Development of an automatic measurement device for double laser shield tail gap based on image recognition technology

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Abstract: Shield tail clearance is an important basis for the selection of segment assembly and shield attitude control. It is the most direct factor affecting shield tail brush wear. Poor shield tail clearance is prone to segment damage and shield tail seal failure. Using manual measurement of the shield tail gap, the measurement data has a certain hysteresis, and can not directly reflect the changing trend of the shield tail gap. Based on image recognition technology, a dual laser shield tail gap measurement device was developed to measure the changes in the shield tail gap during shield tunneling. The field test shows that: 1 The measurement device can monitor the shield tail gap in real time, and can simulate the ellipticity of the shield tail, monitor the deformation of the shield tail and the space state of the shield tail and the tube. 2 The acquisition device adopts a dual laser transmitter, meanwhile, the attitude of the shield machine cannot be controlled in real time, Can accurately establish the geometric relationship between the actual distance and the pixel distance, improve the test accuracy of the measuring device, and control the monitoring accuracy at 3.8 mm.

1. Introduction

With the rapid development of urban rail transit and large-diameter shield tunnels, the development of shield tunnels tends to be larger diameter, longer distance, larger buried depth, and higher water pressure. The environmental conditions for shield construction are becoming more and more complex, and shield construction technology is facing severe challenges. Shield tail clearance is a key technical parameter that requires precise measurement and real-time monitoring during shield tunneling. The shield tail clearance value has important guiding significance for controlling the attitude of the shield machine, reducing the wear of the shield tail brush, and avoiding segment damage. At present, most domestic shield machines adopt manual measurement methods. This method not only has poor measuring accuracy and low automation level, but also has poor real-time performance and severe data lag. It cannot directly reflect the changing law of the shield tail gap. Meanwhile, the attitude of the shield...
machine cannot be controlled in real time. Hence, the present method has limited the guidance of integrated construction management in high degree.

Many scholars have conducted research on the automatic collection device of shield tail clearance. Lu Yati[1] proposed to make holes in the shield tail during making the shield machine, then embed ultrasonic equipment into the shield tail to measure the shield tail clearance. A company installed the scanner on the segment assembly machine, which could scan and measure the shield tail gap by rotating the assembly machine. Li Guang et al.[2] designed a device for measuring the distance between the outer diameter of the tube sheet and the inner wall of the shield tail by installing a distance measuring sensor on the inner wall of the shield tail; Li Rui[3] used several angle measuring sensors installed on the shield tail, which measure the shield tail gap indirectly by geometric relationship between the length of the corresponding connecting rod and its corner position. Sun Lian et al. [4] designed a shield tail gap measurement method based on multi-point scanning distance detection technology, which mainly uses distance measurement The instrument measures the geometric relationship of the shield tail gap.

Shield tail gap measurement based on machine vision is a hot research topic at present. Chen Jian[5] took a shield machine with a diameter of 6 m as a prototype, designed and produced a shield tail gap model of the measurement part, and developed a PC client software based on Qt. In this paper, a dual laser line is used as a prefabricated ruler, and the shield tail gap automatic acquisition equipment is developed and applied in the field. It has achieved good results. It can realize the one-click measurement of the shield tail gap, which can be used as a shield in the process of shield tunneling. Tail gap control provides reference.

2. Test principle
The shield tail automated measurement system is based on visual measurement technology. It uses industrial cameras to collect the image of the end face of the tube, then the system software performs preprocessing and feature extraction. Combining the prefabricated ruler and the geometric relationship of the characteristic lines to solve the shield tail gap value, non-contact measuring.

2.1. Basic assumptions of testing technology
Shield tail gap measurement is carried out based on machine vision. The acquisition instrument integrates a laser and an industrial camera. The laser emits laser light on the ring surface of the tube sheet. The industrial camera collects images on the ring surface of the tube sheet. By using the software to reduce noise point, identifying the image in several parts so as to calculate the shield tail gap of the measuring point position. The device is based on the following assumptions:

1) Arranging two set of lasers in each shield tail gap measurement device, make sure that the lasers lights from the equipment are parallel and not affected by the shape changes of the lasers.

2) The above-mentioned parallel laser rays should be parallel to the axis of the shield shell, or parallel to the inner wall of the shield shell. Meanwhile the center of the two laser lines should connect through the circle of the shield tail. The equipment installation principle is shown in Figure 1 and Figure 2.

![Figure 1. Schematic diagram of collection equipment layout](image1)
![Figure 2. Dual laser](image2)

Figure 1. Schematic diagram of collection equipment layout  Figure 2. Dual laser

2.2. Test principle
Figure 3 shows the positional relationship among the shield shell, the shield segment and the shield tail gap. The two laser equipment which is fixed at the shield tail would cast two laser rays under the shield segments. The parameters l, d, w, h and g are described as follows:
l——The vertical distance from the center of the laser source to the inner wall of the shield;
d——The vertical (physical) distance from the intersection of the laser cross line marking to the inner edge line of the shield segment;
w——The physical distance between the intersection of two laser crosshairs;
h——The thickness of the shield segment;
g——shield tail gap.

