Paper:

Distributed Micro-displacement Monitoring System for Detecting Pier Settlements

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In the construction of large-scale structures, monitoring the displacements increases security and reliability. The existing measuring methods, whether manual techniques or automatic instruments cannot deal with large quantities of objects to be measured. In order to address this problem, we develop a distributed measuring system for detecting micro-displacements to boost precision and automaticity. To reduce the influence of measurement noise, we also develop an algorithm on the basis of linear data reconciliation. The system has already been applied to detecting pier settlements of viaducts used by high-speed railways and proves to be capable to detect displacements with high precision.

Keywords: Micro-displacement Monitoring, Pier Settlement Detection, Linear Data Reconciliation

1. Introduction

In large-scale structures such as bridges, tunnels, and foundation pits, it is crucial to monitor the displacements of the structure or the surrounding environment. Detecting micro-displacements is significant for timely detection of signs of collapse, early evacuation, and timely disposal of collapses. Developing instruments for automatic and precise detection of micro-displacements has been a research hotspot. For example, a monitoring system of landslides based on optic images is proposed in [1], and systematic research results on micro-displacement monitoring technology are proposed in [2].

In the majority of existing literature, the detection of displacements of a single structure is mainly considered. However, distributed measurement equipment remains a gap in the industry, and difficulties still exist in measuring the absolute displacements of large quantities of objects. For instance, viaducts have already been utilized in the construction of high-speed railways in several countries [3], and the settlements of all the piers should be monitored to ensure security. The necessity is even more prominent in China due to the complex terrains in mountain areas, the existence of permafrost regions in Qinghai-Tibet Plateau [4], [5], the need to save land in urban areas [6], additional costs of environmental protection and maintenance [3]. All these factors contribute to the difficulty of building and maintaining roads, or embankments during the construction of high-speed railways. Although building bridges has advantages over other schemes and is often prioritized, the potential risks of pier settlement are inevitable, which threatens the stability and security during the operation of high-speed trains.

Fig. 1. Viaducts and piers of high-speed railways

Continuously welded rails are widely employed during the construction of high-speed railways, which enables high-speed trains to operate smoothly. However, for railways constructed on bridges, especially large-span bridges with high-rise piers [7], both uniform and non-uniform pier settlements have a negative impact on parallelism and smoothness of the rails. In [8] and [9], mapping relations of pier settlements on two types of rails are analyzed and analytical expressions are proposed. It can be derived that for the commonly used structure of bridges, pier settlements generate a low-frequency stimulus to high-speed trains, which might trigger resonance and enormously enlarge the impact.

As a result, measuring and monitoring settlements of piers is essential for ensuring security, which is mainly conducted manually nowadays. Triangular elevation survey using total station [10] and leveling [11] are the major conventional methods applied to measure the absolute position of piers. Such schemes require specific observing positions and manual operation, which are time-consuming, error-prone, and make real-time measurements nearly impossible.

In this paper, we propose a highly automatic system with the capability to measure, estimate and predict the settlement of piers, including a kind of novel measuring device, data processing methods, and the predicting algorithm. The remainder of this paper is organized as follows: In section II, a detailed introduction to our measuring device and its major components is proposed. In section III, the problem of pier settlement is analyzed in detail. A mathematical model and the corresponding solution are proposed. In section IV, an application example with the background of estimating pier settlements is proposed to verify the effectiveness of the algorithm.

2. Hardware System

The hardware system we apply to monitor micro-displacement is a distributed system of Laser Linear CCD Displacement Meter. In this section, we will introduce the composition and functions of each device, as well as the workflow of the entire monitoring system.

2.1. Composition of the device

The composition of the device is illustrated in Figure 2, wherein the installed modules include wireless communication antenna 1, shell 2, Laser Linear CCD sensor 3, telescopic equipment 4, adjustment device 5, laser emitter 6, fixing plate 7 and 8, shell 9 and 10. The device is also equipped with built-in batteries, wireless communication modules, and microprocessors to process and upload measurement data.

