Optic-electronics stereo system for spatial position measurement of railway track*

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(Received 24 January 2022; Revised 2 April 2022)

Railway departments in various countries are looking for a technology with convenient operation, low price, excellent measurement performance and stability for spatial position measurement of railway track. Therefore, we design an optic-electronics stereo system based on the principle of optical stereo measurement. The experimental verification in the real railway environment shows that the performance of the system is that the longitudinal relative displacement measurement range is 200—10 000 mm, the relative distance measurement range is 4 500 mm and the measured root mean square (*RMS*) error value is less than 1.1 mm in the whole process. Therefore, it meets the relevant needs of the Russian Ministry of railways.

Document code: A **Article ID:** 1673-1905(2022)07-0434-6

DOI https://doi.org/10.1007/s11801-022-2013-x

The track geometry determines the safety and comfort of high-speed trains. Therefore, the space position of the orbit relative to the designed reference needs to be measured regularly and strictly[1]. At present, the main equipment for orbit space position measurement in the market adopts the method of multi-technology combination of global positioning system (GPS) differential, inertial calibration, optical auxiliary measurement and so on. For example, the GRP1000 produced by the Austrian company Plasser & Theurer and Swiss Trolley produced by the Swiss company Terra International Surveys Ltd. can initially achieve full automation of measurement. However, in order to obtain higher-precision measuring results, it is necessary to lay multiple GPS base stations or use multiple inertial devices to control the measuring system, so the actual cost is high and the operation process is complicated[2-4].

In recent years, with the rapid development of microwave holography[5,6], photography[7-9], interferometry[10-12] and other optical measuring methods in the field of high dynamic and large size measurement, inexpensive and convenient optical measuring technology for orbit space position measurement has attracted attention. Among them, microwave holography is generally considered to have a large measuring range and the measuring accuracy can reach 0.014—0.030 mm. But it has a large load of measurement equipment because this method needs to add additional reference antennas and phase stable receiving devices. The measuring results obtained need to be calculated twice according to the actual workload of high-speed rail. Interferometry has high measuring accuracy and large measuring range. However, it is sensitive to air vibration and temperature change, so it isn't suitable for outdoor environment. Due to the large-scale production of industrial cameras, photography method has a significant cost advantage compared with other optical measurement methods. In addition, the accuracy of this method has been proved to be as high as 0.05 mm in the measurement of spatial geometry[13,14]. However, in order to be applicable to the geometric position measurement of railway track, the photographic method needs to overcome the influence of the stitching error of photos on the measurement accuracy of the system. Therefore, in practical use, it is required that the carrier of the camera must run at a low and uniform speed and the measurement environment is strict, which cannot be used in environments such as rain, snow, frost and fog.

In order to solve the above problems, a new photographic method to establish the imaging of structured light sources and the perception of the geometric quantity of the measured object are proposed. In 2019, ACEITUNO et al[15] introduced a high-precision dense sampling measurement of track specific mark points by using the total station with structural light source, so as to realize measurement modeling and track space position evaluation.

* This work has been supported by the National Natural Science Foundation of China (No.62005033), the Government of the Russian Federation (08-08), the Basic Research Project of Chongqing Science and Technology Commission (No.CSTC-2020jcyj-msxm0603), and the Science and Technology Research Program of Chongqing Municipal Education Commission (No.KJQN202000609).

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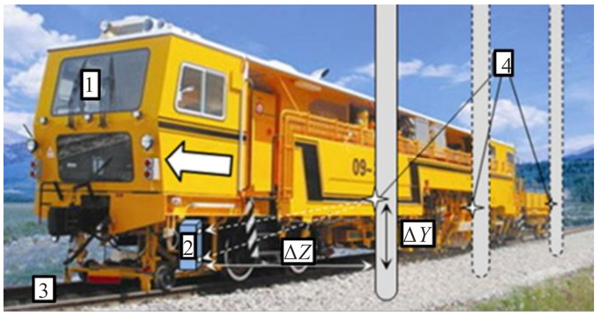
This work fully demonstrates the good anti-interference ability of spatial structured optical photography method and the advantage that the measurement information attached to imaging is easy to be solved quickly. However, the commercial total station model they used did not support the direct processing of measurement data and the integration of auxiliary measurement hardware. Therefore, this work can only be measured manually and has low efficiency. In 2020, PENG et al[16] proposed a structured optical photogrammetry method integrating inertial components, which basically realizes the full-automatic measurement of multiple parameters including track regularity, step difference, spatial position and so on. However, the design concept of measuring the reference coordinate system with gyroscope and accelerometer leads to the serious impact of the drift and error accumulation of inertial devices on the final measurement results of the imaging system. Therefore, it is necessary to use complex error compensation algorithms to ensure the positioning accuracy of the inertial coordinate system.