![Figure 3. Test principle diagram](image)

The assumption has shown that l and h are both known quantities, only d is an unknown quantity which can be obtained by the conversion relationship between the pixel distance and the physical distance. The center physical distance w between the two lasers is fixed, the pixel distance could be calculated according to the pixel coordinates of the laser center point in the image. Suppose the pixel coordinates of the center point of the cross are \((a_1, b_1), (a_2, b_2)\), and the pixel distance is:

\[
w = \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2}
\]

(1)

Establish the proportional relationship between actual distance and pixel distance \(k = w/W_x\).

Calculate the pixel distance from the center line of the two crosses to the inner edge of the tube, and calculate the pixel distance from the center line of the internal test cross to the edge of the tube by the weighted average method to obtain the distance d.

\[
d = w_d * k
\]

(2)

The shield tail gap g can be determined by the following formula

\[
g = l + d - h
\]

(3)

3. Image processing technology

Target detection and image segmentation: The original picture obtained by the camera is too large, and there are many irrelevant factors. As shown in Figure 4, segmenting the original picture and intercepting the relevant parts can improve the operating speed of the system. This technology could draw the processing range in high speed and accuracy which could be achieved by deep network more than 2000 times model training.

Intercepting image preprocessing: Existing complex information could bring negative effect in intercepting image, hence it is necessary to process the complex information before extracting the features of image.

Grayscale processing: In order to improve the running speed, transfer color pictures into grayscale images.

Feature extraction: The calculated gray threshold would separate the target area and background area of shield segment image, then export binary image which is helpful in simplify the subsequent analysis and processing steps.

Edge detection and extraction: Identify the midpoint of the laser line cross to the edge of the tube from the extracted picture, then convert it through Hough to extract the edge of the tube.

Shield tail gap calculation: After obtaining the center point of the laser cross and the pixel coordinates of the inner edge of the tube, calculate the pixel distance d from the center of the laser cross to the edge of the tube, then use formulas (2) and (3) to obtain the shield tail gap.
4. Equipment processing and on-site installation

According to the functions realized by the shield tail gap measurement system based on machine vision, it can be divided into the following modules: image acquisition module, signal transmission module, image processing module, auxiliary electrical control module, server and man-machine interface, and software and hardware platform. A multi-degree of freedom damping device is installed at the bottom of the camera and laser could eliminate the impact of shield equipment vibration on the camera; the device is designed to be waterproof and dustproof to reduce the impact of the shield environment on the equipment.

According to the shield tail situation of the shield machine, 4 sets of automatic collection equipment for the shield tail gap were processed. Compared with the other schemes, the collector adopts a skateboard scheme might be better. The skateboard is fixed on the ribs between the cylinders of the shield machine.

There are some buttons on collector that would help to turn rotation and the height direction (vertical to the direction of the slide surface). Through fine-tuning, the two lasers in the collector basically pass through the center of the circle, which can ensure that the installation of the collector meets the test assumptions. The equipment installation is shown in the figure 6.

5. Field test situation

The values of the shield tail gap were measured and the measurement was manually checked in three time points which include shield tunnelling beginning, processing and ending. There are more than 300 loops were tested on site. After the equipment was debugged and stabilized, several consecutive loops were selected during the tunneling process. The measurement error of the shield tail gap is shown in the figure below:
As shown in Figure 7, the error value of the test equipment is controlled in 3.8mm, and the error of the equipment has a large randomness, which conforms to the distribution law of the error.

The program of automatically fitting the shield tail and segment circumference according to the shield tail clearance test results of 4 acquisition devices is achieved. After each test is completed, the shield tail and segment circumference can be automatically fitted, and the shield tail circle and the segment circumference can be displayed intuitively. The position relationship of the pipe ring can be checked on the spot where the fit is smaller to ensure the safety of the shield tail during the shield tunneling process.

6. Problems and improvements
Use integrated light source, the external light source is obliquely illuminated on the annular surface of the tube sheet. With the change of the test distance, the environment of the annular surface light source of the tube sheet changes greatly, which causes that it difficult to identify image information. The light source is integrated around the camera, and each light source is individually controlled. The system automatically controls and adjusts the light source according to the situation of the captured image, so that the camera can obtain the most degree light environment.

The measurement cannot be performed when there is water on the annular surface of the segment. Added the water seepage treatment module in the ring surface of the pipe segment to preprocess the image of the water seepage pipe segment, adjust the image gray level, and solve the water seepage problem.

7. Conclusion
(1) Based on image recognition technology, this equipment can realize one-click real-time measurement of shield tail gap, which provides a reference for shield tail gap control during shield tunneling.

(2) The use of dual-channel laser as the prefabricated ruler can accurately establish the relationship between the pixel distance and the actual distance, which can effectively improve the measurement accuracy.

(3) The system can fit the relative positional relationship between the shield tail and the annular surface of the segment, which provides a reference for the deformation monitoring of the shield tail.

(4) Due to the complex construction environment of the shield tunnel, it would be interfered during the test. During the on-site test, this device solves the problem of difficulty in identifying the annular water leakage of the segment through the algorithm. The system will be further tested in the subsequent application process, then will improve system reliability and test accuracy.

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