A New Method for Measuring Subgrade Settlement in High-Speed Railway by Using a Linear CCD

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With the rapid development of high-speed and heavy-haul railway in China, the measuring and controlling of the settlement and deformation of the subgrade become more and more important. A new and simple method to measure the subgrade settlement by using a linear CCD is put forward and a device has been developed that consists of several parts: a point light source on a settlement detecting pile, a point-position measurement device by using a linear CCD, GPRS-Modem and a monitor computer. The relative position of the point light source and the point-position measurement device can be measured through the data collection, optical filtering, dynamic threshold determination, light spot center extraction, and the absolute settlement of the measured point on the detecting piles can be obtained. The new device has been already applied in some China railway sites, such as the Jinan section of Beijing-Shanghai high-speed railway, the Yanqing and Datong section of Datong-Qinhuangdao Heavy Haul Railway. It has the advantages of high accuracy, low-cost, easy installation, which is suitable for real-time monitoring the subgrade settlement.

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NOMENCLATURE

cen = center
i = the coordinates of the pixel of linear CCD
l = left
mid = middle
r = right
CCD = Charge-coupled Device
D = distance
GPRS = General Packet Radio Service
G(i) = the gray of i_{th} pixel of linear CCD
L = point light source
LED = Light Emitting Diode
P = position
W = window
Δ_{pixel} = the image sensing element center size of linear CCD
β = the paraxial magnification of the optical system

1. Introduction

Measurement of subgrade settlement plays an important role in the subgrade status detection. Excessive subgrade deformation and irregular settlement seriously affect the safe operation of trains.

Currently, there are some available and common methods for the subgrade settlement measurements, such as settlement monitoring piles[1,2], settlement plates[3], horizontal inclinometer[4-6], optical fiber sensors[7], GPS technology[8], etc.. However, these methods have disadvantages of low measurement accuracy, low measurement efficiency, furthermore, they are only suited for some special environment, and hard to realize the remote and automatic monitoring.

Based on the analysis and comparison of the advantages and disadvantages of the current common settlement measuring methods, a new and simple method using a linear CCD is presented and a simple measurement system is built, which collects the image data of the point light source from a linear CCD，extracts the center of the image of the point light source, and calculates the settlement value of the surface subgrade. In order to enhance the stability and adaptability of this method, some new technologies, such as self-calibration, adaptive and wireless communication technology, have been adopted.

The new device has been used in some China railway sites, such as the Jinan section of Beijing-Shanghai high-speed railway, the Yanqing and Datong section of Datong-Qinhuangdao Heavy Haul Railway. It has the advantages of high accuracy, low-cost, easy installation, which is suitable for real-time monitoring the subgrade settlement.

2. Working Principle

2.1 Measuring principle

As shown in Fig.1, a point light source is set on a settlement detecting pile, and a point position measurement device by using a linear CCD is set on the reference pile. If the railway bed has a settlement value of Δ, the point light source has the same settlement value of Δ, the image of the point light source on the linear CCD has a displacement of Δ', which is proportional to the settlement value. In fact, the displacement of Δ' can be measured directly and the settlement value can be calculated by:

$$\Delta = \frac{\Delta'}{\beta} \tag{1}$$

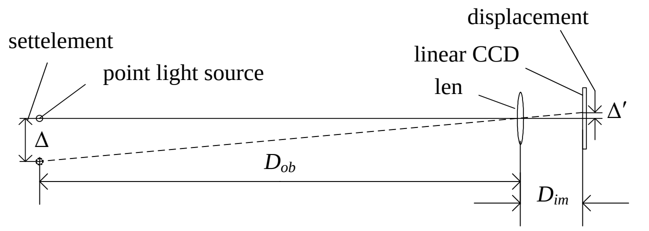


Fig. 1 Measuring principle

2.2 Spot center extraction

The CCD detector, including a linear CCD, a lens and a processing circuit, calculates the image spot position with the intensity distribution. As shown in Eq.(1), the accuracy of the spot center extraction is one of the most influencing factors to the measurement accuracy of the whole system. In addition, during the measuring procedure, there are a lot of disturbances, such as the inclining of the point light source and the linear CCD, the stray light, the beam drift caused by air disturbance, the dust, the winged insect and the flying birds and so on, which lead to the uneven distribution of the spot intensity and the shift between the spot geometric center and the spot centroid. Therefore, how to improve the accuracy of center extraction is the crux of all key technologies in this settlement measuring system.