In order to further improve the measurement efficiency of spatial position of railway track and provide a more reliable and cheaper measurement scheme, we propose an optic-electronics stereo system with simple structure, accurate reference coordinates and fast measurement speed. Although some principles and error analysis of this system have been reported in previous conference papers[17-19], this paper will focus on the system design, implementation and experimental verification in detail. The design theory of this kind of optic-electronics stereo system is the result of a special form of mathematical model of vector coplanar whose main hardware consists of measuring component and tag benchmark. We use the weighted average algorithm as the calculating formula of measured data based on the measurement characteristics of the imaging unit complementary metal-oxide-semiconductor (CMOS). The system adopts the information acquisition method of direct measurement of displacement of reflected beam of structured light source by photoelectric sensors and makes full use of the advantages of high measuring speed, super precision and strong environmental adaptability[20-22] of CMOS matrixes.

Experimental results show that the technical characteristics meet the engineering requirements of a-224U and C-493U documents of the Russian Ministry of Railways and the measuring system of railway track space position requires the following performance. The measuring range of longitudinal section is 300 mm (vertical displacement), the measuring range of the transverse section is 2 000—10 000 mm (lateral displacement), the whole measuring accuracy is better than 1.1 mm and it is suitable for real-time measurement in outdoor environment.

The overall structure of optic-electronics stereo system is shown in Fig.1. The main measuring unit (MU) for signal acquisition and processing is installed in the levelling-tamping machine. Reference marks (RMs) are fixed on the catenary support of the railway and used as an RM for measurement. The installation position of RMs on posts of electric overhead contact system will be strictly calibrated to ensure that the vertical accuracy after installation is better than 1 mm.



1: levelling-tamping machine; 2: MU; 3: track; 4: RMs

Fig.1 Working principle of the spatial position correction of railway track

The optic-electronics stereo system will measure its longitudinal relative displacement ΔY and relative distance variation ΔZ with RMs when the leveling-tamping machine moves along the track. Since the positions of the optic-electronics stereo system's coordinate system relative to the level stamping machine's coordinate system and the level stamping machine relative to the track coordinate system are known, the position of the track relative to the RM is measured by the MU. When the vertical relative displacement ΔY and horizontal relative displacement ΔZ are measured to be greater than 2 mm, the leveling-tamping machine generates a command to correct the spatial position of the rail.

The received system of the MU consists of two digital video cameras (VCs)[17,18]. Each camera includes an objective lens and matrix photoreceiver (CMOS). Optical axes of objective lenses are parallel, and the baseline distance between them is B, as shown in Fig.2. Coordinate system of the MU is denoted as $OX_0Y_0Z_0$. Axis OY_0 (axis of vertical displacements) is upwards and passes through the principle points of lenses in VC1 and VC2. Axis OZ_0 (axis of distance) is parallel to optical axes of objective lenses. The baseline distances from axis OZ_0 to optical axes of objective lenses in VC1 and VC2 are $B/2$. The two cameras have local coordinate systems of $X_1Y_1Z_1$ and $X_2Y_2Z_2$, respectively. The axes of these coordinate systems are parallel to the axes system $X_0Y_0Z_0$. The axes OY_1 and OY_2 lie in sensitivity surfaces of matrix photoreceivers, and the axes OZ_1 and OZ_2 match to the optical axes of objective lenses.

