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Distortion calibrating method of measuring rail profile based on local affine invariant feature descriptor

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ABSTRACT

Measuring rail profile in the presence of multiple degrees of freedom vibration is a very challenging task. This paper presents a novel method based on the local affine invariant feature descriptor to calibrate distorted profiles, which are obtained by traditional rail measurement system. It has three major modules: local affine invariant (LAI) feature descriptor, affine transformation estimation and parameters refinement. LAI feature descriptor is based on the affine geometry invariant and generated by calculating the proportions of different areas. Using the proposed LAI descriptor, we implement a three-stage profile calibration including matching, estimation, and refinement based on grouping and fast iterative closest point (FICP) algorithm. The performance of proposed LAI descriptor and calibrating method is tested by performing extensive experiments. The experimental results show that our LAI descriptor is highly descriptive and robust with respect to varying resolution and noise, and the LAI descriptor based calibration is effective and repeatable.

1. Introduction

Steel rails are used in the transport sector and in a wide range of industries. A more accurate and effective rail measuring technique is vital to transporting smoothly and efficiently [1]. Furthermore, rail profile measurement plays a key role in the rail measuring process. Its results not only reflect the rail wear levels directly, but also provide a scientific reference for rail maintenance.

Existing methods for rail profile measurement can broadly be classified into two categories, i.e., contact and non-contact methods. The former contacts with the surface of an object utilizing a mechanical sensor, and the latter utilizes non-contact devices based on magnetic, optical or acoustic principles [2,3] to inspect object. Such devices commonly refer to the CCD camera and line structured-light laser projector. Based on the used types of way of the CCD image data handling, these non-contact methods can be divided into the laser visual technique (LVT) [4–6] and the laser displacement technique (LDT) [7–9].

LVT extracts the rail profile from real images by implementing a series of image processing operations, including binarization [10], edge detection [11] and center extraction. Using the camera calibration [12], LVT can reconstruct the 3D structure of rail profile from the image. Yet, this processes is time-consuming (the sampling rate is no more than 250 profiles/s generally). Moreover, the real images would suffer from objective environment [13], including light, multiple reflections, oxidation, greasy track and speckle, which would lead to relatively lower measurement accuracy.

Based on geometric principle, LDT calculates the distance to the object for each point of the set along the laser line on the object. So, it can acquire the coordinates of sampling points directly. Compared with LVT, LDT is efficient and simple. The sampling rate can reach to 1800 profiles/s. It is therefore suitable for high-speed rail inspection.

In order to get correct measurement results, the light plane radiated by the laser projector must be vertical with the rail longitudinal axis. However, measurement systems are commonly mounted on track inspection vehicle or rail maintenance train. When they are running, the track un-flatness [14,15] would cause multiple degrees of freedom vibration, which would leads to non-perpendicular relationship between the light plane and the rail longitudinal axis. In this case, neither traditional LVT nor LDT can obtain high measurement accuracy due to the distorted profiles caused by non-perpendicular relationship.

To solve the problem mentioned above, a number of valid methods of calibrating distorted profiles have been proposed in the literatures, including the vibration decoupling and compensation

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based on orthogonal decomposition [16,17], the non-rigid iterative closest point (ICP) based geometric objects registration [18–21], and the motion deviation rectifying method based on multi-line structured-light vision [22,23]. Most of these methods are based on the improved LVT and can calibrate distorted profiles effectively. However, belonging to the LVT category in essence, the above methods still suffer from either low accuracy or weak robustness. As previously stated, LDT is an efficient and simple way to realize high-speed rail inspection. Yet, due to the lack of coordinates along the rail longitudinal axis, it is hard to calibrate distorted profiles using traditional LDT. So, LDT-based measuring rail profile in the presence of nuisances is still a challenging task.

In this work, we present a local affine invariant feature descriptor together with an efficient method of calibrating distortion for LDT-based rail profile measurement. The paper first analyzes the distortion caused by multiple degrees of freedom vibration, and points out that the relationship between the distorted profile and the normal one can be modeled using an affine transformation (Section 2). A novel local affine invariant (LAI) feature descriptor is then presented (Section 3). This descriptor is used for matching points on the distorted profile and the normal one, and is generated by calculating the proportions of different areas (e.g., triangle bounded by a key point, rail jaw and an intersection, area bounded by a key point, rail jaw point and rail waist and area bounded by a key point, an intersection and rail foot). Finally, we present a three-stage method based on the proposed LAI feature descriptor to calibrate distortion for rail profile measurement (Section 4). Experiments were performed on the real rail to evaluate the performance of the proposed method (Section 5).