2.2.1 Background removing

There is some redundant information, such as stray light, dust and so on. In order to improve the measuring precision, it is very necessary to eliminate these disturbances, and the procedures shown in Fig.2 are used for removing background.

As the time interval between Step.2 and Step.4 is very short, the intensity distribution of the background of image.1 and image.2 is nearly the same, therefore the background can be removed by subtracting image.1 from image.2 in the Step.5. Especially, on the existence of some points which are too bright or too dark, image those points can be removed through image subtraction and the wrong center extraction is avoided. Thus the measurement accuracy is improved.

2.2.2 Dynamic threshold selection

As the spot image only occupies a small part of the linear CCD, the majority of the image is almost useless for initial location of the spot center. In order to decrease computational complexity and increase the running speed, it is necessary to select a window fitting the range of the spot image, which is usually with the width less than 200 pixels. Because the intensity distribution of the light source on the CCD match Gaussian distribution closely, pixel with the maximum gray in the image.3 is found and regarded as the center of the window, then the spot data in the window is calculated. The mean of the maximum gray and the minimum gray is set as the dynamic threshold. On left side of the center pixel, the coordinates of the first pixel, which the gray is below the threshold, is denoted as P_l, and so does the right side, where the pixel is denoted as P_r. Then the initial location of the spot center is the mean of P_l and P_r, which is denoted as P_{mid}.

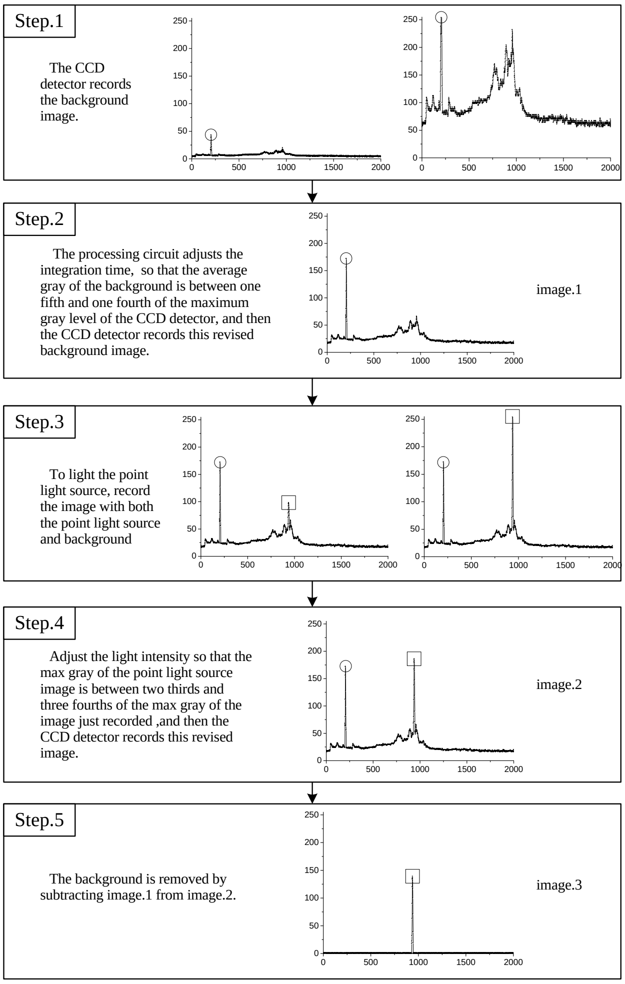


Fig. 2 Removing background procedures

2.2.3 Weighted centroid method

There are many kinds of methods to extract the spot center of the image captured by linear image sensor CCD in sub-pixel level[9,10], such as center method[9], centroid method[10,11], weighted centroid method[10], gauss curve fitting[10], paraboloid curve fitting[10] and so on. In this paper, the centroid method is chosen through a comprehensive consideration the balance between the precision and the calculation speed.

