Track detection system of UAV based on line structure light

Ruiting Huang1*, Mengyao Jia2 and Simeng Guo3

1 School of Information Engineering, Wuhan University of Technology, Hubei, Wuhan, 430070, China
*Corresponding author’s e-mail: hrt3347@163.com

Abstract. Aiming at the present problems of strong subjectivity and low efficiency of manual push flaw detection vehicle, in order to meet the requirements of high-speed rail detection, this system uses UAV aircraft combined with line structured light technology to realize a track detection system based on multiple sensors. In the method of joint positioning, after coarse positioning of the UAV through satellite positioning, the camera on the UAV is used to identify the image of the track to complete accurate positioning and single-track tracking. The high precision and fast scanning speed of structural light are used to obtain the profile data of rail. The obtained measurement data were calibrated by combining the mathematical model established with the track CAD model to eliminate the influence of the UAV's self-disturbance on the acquired data and achieve the acquisition of rail wear data. At the same time, the computer vision technology is used to extract the window in the track, and the track intrusion detection is carried out through the analysis of the gray map distribution in the window.

1. Introduction
Today, China's high-speed rail technology is developing rapidly. By 2019, the total length of China's railways in operation was over 131,000 kilometres, ranking second in the world. Among them, the high-speed railway is nearly 30,000 kilometres, ranking first in the world. Compared with ordinary railway, the driving speed of high-speed railway is greatly improved and it is more sensitive to the driving environment. Therefore, high-speed rail has a stricter definition on the surface geometric parameters and higher requirements on the detection of rail loss of high-speed railway. If the damage on the track surface is not dealt with in time, it will greatly increase the probability of derailment and cause serious traffic accidents. Therefore, it is very necessary to detect railway track. However, most of the current detection relies on digital display mechanical measuring rod, which relies heavily on manual work and has a single function. Therefore, it is not suitable for the rapidly developing high-speed railway. This system proposes a new multifunctional method for detecting railway track.

Combined with the characteristics of UAV and linear structural light, this system USES the camera to collect the plane slit light projected from the slit light on the track, calculates the position and depth of the object according to the change of the light signal caused by the object, and then recovers the whole three-dimensional space. Then the obtained image is filtered and denoised to retain the edge information and extract the gray center of gravity curve of the light fringe. After the ICP iterative point cloud matching, the corresponding track CAD engineering parameters were compared to complete the damage detection. At the same time, the camera can also take pictures of the railway track. After a series of processing, such as gaussian blur processing, the gray information of the extraction window is drawn into a graph, and then the appropriate threshold can be set to detect whether there is any foreign body invasion on the railway track.
2. Line structure light detection

2.1. Principle of structural light detection
The fan laser plane emitted by the laser is projected on the surface of the measured object. The camera and the laser are in a fixed position relative to each other. The pixel coordinates of the highlight bar in the image are determined by the parameters of the visual sensor and the three-dimensional shape of the object surface. When the relative position parameters between the laser and the camera are known, the world coordinates of the object's surface can be recovered from the image coordinates of the distorted two-dimensional light bar based on the measurement principle of optical triangulation, and the measurement of the object's surface can be completed. In this system, a red laser with a wavelength of 660nm is selected. In order to get better measurement effect and filter out the interference of impurity light, a filter shall be installed on the lens. According to the selected laser, a band pass filter of about 660nm was selected. High-speed industrial CMOS camera was used to capture images.

2.2. Structural light visual detection model
Linear optical vision sensor is simple in structure, mainly composed of camera and linear laser. The camera and the line laser are fixed relative to each other, and the camera and the structure light plane are installed at a certain Angle. The fan-shaped laser plane projected by the line laser cuts the measured object and forms a bright light strip on the surface of the object. When the camera shoots from another fixed Angle, the structural light strip image of the measured object can be obtained. If a point P on the surface of an object is illuminated by a laser, the point is on the plane of structural light. The equation of the light plane in world coordinates.

If the image point of point P in the camera is P, according to the perspective imaging principle, then the connection between point P and point P goes through the optical center Oc of the camera. In figure 00 1, O1 is the main point of the imaging surface, and O1Oc is the optical axis of the camera. If the internal and external parameters of the camera are known, the coordinates of the image point p and the optical center Oc in the world coordinate system (x, y, z) and (x1, y1, z1) can be solved, and the equation of line OcP can be solved. The coordinates of the intersection point P in the world system can be obtained from the equations of simultaneous plane and line.

