Research on the three-dimensional detection system of the rail full profile

Zhendong Zhou1,3, Haima Yang1 and Jin Liu2

1 University of Shanghai for Science and Technology, Shanghai 200093, China
2 Shanghai University of Engineering Science, Shanghai 201620, China
3 E-mail: 1150927958@qq.com

Abstract. To solve the problem of slow speed, low precision and low efficiency of manual measurement in the current inspection of rail. Based on the non-contact laser profilers, a three-dimensional detection system of the full profile of rail is proposed by using the integrated combination of four laser profilers. The top straightness of the rail is detected by two-point connection method and the bottom distortion of the rail is detected by the common-plane method. After field testing, the machine measurement accuracy of the rail height, rail head width, rail bottom width and rail waist width in both rail head and tail are 0.039, 0.037, 0.029, 0.036mm and 0.047, 0.037, 0.039, 0.042mm respectively; The distortion are 0.035 and 0.039mm respectively. Experiments show that the system can complete the measurement of rail efficiently and steadily, and improve the speed, accuracy and efficiency of measurement.

1. Introduction
In recent years, the rapid development of China's high-speed railway has greatly promoted the country's economic growth, but also put forward higher requirements for high-quality railway construction. The profile size of the rail [1], especially the parameters such as the rail height, rail head width, rail bottom width, rail waist width and the straightness and distortion, which are the important criteria for determining whether the steel rail quality is qualified. Therefore, the three-dimensional detection of the rail full profile is an important safety guarantee for the construction of high-quality railway [2].

At present, the full profile measurement of rail is divided into two main types, one is contact measurement [3–4], the other is non-contact measurement [5–6]. Contact measurement is mainly mechanical contact measurement, using a variety of gauges and steel rails for contact. Now most of the major welding rail bases in China use this measurement method [7]. The method has low measurement accuracy, low efficiency and high work intensity, which can not meet the current needs of high-speed railway development.

Therefore, a non-contact three-dimensional detection system of the full profile of rail is studied, which based on the high-precision laser profilers. The steel rail is scanned in all directions by using the integrated combination of four laser profilers, and the profile size and straightness and distortion of the steel rail are obtained. The system has the advantages of fast detection speed, high precision and high degree of automation.
2. Slide measuring mechanism

In order to cooperate with the test and use of steel rails, the system uses a slide measuring mechanism, the system is divided into three parts: 1 front rail delivery mechanism; 2 slide measuring mechanism; 3 rear rail delivery mechanism. The front and rear rail delivery units are powered by motor and hydraulic, and the front rails are used to clamp the rails when the rails enter from the roller line and provide forward power. The rear rail is a clamping pair for the output measurement area during the inspection of the rail, which provides stable conditions for the measurement.

The detection work is mainly finished by the slide mechanism, the inside of the slide is equipped with 4 laser profilers, from the top, left, right and bottom directions of the steel rail to scan the rail respectively. Top and bottom 2 laser profilers are fixed, left and right 2 laser profilers can turn a certain angle to achieve the rail end surface and rail body scanning and shooting, using 4 profilers can achieve the function of 6, servo motor through the reducer and high-precision screw connection, driving the slide platform back and forth sliding detection. The physical map of the slide measuring mechanism is shown in Figure 1(a). The model image of four laser profilers is shown in Figure 1(b).

![Figure 1](image)

**Figure 1.** Slide measuring mechanism: (a) physical map; (b) model image of four laser profilers.

The front rail delivery mechanism stops the delivery after the rail is delivered to the static detection area, and then the inspection platform makes a static measurement of three meters at the rail end. The data collected by the laser profiler is transmitted over Ethernet to the upper machine in real time. Then through the software to process data, finally get the static parameter detection value, and display on the screen.

After the static detection, the front rail mechanism continues to control the rail to move forward at uniform speed, the detection platform makes dynamic measurement, and the laser profiler collects the steel rail profile [8] data. After the dynamic detection, the rear rail mechanism continues to deliver the tail of the rail to the designated location, and then the static detection of the end of the rail three meters, the operation is the same as the three meters detection at the rail end. After all the testing is completed, the rear rail mechanism moves the rail out of the testing center.

3. Laser profiler

3.1. Principle of direct laser triangulation

Direct laser triangulation method [9-10] is a triangular distance measurement method for the incident beam perpendicular to the surface to be measured. The light emitted by the laser is directed vertically to the surface of the object under test after focusing through the convergence lens, and the object moves or its surface changes, causing the incident point to move along the incident light axis, and the scattered light at the incident point is incidented on the photoelectric detector through the receiving lens, and the scattered light imaged on the photoelectric detector. The two images collected before and
after moving the object are obtained by software processing, and the actual moving distance of the object can be obtained according to the formula derived. Figure 2 shows a direct laser triangulation schematic.

Figure 2. Direct laser triangulation schematic.

