Study on Detection System of Grooved Rail Based on Inertial Measurement - Laser Triangulation Comprehensive Algorithm

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Abstract. In order to meet the requirement of grooved rail geometric parameter detection, based on the previous research of the project team, this paper combines the principle of inertial measurement and laser triangulation, a comprehensive algorithm to develop a grooved rail detection system for detecting the longitudinal and alignment irregularity. The system is composed of geometric parameter detecting vehicle and upper computer software. Firstly, the outline data of grooved rail are measured by 2D laser sensors, and the motion data of the vehicle are measured by inertial sensors. Then, this paper presents an inertial measurement - laser triangulation comprehensive algorithm and the laser triangulation is used to process the outline data and calculate the gauge of grooved rail. The error of laser triangulation and the attitude angle of vehicle are corrected through inertial measurement method. Finally, the longitudinal irregularity and alignment irregularity are calculated through numerical integration method in the upper computer. The stability and accuracy of the system are verified by designing experiments. The results show that the repeating precision of the irregularity is less than 0.5mm while the detection accuracy is within ±0.7mm.

1. INTRODUCTION

With the development of modern tram, the operating mileage of China's modern trams will continue to increase rapidly and many cities have officially operated trams¹. Therefore, the safety of trams is becoming more and more important.

However, the detection technology for geometry parameters of grooved rail in China is still lagging behind. Compared to grooved rail, i-rail has a more mature detection technology. In recent years, many experts and scholars have begun to deeply research the rail geometry parameter detection. Chen(2014) proposed an i-rail detection technology based on image recognition with two cameras that are parallel and perpendicular to the rail moving forward². With the growing maturity of laser sensor technology, it has been widely used in the field of rail geometry parameter detection. And many new rail detection vehicles in China are using laser sensors as the hardware foundation like GJ-5, GJ-6 and so on. We now take GJ-6 as an example. It uses foreign advanced technology to finish rail detection such as laser sensors technology, RFID mileage positioning technology and other technologies³. Although the detection technology of i-rail is becoming more and more mature, the above technologies cannot be directly applied to the field of grooved rail geometric parameters detection through simple
modification because of the structural differences between i-rail and grooved rail. In the early stage, the project team had studied the application of laser triangulation method in grooved rail detection, and realized the function of the detection system to detect gauge and abrasion of grooved rail, but the team could not achieve the detection of parameters such as the longitudinal irregularity and alignment irregularity. In this paper, we conduct a study about the longitudinal irregularity and alignment irregularity with the method combined with both inertial measurement and laser triangulation.

The rest of paper is organized as follows: The Section 2 introduces the main measurement methods and the algorithm of the system in this paper. The Section 3 introduces the structure of the system. The Section 4 introduces the designed experiment, and displays the experimental data. And the Section 5 is conclusion.

2. PRINCIPLE AND ALGORITHM

2.1. Detection Principle

2.1.1. Laser Triangulation

In order to meet the requirement of gauge measuring and to improve the precision of calculation results, a direct laser triangulation method with the advantages of one-to-one correspondence of direct spot and position, broad spot and high light intensity concentrated is selected in this paper[4]. The direct laser triangulation method is a kind of laser triangulation methods used in a special situation when the angle of incidence between the laser beam of the sensor and the measured object is 90 degrees, or, when the incident beam is perpendicular to the measured object. The measurement formula is as follow[5]:

\[
y = \frac{x(a - f) \sin \beta}{f \sin \alpha \pm x(1 - \frac{f}{a}) \sin(\alpha + \beta)}
\]

In the formula, \(\alpha\) is the working angle, that is, the angle between the reflected light OP and normal; \(\beta\) is the angle between the photosensitive element and O'P'; \(a\) is object distance; \(b\) is image distance; \(f\) is focal length; \(y\) is the moving distance of the measured object relative to the reference point O; \(x\) is the moving distance of the imaging point P' relative to the reference point P.

2.1.2. Algorithm of Quaternion

It is assumed that the coordinate system of grooved rail detecting vehicle is A system, and the geographic coordinate system is N system. The roll, pitch and yaw of vehicle can be obtained by determining the attitude matrix of the A system relative to the N system[6-7]. The attitude differential equation of the grooved rail inspection vehicle expressed by quaternion is as follow:
In the above formula, $u^N$ is the rotary instantaneous axis and rotary direction; $\theta$ is the rotation of grooved rail detecting vehicle. The attitude matrix of the A system relative to the N system $C_N^A$ is obtained through quater-nion. The formula is as follow:

$$C_N^A = \begin{bmatrix}
1 - 2(q_2^2 + q_3^2) & 2(q_1q_2 - q_0q_3) & 2(q_1q_3 + q_0q_2) \\
2(q_1q_2 + q_0q_3) & 1 - 2(q_1^2 + q_3^2) & 2(q_2q_3 - q_0q_1) \\
2(q_1q_3 - q_0q_2) & 2(q_2q_3 + q_0q_1) & 1 - 2(q_1^2 + q_2^2)
\end{bmatrix}$$

The relation between the attitude matrix and rotation angle can be deduced by the relation between the quater-nion and rotation angle, and then the attitude angle of the grooved rail detecting vehicle can be deduced.