Sensitive surfaces of the CMOS matrix photoreceivers and focal planes of the lenses are merged. The RM is the infrared emission diode on sight target (ST). In the measuring process, lenses of VCs formed images of the

RM on sensitive surfaces of CMOS due to closeness between the plane of image and the focal plane, if the condition $f<<\Delta Z$ is done. Every VC forms digital frame that comes to the calculation block. There are two steps to determine the coordinates ΔY and ΔZ of RM relative to base point in vertical axis OY_0 and longitudinal axis OZ_0. At first, vertical y_1 and y_2 coordinates of RM's images energy centers are calculated in processing block. Algorithm of energy center's determination provides an accuracy close to 0.01 of pixel's size[18,19].

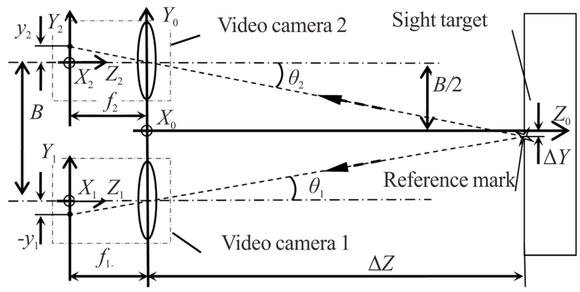


Fig.2 Measuring scheme of the optics-electronic stereo system

Secondly, on basis of mathematical model of stereoscopic systems, the sight angles Θ_1, Θ_2 and coordinates ΔY, ΔZ of RM in coordinate system $X_0Y_0Z_0$ of the MU are calculated as follows

$$\tan(\Theta_1)=\frac{-y_1}{f_1},\ \tan(\Theta_2)=\frac{y_2}{f_1}, \tag{1}$$

$$\Delta Y=\frac{-B}{2}\left(\frac{\tan(\Theta_1)+\tan(\Theta_2)}{\tan(\Theta_2)-\tan(\Theta_1)}\right),$$

$$\Delta Z=\frac{B}{\tan(\Theta_2)-\tan(\Theta_1)}. \tag{2}$$

In the first stage of the experiments, the MU is calibrated. The method by using the "chess" template is implemented and the data is processed by the MATLAB Camera Calibration Toolbox[23,24]. The calibration procedure was made 8 times to adjust the direction of the optical axes of the VC lenses to parallel position. The completed worksheet of calibration results is as follows.

Intrinsic parameters of left camera are focal length fc_left (pixels)=[5 685.774 62, 5 690.732 16]±[13.711 79, 13.868 23], and distortion kc_left=[−0.349 14, −0.108 11, −0.001 30, −0.002 41, 0.000 00]±[0.042 71, 0.529 61, 0.000 97, 0.002 42, 0.000 00].

Intrinsic parameters of right camera are focal length fc_right (pixels)=[5 673.337 20, 5 678.983 17]± [15.806 45, 15.696 17], and distortion kc_right=[−0.372 00, 0.380 66, −0.003 29, 0.000 10, 0.000 00]±[0.045 65, 0.712 49, 0.001 27, 0.002 19, 0.000 00].

Extrinsic parameters (position of right camera relative to left camera) are rotation vector (rad) *om*=[0.000 202, −0.000 12, 0.000 125], and translation vector (mm) *T*= [301.475 64, −1.172 38, −1.376 62].

The VC1 and VC2 use super extended graphics array (SXGA) mode, therefore the virtual size of the pixel is 0.004 4 mm×0.004 4 mm. As result, the focal length of lenses is calculated as

$$f_1=\frac{5\,685.774\,62+5\,690.732\,16}{2}\pm\frac{13.711\,79+13.868\,23}{2}\approx 5\,688\pm14(\text{pixel})=25.027\pm0.063(\text{mm}). \tag{3}$$

Error of f_1 determination is 0.25%.

$$f_2=\frac{5\,673.337\,20+5\,678.983\,17}{2}\pm\frac{15.806\,45+15.696\,17}{2}\approx 5\,676\pm16(\text{pixel})=24.974\pm0.072(\text{mm}). \tag{4}$$

Errors of f_1 and f_2 determinations are 0.25% and 0.3% accordingly. The non-parallelism of the lenses axes is 0.000 1 rad. These errors are acceptable for optic-electronics stereo system in measuring rail track position.