When this model is applied to measurement, it is necessary to know the equation of the light plane in the world coordinate system and the equation of the camera in the world coordinate system. It is difficult to get the equation of the light plane directly. Therefore, when selecting coordinate system, some special restrictions can be made to establish a measurement model that is easy to apply. In order to establish the mathematical model of the structural light vision measurement system composed of camera and line laser, the coordinate system as shown in figure 1 is established.

The world coordinate system OxwYzw is established to make the plane coincide with the light plane of Owxwyzw. Owxwyzw is the two-dimensional measurement coordinate system, and then the equation of the light plane in the world coordinate system is: zw=0. Taking lens distortion into account, the nonlinear imaging model can be obtained as follows:

\[
S \begin{pmatrix}
U_d + \delta_u \\
V_d + \delta_v \\
1
\end{pmatrix} = \begin{pmatrix}
a_1 & a_2 & a_3 \\
a_4 & a_5 & a_6 \\
a_7 & a_8 & 1
\end{pmatrix} \begin{pmatrix}
X_w \\
yw \\
1
\end{pmatrix}
\]

(1)

The model takes lens distortion into account, and the model includes parameters a1~as, k1~kn(lens distortion parameters). According to equation (1), the mapping relationship between the measured coordinates of any point in the optical plane and the coordinates of its image point in the image plane is determined. Therefore, the 3d coordinate of rail contour can be recovered from the light bar image of rail contour by using this model, and the contour measurement can be completed.
2.3. Calibration model and principle based on planar checkerboard target

It is an important point in the calibration process of structural light vision measurement system to obtain the accurate marking point. In the process of measurement, lens distortion is considered and only the second order distortion is considered. Nonlinear measurement model is adopted:

$$s \begin{pmatrix} u_d + (u_d - u_0)(k_1 r^2 + k_2 r^4) \\ v_d + (v_d - v_0)(k_1 r^2 + k_2 r^4) \end{pmatrix} = \begin{pmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{pmatrix} \begin{pmatrix} x_w \\ y_w \end{pmatrix}$$  (2)

By eliminating the scaling factor $s$ of the above equation, the following equation can be obtained:

$$f_u = a_1 x_w + a_2 y_w + a_3 - (a_7 x_w + a_8 y_w + 1)(u_d + (u_d - u_0)(k_1 r^2 + k_2 r^4)) = 0$$
$$f_v = a_4 x_w + a_5 y_w + a_6 - (a_7 x_w + a_8 y_w + 1)(v_d + (v_d - v_0)(k_1 r^2 + k_2 r^4)) = 0$$  (3)

In the actual measurement process, due to the existence of errors, the above equations cannot be strictly established. In order to ensure the accuracy of calibration, multiple points can be calibrated to obtain the coordinates of $n$ points on the optical plane and the corresponding $n$ image points, and $n$ groups of functions can be obtained:

$$f_u(\mathbf{a}) = a_1 x_w + a_2 y_w + a_3 - (a_7 x_w + a_8 y_w + 1)(u_d + (u_d - u_0)(k_1 r^2 + k_2 r^4)) = 0$$
$$f_v(\mathbf{a}) = a_4 x_w + a_5 y_w + a_6 - (a_7 x_w + a_8 y_w + 1)(v_d + (v_d - v_0)(k_1 r^2 + k_2 r^4)) = 0$$  (4)

Type in the $\mathbf{a} = [a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9, k_1, k_2]^T, i = 1 \cdots n$

If

$$F(\mathbf{a}) = \sum_{i=1}^{n} (f_{ui}^2 + f_{vi}^2)$$

Find $\mathbf{a}$ to get the minimum value of $F(\mathbf{a})$, that is, the relatively accurate model parameters. $\mathbf{a}$ is a nonlinear least square problem, which is stable and converges quickly by using L-M algorithm.