2.2. Algorithm

2.2.1. Comprehensive Algorithm

Combining inertial measurement method and laser triangulation method, this paper proposes comprehensive algorithm for detecting grooved rail irregularities. First of all, 2D laser sensors collect the outline data of grooved rail. Then, the grooved rail contour feature points are extracted through the project team's mature gauge algorithm\textsuperscript{[5]}. For the convenience of calculation, this paper selects gauge point as the irregularity measurement point. Next, the upper computer find the distance between the irregularity measurement point and the sensor from the data flow returned by laser sensors, which is used to calculate the irregularity. Finally, inertial sensors obtain the motion data of the system, and the correct attitude angle of the grooved rail inspection vehicle is obtained through the quaternion algorithm. The algorithm flow chart is as follow:
2.2.2. Longitudinal Irregularity Algorithm

Algorithm of longitudinal irregularity is as follow:

Step.1: Connect the sensors. At first, detect the data returned by inertial sensors and get vertical acceleration Acc of the grooved rail detecting vehicle. Furthermore, the upper computer detects the data returned by 2D laser sensors and gets vertical distance Y between gauge point and sensors.

Step.2: Transmit data. The sensors collect the service data within 10ms of the vehicle's operation and upload it to the upper computer. The upper computer determines whether the data is integrated or not. If so, the data will be segmented and stored.

Step.3: Detect. The upper computer determines whether the data is satisfactory. If not, the computer will reject the data and repeat executing Step.3.

Step.4: Calculate. The distance between the gauge point of the left and right grooved rail and the sensors at time t is Y1, and Y2, respectively. Let m and n be two moments and m is less than n. Then, the relative vertical displacement of the left and right grooved rail named W1 and W2 can be calculated. Furthermore, the inertial sensors measure the vertical acceleration of the vehicle at equal time intervals in 50ms at 4 points, which was recorded as Acc1 to Acc4. Setting up vertical acceleration Acc1=0 of vehicle at first time. The upper computer obtains the vertical displacement Z of the vehicle through numerical integral method. Finally, the upper computer calculates the longitudinal irregularity of grooved rail.

Step.5: Save data.

2.2.3. Alignment Irregularity Algorithm

Based on application of inertial measurement principle to i-rail, this paper explores a method of applying inertial measurement principle and laser triangulation to the detection of grooved rail geometric parameters. The inertial measurement principle is applied to get the formula of alignment irregularity and to realize the detection. The formula of alignment irregularity is as follow:
Left: \[ Y_L = Z + \frac{S}{2} = \int \int a_0 \cdot dt \cdot dt + \frac{S}{2} \]
Right: \[ Y_R = Z - \frac{S}{2} = \int \int a_0 \cdot dt \cdot dt - \frac{S}{2} \]

In the formula, \( Y_L \) is the alignment irregularity of left grooved rail and \( Y_R \) is right; \( a_0 \) is modified inertial acceleration; \( S \) is gauge. In the set inertial coordinate system, the detection system will draw two orbital curves, namely, the plane strike diagram of the grooved rail. \( a_0 \) is the inertial acceleration detected by gyroscope; \( g \) is the acceleration of gravity; \( \theta \) is the angle between grooved rail and ground; \( v \) is speed of grooved rail inspection vehicle; \( R \) is the radius of rail and \( \dot{\theta} \) is the angular velocity of \( \theta \). Then, using \( g, \theta, v, R, \theta, \) and \( S \) to modify \( a_0 \).

In the alignment irregularity algorithm, \( R \) cannot be measured simply, but it can be obtained indirectly by calculating the curvature of grooved rail. The formula of the curvature is: \( K = \frac{d\alpha}{ds} \). The curvature at a point on the curve is equal to the tangent instant angle \( d\alpha \) over the instantaneous arc length \( ds \). Based on the definition and formula of curvature, the curvature of grooved rail is equal to the angular velocity of the yaw: \( K = \omega \). In the formula, \( K \) is the curvature and the \( \omega \) is the angular velocity of the yaw. Through the above formula, \( a_0 \) can be corrected more accurately.