As shown in Fig.3, the optic-electronics stereo system consists of ST, MU and processing unit (PU). The MU and PU are fixed with the levelling-tamping machine and the ST is located on the post of electric overhead contact system close to rails track.

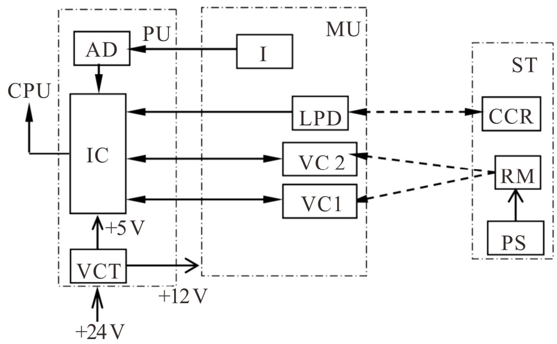


Fig.3 Structure of the optic-electronics stereoscopic measuring system

MU concludes two VCs (VC1, VC2), laser position detector (LPD) and complementing inclinometer (I). The PU is composed of industrial computer (IC), analog-to-digital converter (ADC) and voltage converter (VCT). The VC is the power supply (PS) to VC1, VC2, LPD and I. I, and VC1, VC2 and LPD are connected to IC. The ST consists of cube corner reflector (CCR), RM as infrared emission diode and its storage battery PS. The measurement process of optic-electronics stereo system is as follows.

1. The LPD will generate a laser beam which is then reflected from the CCR and received by the LPD when the levelling-tamping machine drives past the post of electric overhead contact system installed with ST.

2. The LPD generates code signals and transmits them to IC which sends instructions to VC1 and VC2 for picture capture.

3. The VC1 and VC2 image the infrared emission diode on their CMOS sensors respectively to form the image of

the RM as shown in Fig.2. The image signal will be processed by IC.

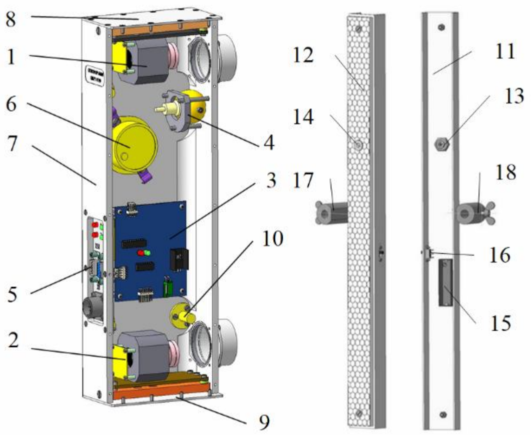
4. The IC processes the two frames of images to obtain the coordinates of RM image and calculate the displacement of RM relative to MB coordinate system at the same time.

5. The position information of RM is transmitted to the CPU calculation unit of the levelling-tamping machine, and the levelling-tamping machine corrects the track to the correct position according to the calculation result.

In addition, the complementing inclinometer will measure the attitude deviation of MU relative to the horizon in real time, while the above work steps are carried out. The measurement data is used to revise the random rotation error of MU coordinate system in real time.

The optical measurement structure of the optic-electronics stereo system consists of MU and ST, in which the specific construction of the MU is shown in Fig.4(a). VC1 and VC2 respectively contain Computer 80G lens (f=25 mm, D/f=1:1.4) with special infrared filter and an OV5610Color CMOS produced by OmniVision. The PRKL 318 LPD manufactured by Leuze Electronic GmbH+Co KG is installed at position 4 (sensing distance is more than 15 m, response time is 0.1 ms, and peak wavelength is 650 nm). Position 5 is a customized universal serial bus (USB) interface for signal transmission. An I NG2U (angle measuring range is ±10°, and resolution is 0.005°) produced by Seika is set at position 6 and fixed to the main structure of the measuring system by screw 7. Two caps 8 and 9 provide additional rigid fixing conditions for the measuring system.

