method is used to construct a linear structured light measurement system with sub-millimeter accuracy, and the gray center of gravity method is improved to achieve high-precision extraction of the center line of the light fringes, so that the root mean square error of point cloud reconstruction is less than 0.32mm and has strong noise immunity. Then, the detection coordinate system was established by fitting the bolt circle surface with the RANSAC algorithm, and the improved region growth algorithm was used to complete the accurate segmentation of parts. In the fault detection link, the loosening state was quantified by ICP registration analysis of the height change of the elastic bar, and the distance between the nut and the baffle was innovatively converted to realize the high-precision diagnosis of the loosening detection error of <1mm. Finally, the C-mounted computer system was developed to complete the engineering verification, with an abnormal detection rate of 95% and a false detection rate of 3%, which proved that the three-dimensional detection effectively made up for the limitations of two-

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dimensional vision, and provided an efficient and reliable three-dimensional intelligent detection solution for railway fastener maintenance.

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