3. SYSTEM STRUCTURE
The detection system includes software and hardware. In terms of hardware, 2D laser sensors detect the outline data of grooved rail and transmit it to the upper computer through Ethernet communication while the inclinometer, inertial sensors and gyroscope collect the motion data of vehicle. As for software, it has functions of real time data displaying, image rendering, out of limit alarming and so on. The detection system implementation flowchart shows as follow:

Figure 4. The detection system implementation flowchart
4. EXPERIMENT

In order to meet the requirement of experiment, we set a 6m long 60R2 grooved rail in the laboratory. According to the standard of i-rail detecting vehicle, it requires that the indication error of the grooved rail irregularity detection system is within ±0.7mm while the grooved rail is shorter than 10m chord, and the repeatable measurement error is less than 0.5mm on the same length of grooved rail[8].

4.1. Verification Experiment of Height

In order to verify the longitudinal irregularity algorithm, this paper takes the grooved rail in the laboratory as the standard grooved rail, which is, the longitudinal irregularity of the grooved rail in the laboratory is nonexistent. So that the precision of the longitudinal irregularity algorithm can be obtained by comparing the ideal longitudinal irregularity(height) and the measurement. From the experimental data, it can be seen that the maximum error of system detection is 0.5947 mm, less than 0.7 mm, which meets the requirements of modern grooved rail geometric parameters detection. The data is as follow:

| Sequence Number | Ideal value | Measured value | Measurement error |
|-----------------|-------------|----------------|-------------------|
| NO.1            | 0           | -0.0101        | 0.0101            |
| NO.2            | 0           | -0.0177        | 0.0177            |
| NO.3            | 0           | -0.0156        | 0.0156            |
| NO.4            | 0           | 0.0901         | 0.0901            |
| NO.5            | 0           | 0.0368         | 0.0368            |
| NO.6            | 0           | 0.0374         | 0.0374            |
| NO.7            | 0           | -0.0320        | 0.0320            |
| NO.8            | 0           | -0.0151        | 0.0151            |
| NO.9            | 0           | 0.0206         | 0.0206            |
| NO.10           | 0           | 0.5947         | 0.5947            |
Besides, repeating the experiment to verify whether the algorithm meet the requirement of the repeatable measurement error. From the data, it shows that the maximum error of system detection is 0.137 mm, less than 0.5 mm, which meets the accuracy requirements of repeated experiments. The data is as follow:

![Figure 6. Ideal value and measurement of height](image)

4.2. Verification Experiment of Rail Direction

In order to verify the alignment irregularity algorithm, this paper takes the grooved rail in the laboratory as the standard grooved rail, which means, the grooved rail in the laboratory is straight and parallel. We now take the left rail as an example, the ideal grooved rail alignment irregularity(direction) and the measurement are compared under the same coordinate system to obtain the precision of detection system. From the experimental data, it shows that the maximum error of system detection is 0.657 mm, less than 0.7 mm, which meets the requirements of modern grooved rail geometric parameters detection. The data is as follow:

![Figure 7. The result of repeating experiment](image)

| Sequence Number | Experimental Data(unit: mm) |   |   |
|-----------------|----------------------------|---|---|
|                 | Ideal value                | Measured value | Measurement error |
| NO.1            | 0                          | 0.1303          | 0.1303             |
| NO.2            | 0                          | 0.4230          | 0.4230             |
| NO.3            | 0                          | 0.0346          | 0.0346             |
| NO.  | Value | Measurement |
|------|-------|-------------|
| 4    | 0     | 0.0656      |
| 5    | 0     | 0.2320      |
| 6    | 0     | 0.3580      |
| 7    | 0     | 0.0374      |
| 8    | 0     | 0.5218      |
| 9    | 0     | 0.6566      |
| 10   | 0     | 0.2339      |

Figure 8. Ideal value and measurement of rail direction

5. CONCLUSIONS
Based on the inertial measurement - laser triangulation comprehensive algorithm, this paper presents a practical and feasible scheme of the longitudinal irregularity and alignment irregularity of grooved rail detection. The original modern tram detection system developed by the project team is perfected and the inertial measurement - laser triangulation algorithm is verified by experiment in this paper. From the experimental data, it shows that the measured value of the alignment irregularity fluctuates greatly. Although the experimental data shows that it has met the requirement of the grooved rail detection, its error is huge. The reason for this may be the vibration of detection vehicle, resulting in a huge error in its attitude data, which makes the algorithm unstable. The next phase of the project team will focus on eliminating the impact of the vibration of detection vehicles.

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