To further improve the calculation speed, a new small window, denoted as W, is selected according to the rules as following:

$$W = \begin{cases} [P_{mid} - k, P_{mid} + k], P_{mid} \text{ is a natural number} \\ [P_{mid} - k - 0.5, P_{mid} + k - 0.5], else \end{cases} \tag{2}$$

Under the two conditions, the spot center P_{cen} is given by

$$P_{cen} = \frac{\sum_{i \in W} \left(G(i)^2 \cdot i \right)}{\sum_{i \in W} \left(G(i)^2 \right)} \tag{3}$$

2.3 Settlement calculation

2.3.1 Calibration

As the settlement value of Δ is calculated base on the paraxial magnification β of the optical system shown in Eq.(1), the accuracy of paraxial magnification β is another important factor influencing the accuracy of the measurement system.

In theory, the paraxial magnification β, which can be calculated by means of object distance D_{ob} and image distance D_{im} , is given by:

$$\beta = \frac{D_{ob}}{D_{im}} \tag{4}$$

However, it's difficult to measure accurate object distance D_{ob}. As a result, the lateral magnification β must be calculated with another method. In this paper, calibration is used as following:

There are two point light source, one for measuring (denoted as *L1*), and another for calibrating paraxial magnification β (denoted as *L2*). At the first time after installment, the two point light source is lighted and captured one by one, the spot centers $P^1_{cen}(0)$, $P^2_{cen}(0)$ are obtained and saved. With the known vertical distance D_L between *L1* and *L2*, the paraxial magnification β is calculated as the equation given by

$$\beta = \frac{D_L}{\Delta_{pixel} \cdot (P^1_{cen}(0) - P^2_{cen}(0))} \tag{5}$$

2.3.1 Calculation

When the spot centers $P^1_{cen}(0)$ is obtained as the initial position without settlement, the position of *L1* (denoted as *P(0)*) is marked. Once settlement occurs at the measuring point, the position of *L1* is denoted as *P(t)*. With the paraxial magnification β, the position of *L1* is given by

$$P(t) = \beta \cdot \Delta_{pixel} \cdot \left(P^1_{cen}(t) - P^1_{cen}(0)\right) - P(0) \tag{6}$$

The settlement of the measuring point is given by

$$S(t) = P(t) - P(0) = \beta \cdot \Delta_{pixel} \cdot \left(P^1_{cen}(t) - P^1_{cen}(0)\right) \tag{7}$$

Then, the spot center (in pixel) is converted into the settlement (in millimeters).

2.4 Hardware system and GPRS technology

As shown in Fig.3, the hardware system for the subgrade settlement measurement consists of a detection module, a GPRS-Modem and a monitor computer. The settlement data is gathered and packed in a frame with the measuring location, time and data by the detection module. And then the frame is uploaded to the GPRS-Modem and transmitted to the monitoring via the internet.

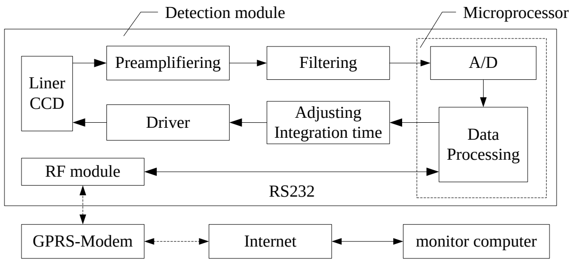


Fig. 3 Block diagram of system hardware

With the GPRS technology, the settlement data information and controlling command are transmitted remotely and wirelessly. It is very suitable for some areas without cable, such as the area along the railway line. And it could raise the efficiency of settlement data information's acquisition and transmission.

3. Experiment

To verify the measurement accuracy of the system, simulation experiments were carried out in the laboratory.

The point light source was made of two LEDs with the central wavelength of 623nm , and the two LEDs were installed on a vertical mounted guide, and the CCD detector was fixed on a platform 16m from the LED unit.