Figure 2 shows that parameters should meet the following criteria:

\[ \cos \alpha = \frac{\left(x^2 - n^2\right)^{1/2}}{x} \]  \hspace{1cm} (1)

\[ \sin \alpha = \frac{n}{x} \]  \hspace{1cm} (2)

\[ \cos \beta = \frac{n}{m} \]  \hspace{1cm} (3)

\[ \cos \beta = \cos\left[180^\circ - \theta - (90^\circ - \alpha)\right] \]  \hspace{1cm} (4)

Available by similar triangles:

\[ \frac{p}{n} = \frac{y}{\left(x^2 - n^2\right)^{1/2}} \]  \hspace{1cm} (5)

Joint vertical (1) - (5) to obtain the actual distance of the object's movement:

\[ m = \frac{xp}{y \sin \theta - p \cos \theta} \]  \hspace{1cm} (6)

In the above formulas: \( \theta \) is angle between incident laser beam and scattered light; \( \alpha \) is angle between the incident laser beam and the scattered light after moving an object; \( y \) is the distance from the photoelectric detector to the receiving lens; \( p \) is the distance during the scattered light before and after moving object; \( x \) is the distance between the receiving lens and the incident point; \( n \) is the distance between incident and scattered light after moving the object; \( \beta \) is auxiliary angle; \( m \) is the moving distance of the object.

3.2. Laser profiler coordinate system

Each laser profiler has its own independent coordinate system, where the X-axis represents the far-range proximity of the measuring points of the rail section, the Y-axis represents the measuring range
of the laser profiler, and the Z-axis represents the direction of the rail detection. The map of the outline of the measured rail is shown in Figure 3, and the four three-dimensional spatial coordinate systems are shown in Figure 4.

**Figure 3.** Measuring the outline of the rail.

**Figure 4.** Laser profiler coordinate system distribution.
Because the four coordinate systems are independent, in order to simplify the model to reduce the
difficulty of calculation, the coordinate system $O_2$, $O_3$ conversion to $O_1$, where
the coordinate system $O_2$ is rotated 90 degrees around the Z axis relative to the coordinate system $O_1$, the coordinate system $O_3$ is rotated 90 degrees around the Z axis relative to the coordinate system $O_2$, the rotation matrix of the coordinate system $O_2$, $O_3$ relative to $O_1$ are recorded as $R_2$, $R_3$ respectively. The translation transformation matrix of $O_2$, $O_3$, and $O_4$ relative to $O_1$ are recorded as $T_2$, $T_3$, and $T_4$ respectively. The rotation matrix is shown as the Formulas (7), (8). Its translation transformation matrix can be obtained according to the actual relative mounting position of the laser profilers.

$$
R_2 = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}
$$

(7)

$$
R_3 = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
$$

(8)

4. Three-dimensional parameter detection of rail

4.1. Straightness detection

According to the method of measuring straightness of electronic ruler, this paper uses the two-point
connection model to solve the straightness calculation. Curve $AB$ is the profile curve in the length
direction of the rail surface, and the first and last two points are connected in a straight line as the reference plane, and the maximum distance from the remaining points to the reference plane is straightness. This system measures the straightness of the top surface of the 0-1.5m range at the end of the rail as an example. The two-point connection model is shown in Figure 5.

![Figure 5. Two-point connection model.](image)

The distance of a series of points to the sensor on the top and side of the rail by a laser profiler as $y$, and the number of measuring points as $x$, and by the Minimum square-multiply:

$$
A = \sum xy - \frac{1}{N} \sum x \sum y - \frac{1}{N} (\sum x^2) - \frac{1}{N} (\sum y^2)
$$

(9)

$$
B = y - Ax
$$

(10)
Find a fitting straight line \( y = Ax + B \), calculating the distance between points and regression lines by formula \( d = \frac{|Ax_0 + By_0 + C|}{\sqrt{A^2 + B^2}} \). To get a top maximum distance and the bottom maximum distance is the maximum error and the minimum error.

4.2. Distortion detection

The rail distortion refers to the distortion degree of the vertical rail, and the data within 1m of the bottom surface of the rail can be collected, and the relative distortion should not exceed 0.45mm [11]. As shown in Figure 6, according to the measurement method of the electronic warp ruler, the distortion degree is solved by the common-plane model. The data measured by the laser profiler is a two-dimensional plane, and the common plane method requires three-dimensional spatial calculation, so this paper defines the direction of the motion of the detection platform as the direction of Z-axis.

Figure 6 is a common-plane model, plane \( S \) is the plane in which \( A, B \) and \( C \) points are located. Then the distance between \( D \) point and plane \( S \) is the distortion [12].