2. LDT-based profile measuring system

2.1. System principle

As shown in Fig. 1, the rail profile measuring system based on LDT mainly consists of two laser displacement sensors, an odometer, a data transmitting unit and a data processing unit. When the vehicle is running, trigger pulse signals are emitted by the optical-electrical encoder and sent to the sensors. Controlled by these signals, two laser sensors sample the rail profiles synchronously. The operation of the sensors is base on the triangulation measuring principle, which could calculate the actual distance between the sensor and the rail. Utilizing the distance data, we can depict the 2D rail profile easily. By comparing the measured profile with the standard one, the rail wear results are obtained.

2.2. System defect

When the train is running, there are six degrees of freedom random vibrations, including the stretching vibration along axis Z, the swaying vibration along axis X, the bouncing vibration along axis Y, the rolling vibration around axis Z, the pitching vibration around axis X, and the heading vibration around axis Y. Here, axis X is parallel to the transversal direction, axis Y is vertical to rail tread, and axis Z is parallel to the rail longitudinal.

Among all vibrations, the first four have no effect on the verticality between the light plane and the rail longitudinal axis. The acquisitions are still normal profiles. The remaining pitching and heading vibrations make light plane non-perpendicular to the rail longitudinal axis. As shown in Fig. 2, the distorted profiles caused by pitching and heading are equivalent to vertical equal-scale stretch and horizontal equal-scale stretch, respectively. They can be modeled with $y' = y/\cos\theta_1$ and $x' = x/\cos\theta_2$, where θ_1 is the pitching angle, θ_2 is the heading angle. (x, y) and (x', y') are coordinates of the point in normal profile and corresponding one in distorted profile, respectively.

In reality, laser displacement sensor is fixed slantwise so that we can obtain a complete profile that contains the unworn rail waist section. The relationship between (x, y) and (x', y') can be represented as

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_x & 0 & 0 \\ 0 & S_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ T_x & T_y & 1 \end{bmatrix}, \tag{1}$$

where θ is the tilted angle of sensor, T_x and T_y are the translation amounts. They are related with the location and position of the sensor. S_x and S_y are coefficients of axial deformation along horizontal and vertical direction respectively. They are related with the degree

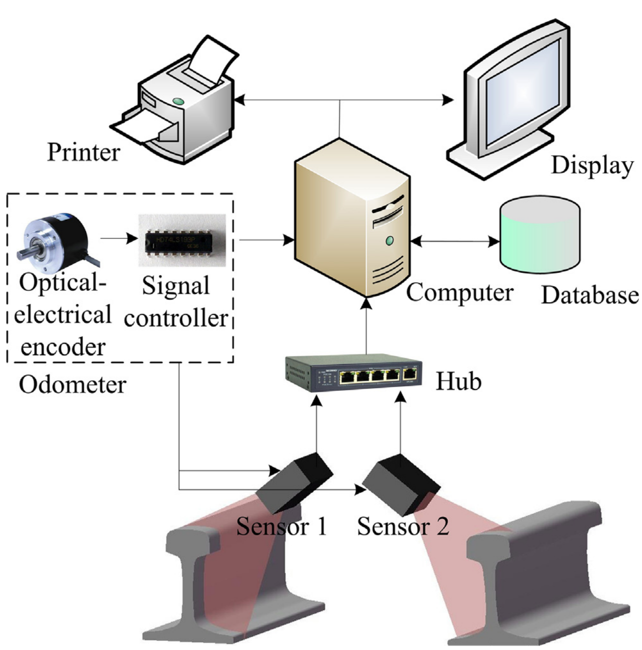

Fig. 1. LDT-based rail profile measuring system.

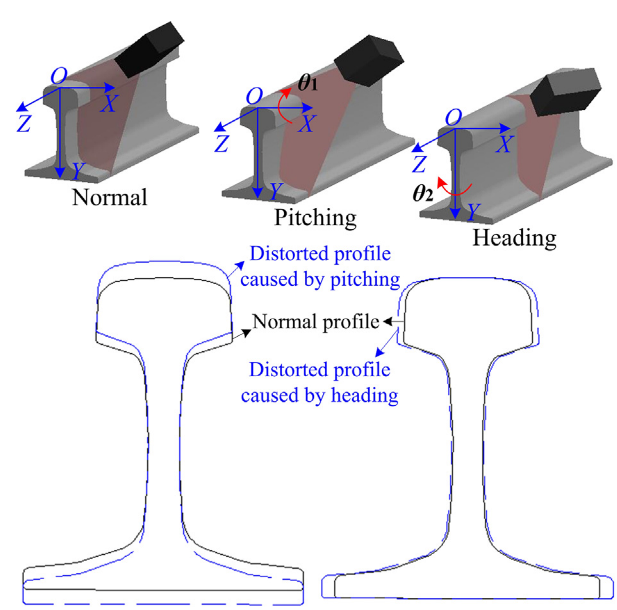

Fig. 2. Influence caused by pitching and heading.