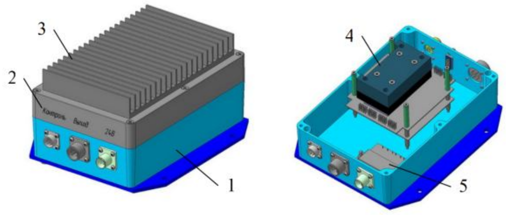
As shown in Fig.4, main body of ST 11 is a duralumin structure. CCR 12 (TKS30x500 produced by Leuze Electronic) and RM 14 as infrared emitting diode are the main parts of the ST. RMs are fixed on the front panel of the ST of main body by a tube sleeve 13. There is an SFH485P infrared emitting diode 14 manufactured by Simens (λ=880 nm) in tube sleeve as the reference light source to determine the space position of railway track directly. The base charge of the infrared emitting diode is provided by an “AA” battery 15. Positions 16, 17 and 18 are fixed mechanisms of the standard ST.



(a) (b)

Fig.4 Construction of (a) MU and (b) ST

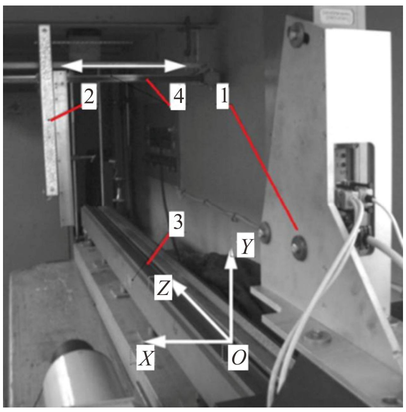
Fig.5 shows the detailed structure of PU of optic-electronics stereoscopic measuring system. It is composed of shell, cover plate with heat sink, IC and VCT (TEN 40-2431 VCT produced by TRACOPOWER). The function of VCT is to convert the load PC voltage (+24 V) of the levelling-tamping machine into the PS voltage (+5 V and +12 V) of IC and MU.



1: shell; 2: cover plate; 3: heat sink; 4: IC; 5: VCT

Fig.5 Detailed structure of PU

The test platform is shown in Fig.6. The MU of the tested stereoscopic system is rigidly fixed on the optical bench and the trolley moves along the OZ axis of the optical bench track platform. The ST is positioned on the trolley and it is slid along the OX axis by parallel slider.



1: MU; 2: ST; 3: optical bench; 4: trolley

Fig.6 Dynamic test platform of autocollimation stereo system

In the experiment, the original distance Z between the MU and ST is 2 000 mm. At this time, ST is slid along the OX axis by the hand force with an estimated speed of 2 m/s in the range of 500 mm by the parallel slider. In this process, the tested stereo system measures the ΔY and ΔZ coordinates of the RM in real time. This action repeated on another distance within the range of 2 000—10 000 mm by a 1 000 mm step along the OZ axis, and the measurement results are shown in Fig.7.

According to the dynamic test results, it can be concluded that when the distance between RM and the tested stereo system position along the OZ axis is within the range of 2 000—6 000 mm, the measuring error of the positions along OZ axis is better than the required 2 mm and the measuring error of the positions along OY

axis not more than 0.05 mm. When the distance between the RM and the autocollimation stereo system is within 6 000—10 000 mm along the *OZ* axis, the measuring accuracy of the RM along the *OX* and *OY* axes is better than 0.12 mm.

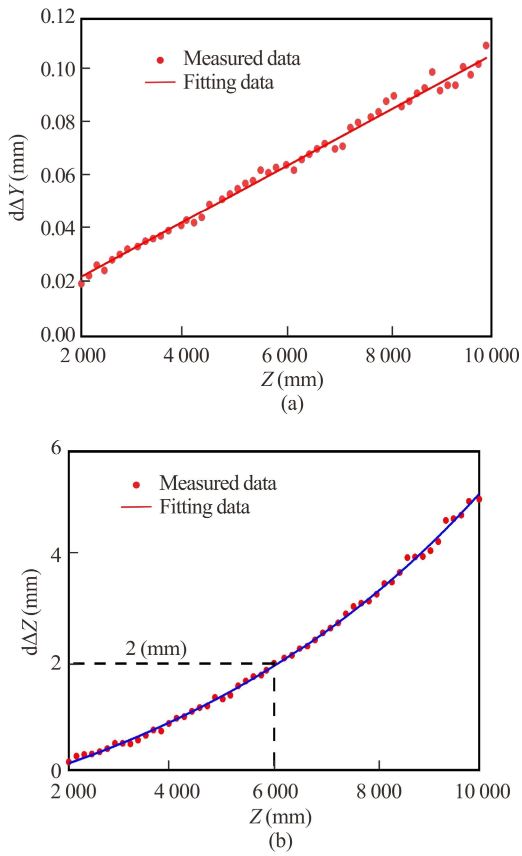


Fig.7 Dynamic test results of the stereo system: (a) Vertical displacement measurement along the *OY* axis; (b) Horizontal displacement measurement along the *OZ* axis