Let $f = [f_{u1} f_{v1} f_{u2} f_{v2} \cdots f_{un} f_{vn}]^T$, then the iterative solution model of calibration parameters based on l-m algorithm is as follows:

$$\left\{ \begin{array}{c} f(a^k) = \frac{\partial f_i}{\partial a_j}(a^k) \\ (J^T J + \mu I)h_{im} = -J^T f \\ a^{k+1} = a^k + h_{im} \end{array} \right.$$  (5)

Where $k$ is the number of iterations and is the damping coefficient.
3. Line structure light and foreign body detection results

3.1. The calibration process
The calibration accuracy is of great significance, which directly affects the calculation accuracy of 3d coordinate points and the subsequent data processing accuracy. In this system, the checkerboard calibration method is adopted to correspond the pixel coordinates of the image to the world system coordinates. First, the light plane is coincident with the board surface and the board is filmed with a camera. The image was processed by MATLAB, and the distortion was restored after the corner point was demarcated to obtain the lens distortion parameters. The lens distortion parameters were imported into Zhang's calibration database in open CV to obtain the more accurate parameters outside the camera. After obtaining multiple sets of data, the fastest convergence optimal solution is obtained, as shown in figure 2.

![Figure 2. More accurate camera external parameters.](image)

3.2. Line structure light detection results
First, the line laser emits slit light and projects it on the rail to form a bright distorted light bar. The 2d distorted image of the light bar obtained by camera is shown in figure 3. After that, simple filtering and denoising operations were carried out on the captured picture to retain the edge information, and then the gray center of gravity curve of the light stripe was extracted, that is, the contour map of the track was obtained as shown in figure 4.

![Figure 3. Take pictures of the tracks.](image)

![Figure 4. Light fringe gray center of gravity curve.](image)
During dynamic detection, due to the attitude change of the laser camera component, the contour data obtained by dynamic measurement cannot be aligned with the standard data. Therefore, it is necessary to calibrate the dynamic data to align it with the standard data so that it can be compared with the standard data and obtain the defect information of the rail. Rail contour data calibration, that is, the affine transformation parameters between the dynamic contour data of the unworn part of the rail and the corresponding standard data were calculated, and the dynamic data were converted to the standard coordinate system to align the dynamic data with the standard data. Therefore, the extracted gray center curve picture was compared with the corresponding rail CAD engineering parameters after ICP iterative point cloud matching, and the damage detection was completed.

3.3. foreign body intrusion detection

Because the research goal is to detect cheating on foreign body, first of all to gaussian blur image processing, reduce the graphics sharpness before open algorithm, image edge information and then detected by rapid and accurate, the Hough transform to detect the track to track image window to detect and segment the foreign body for work, in order to avoid unnecessary objects within the whole image, improve the system operation speed and accuracy. Most of the tracks form a straight line over a short distance in the range where the train is running. At the same time, in a railway on the acquisition of video image, the tracks of the two straight lines length compared with other background objects is one of the longest, so can use Hough transform the nature of the two peaks are selected, the two points on the k - b the values in the coordinate system respectively corresponding to the two track equation of the straight line parameters, namely the linear equation of the track is presented. In order to improve the speed of track detection, first of all, the pre-treatment of image edge detection.

According to the binary edge image obtained by the edge detection operator, Hough transform is carried out to search out the line that conforms to the Hough transform condition and the set threshold, and then record it according to the equation and starting and ending points of the line. It should be noted that in the collected video image, not only the rail target is in a straight line, but also other object structures have the characteristics of a straight line (such as wire, roadbed, house, etc.). Therefore, measures must be taken to distinguish the linear characteristics of the track from other linear characteristics. According to the experimental analysis, in the video images collected in this paper, the edge information of the rail is the strongest and the length is the longest. Therefore, in the detection process, the strong edge and the edge length of the image are the most effective information to determine the detection target. Through the detection of the track, the linear equation of the two tracks has been obtained. In this way, the edge of the track can be used as the basis to establish the detection window. As shown in figure 5, the image is processed by gaussian blur, opening algorithm and Hough transformation.

Figure 5. Track image processing.

After the edge window is determined, the existence of foreign body is determined by the gray scale change in the detection window. As shown in figure 6 and figure 7, when there is a foreign body in the detection window, its gray scale histogram will have one more wave peak than that in the barrier-free histogram, causing a double-peak phenomenon. Therefore, the threshold can be set to determine whether there is foreign body invasion.
4. conclusion
This track detection system combines the characteristics of high precision, fast speed, high flexibility of UAV and low labor cost, etc. It can make use of the intermittent time of daytime train operation to conduct reliable and efficient track detection. In addition, it can timely detect whether there is a foreign body invading on the track and bring safety risks to the track running, which is of certain significance in practical application.

Acknowledgments
This work was supported by National Innovation and Entrepreneurship Training Program for College Students of China (S201910497051)

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