Suppose plane \( S \) equation: \( ax + by + cz + d = 0 \), the coordinates of \( A, B \) and \( C \) points are respectively \( (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3) \), according to Clem's law, the coefficient expression of plane \( S \) can be obtained:

\[
\begin{align*}
    a &= y_1 z_2 - y_1 z_3 - y_2 z_1 + y_2 z_3 + y_3 z_1 - y_3 z_2 \\
    b &= x_1 z_2 + x_1 z_3 + x_2 z_1 - x_2 z_3 - x_3 z_1 + x_3 z_2 \\
    c &= x_1 y_2 - x_1 y_3 - x_2 y_1 + x_2 y_3 + x_3 y_1 - x_3 y_2 \\
    d &= x_1 x_2 z_3 - x_1 x_3 z_2 - x_2 x_1 z_3 + x_2 x_3 z_1 + x_3 x_2 z_1 - x_3 x_2 z_1
\end{align*}
\]

(11)

Then \( L \) is the distance between \( D \) point \( (x_0, y_0, z_0) \) and plane \( S \):

\[
L = \frac{|ax_0 + by_0 + cz_0 + d|}{\sqrt{a^2 + b^2 + c^2}}
\]

(12)

5. Experimental test

5.1. Profile test

Selecting the same rail for repetitive test and accuracy test to verify the accuracy of the system proposed in this paper. The test results for the rail head and tail are shown in Figure 7.
As shown in Figure 7, the machine measurement accuracy of the rail height, rail head width, rail bottom width and rail waist width of the rail head and tail are 0.039, 0.037, 0.029, 0.036mm and 0.047, 0.037, 0.039, 0.042mm respectively. This shows the system is faster and more stable than manual measurement.

5.2. Straightness test
In this paper, the experimental test takes 0-1.5m range at the end of the rail as an example, the laser profiler shoots one frame every 4mm, so there are 375 points in the 1500mm range. Because of the presence of iron chips and other impurities on the top surface of the rail, and the exposure of dust and light, the straightness data of the rail needs to be filtered and fitted. The exception point is culled before filtering, and the string height difference method is used to eliminate the abnormal point.

![Figure 8. String height difference method.](image-url)
Figure 8 is string height difference method, connecting two points $P_{n-1}$ and $P_{n+1}$ before and after the detection point $P_n$, and then calculate the distance $d$ from the point $P_n$ to the connecting line. If $|d| \geq \varepsilon$ (where $\varepsilon$ is a given permissible deviation), then $P_n$ should be culled for the exception point.

After eliminating the exception points, smooth filtering and polynomial 5-order fitting are used respectively, and the processing effect is shown in Figure 9.

![Figure 9](image)

**Figure 9.** Straightness processing effect: (a) raw data; (b) smooth filtering; (c) polynomial 5-order fitting.

5.3. Distortion test

As shown in Figure 10, this paper selects the same rail to repeating test. In addition to verifying repeatability, but also to check its accuracy, and then randomly select 3 steel rails. Each rail is measured 10 times at 1m from the rail end, and the test results are shown in Figure 11.

![Figure 10](image)

**Figure 10.** Distortion repeat test.

![Figure 11](image)

**Figure 11.** Distortion accuracy test.

Figure 10 shows the machine measurement accuracy of the rail head and tail are 0.035 and 0.039 mm respectively. From Figure 11, it can be seen that the measurement values of three rails do
not show major fluctuation, the data measured by the system are within 0.12mm. By compared with the manual measurement, the proposed system has a better accuracy.

6. Conclusions
For the steel rail detection has been studied, now the welding rail base is using a variety of manual use of various gauges to measure rail, because of the slow speed, low efficiency of manual measurement. Thus, a three-dimensional detection system of rail full profile is proposed, using the integrated combination of four high-precision laser profilers to achieve all the comprehensive measurement (profile size, straightness, distortion).

The abnormal points in the top straightness data, which are eliminated by string height differential method, contributing to better smooth filtering and polynomial fit. At the same time, the distortion test is carried out by the common-plane method. The experimental results show that the system has good repeatability and accuracy, and improves the current situation of low automation of manual measurement, and promotes the development of three-dimensional detection of the rail full profile.

Acknowledgements
The authors would like to thank National Natural Science Foundation of China (61701296 and U1831133) and Shanghai Natural Science Foundation (17ZR1443500) for the support given to this research.

References
[1] Li W, Li L, Gao Z K, et al. 2014 Railway Building 9 125-127
[2] Zhu X R, Guo Z T, Zhou Y X, et al. 2018 Railway Science and Engineering Journal 15 2401-2406
[3] Cao X C 2013 Development of Rail Profile Measuring Instrument Nanchang University
[4] Guo Y Y F 2016 Design and Implementation of Rail Profile Detection System Hunan University
[5] Wang S Y 2011 Rail Wear Automatic Detection System University of Electronic Science and Technology of China
[6] Gao W J 2012 Study on the Detection System of Rail Silhouette Based on Machine Vision Beijing Jiaotong University
[7] Zheng S B, Chai X D, An X X, et al. 2013 China Railway Science 7-12
[8] Zhou Q Y, Zhang Y H, Tian C H, et al. 2014 China Railway Science 35 128-134
[9] Zhang Y W 2015 Research about the Information Acquisition System of 2D Laser Displacement Sensor Jilin University
[10] Zhang M 2015 The Measurement System of Objects’ Three-dimension Figure Based on the Laser Triangulation Wuhan University of Technology
[11] Chen D S and Tian X Y 2008 Railway Building 82-86
[12] Sun J H, Wang W H, Liu Z, et al. 2010 Journal of Beijing University of Aeronautics and Astronautics 36 1026-1029