The tested optic-electronics stereoscopic measuring system was set on levelling-tamping machine Duomatic 09-32CSM (Plasser & Theurer, Austria). On the route from Moscow to St. Petersburg in Russia which includes both curves and straights, we used the optic-electronics stereo measuring system to test 30 RMs arranged on track whose length is about 2 km. The actual test picture is shown in Fig.8.

Russian Railway Department fixed the 30 designed STs to the calibrated track. The distance between RMs and these STs and levelling-tamping machine is close to 4 500 mm. The experimental results for measuring the positions of 30 RMs are shown on Fig.9.

In this case, the root mean square (*RMS*) error of measuring the vertical position is dΔY=0.8 mm and that of the horizontal position is dΔZ=1.1 mm.

Aiming at the practical engineering demand of spatial position measurement of railway track, an optic-electronics stereo system is proposed in this paper.

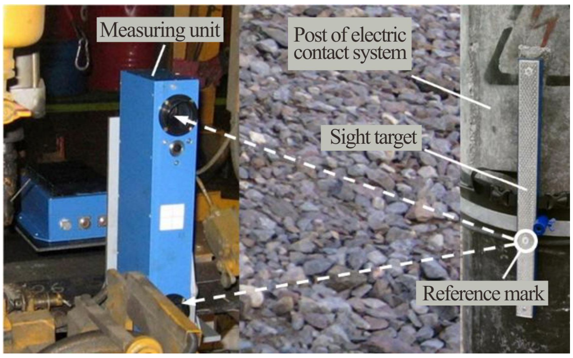


Fig.8 Actual test picture of the optical-electronics stereo measuring system

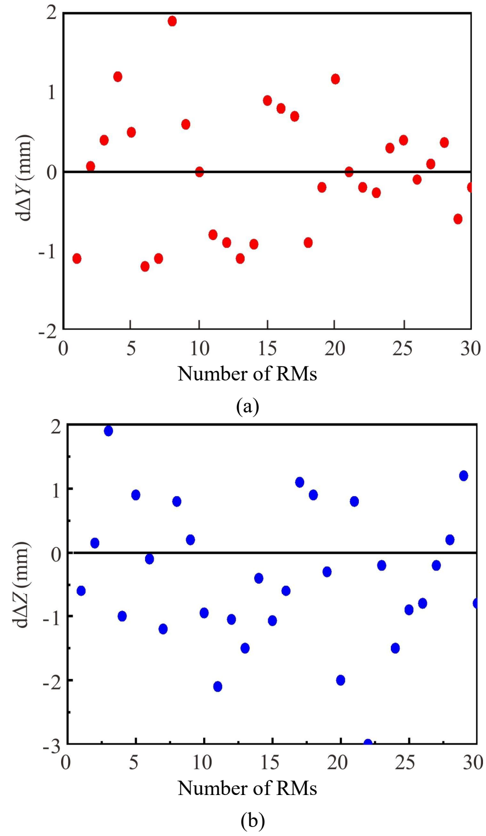


Fig.9 Measuring errors of the tested system in real scene: (a) *Y* position of RM; (b) *Z* position of RM

The system consists of ST, MU and PU. The vertical relative displacement ΔY and horizontal relative displacement ΔZ of track relative to RM can be measured. The optical measurement principle of the system is analyzed and the corresponding algorithm is given. The dynamic experimental results in laboratory and real railway test environments show that the system matches with the requirements of the Russian Ministry of Railways. The measurement range of longitudinal relative displacement is 200—10 000 mm, the measurement range of relative distance is 4 500 mm, and the measured *RMS* error is lower than 1.1 mm in the whole process.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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