In the experiment, the initial position of the two LEDs were measured and saved at first to calculate the paraxial magnification. And then, the two LEDs were moved down 0.5mm each time to simulate subgrade settlement. At each position the image of one of the LEDs was measured 5 times, and the average of the results was the height of the LED. The experimental results are shown in Fig.4 and Tab.1 below.

actual position	measuring position		Error
mm	pixel	mm	mm
0	2316.5	0	0
0.5	2318.8	0.5	0
1	2321.5	1.07	-0.07
1.5	2324	1.62	-0.12
2	2326.1	2.07	-0.07
2.5	2328.5	2.58	-0.08
3	2330.9	3.1	-0.1
3.5	2332.9	3.52	-0.02
4	2335.1	4	0

Table. 1 Actual position, measuring position and error

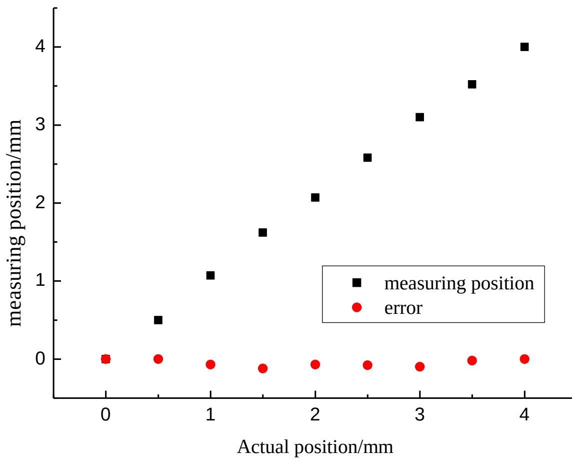
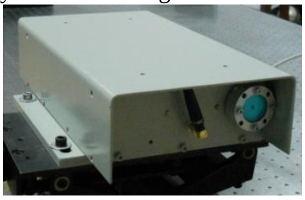


Fig. 4 Actual position-Measuring position plot

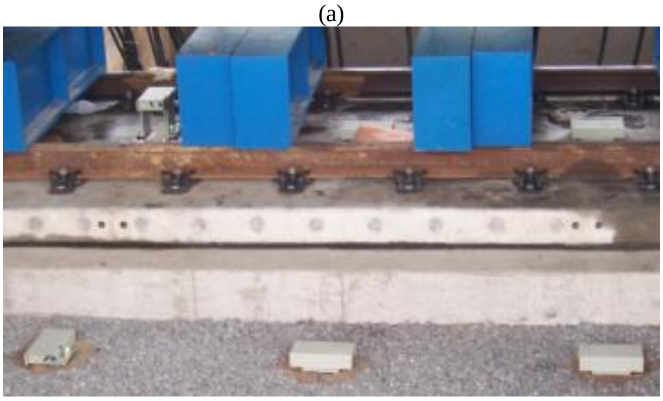
From the experiment data it is clear that the measuring error of the system, with the object distance of 16m, is less than 0.12mm with the measuring range of 4mm. When the LED is moved 0.5mm, the spot center of the image is moved 2.3 pixels on the linear CCD. If one pixel of the CCD can be resolved, the resolution is about 0.2mm. If half pixel can be resolved, then the resolution can be enhanced to about 0.1mm.

As the measurement accuracy has been verified, the device has been used in some China railway sites and some laboratories.

The device developed for measuring the subgrade settlement is shown in Fig. 5(a). And as shown in Fig.5(b) , the devices have been applied in a laboratory of the Institute of Geotechnical Engineering in Zhejiang University to measure subgrade settlement of railway ballast.



(a)



(b)

Fig. 5 (a) the developed device; (b) Applications of the device for measuring the subgrade settlement of railway ballast.

4. Conclusions

A method measuring subgrade settlement in high-speed railway with linear CCD is presented. According to the point light source imaging principle, a subgrade settlement measuring device is developed. Some new technologies, such as self-calibration technology, adaptive technology and wireless communication technology are employed to enhance the stability and adaptability. The experimental results show that the device developed can meet the requirements of monitoring subgrade settlement in high-speed railway.

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