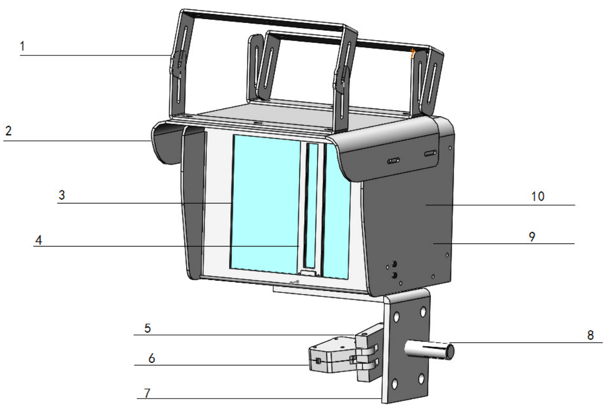

Fig. 2. Composition of the device

GPS antenna wire and wireless communication module are applied to obtain the location of the device and to get in contact with the central server through the mobile wireless network. This device can obtain access to the Internet through GPRS/3G or other protocols, where the redundancy of communication mode increases the reliability of data transmission.

The laser line array detection sensor consists of a line CCD array and a mechanical structure for scanning, which measures the shape and center position of the laser

Fig. 3. A device in operation

spot that is irradiated on the surface of the sensor. Line CCD array scans a straight line to obtain the light intensity on it so that the light intensity distribution on the sensor surface can be obtained after horizontally scanning. Subsequently, the data collected can be stored in the memory of the microcontroller. Raw data obtained by the sensor includes the light intensity at the sampling point array, so that the position with maximum light intensity can be estimated using the method of interpolation, which will be later considered as the center of the light spot. Using this sensor and calculating method, the minimum resolution of the system can be up to 0.05mm in a well-lit environment.

The laser transmitter on the device is mounted on a rotating head, which controls the horizontal and vertical position of the laser transmitter, and can be properly adjusted so that the emitted laser is irradiated right on the measuring surface of the sensor. After the device is fixed to the piers, the settlements of piers will be reflected in the relative displacement of the laser light spot, which can be easily detected with the sensor installed in the device.

An efficient power management module significantly prolongs the interval between recharging the battery. The device has a built-in clock and wake-up device, powered by a separate battery as an independent power source. After the device has completed the measurement task, the start-up time for the next measurement is set and the measurement device is completed powered off. The host is re-activated by the wake-up device at a previously set moment in order to prepare for the next measurement.

2.2. Measurement principles and workflow of the equipment

Before starting the measurement, one device should be installed at the measuring position of each pier, and the

Fig. 4. A device installed on a pier

laser transmitter on the device should be adjusted so that the emitted laser directly points to the sensor of the device installed on the previous pier. By scanning the laser spot, the device can estimate the shape of the spot and calculate the position of its center. When the pier settlements take place, the relative position of the laser spot changes, which can be detected by the device through precise measurement. The relative displacement of adjacent piers can be calculated by measuring changes in the relative position of the laser spot, and the settling levels of a series of piers can be calculated by using the reference point/measurement reference point.

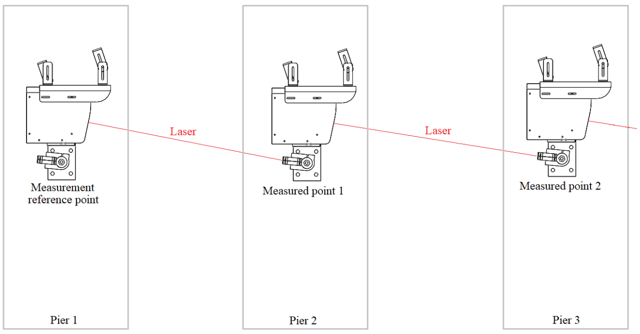

Fig. 5. Architecture of the system

After the measuring device is launched, the communication module will be connected to the central server via the wireless network to obtain time information. The internal clock of the device will then be synchronized, and the next start-up time will be set simultaneously. The device activates its laser transmitter which emits laser towards the sensor of the device it points to. Using its own laser line array sensor, the device measures the position of the laser spot from the next device and compares the position with the reference position, which is previously set when the device is installed in order to obtain the relative displacement between the two piers. After measuring the location of the laser spot, the device uses the built-in wireless communication module to send the measurement data to the specified server for storage and analysis of the data through communication methods such as GPRS or 3G. Power off the measuring device, while the wake-up device continues to operate under a low power consumption, which will restart the measuring device when the time set for the next measurement reaches.

2.3. The meaning of the system

Under the current design of "bridges instead of roads" for high-speed railways, the majority of the railways are built on viaducts, where a pier is needed approximately every 35 meters, which means that nearly 30 piers will be built every kilometer. During the process of construction and maintenance, settlements and displacement of these piers need to be measured regularly. At present, subsidence and displacement measurements of buildings, including bridge piers, are mostly conducted using instruments such as Total Station or Static Level, where large quantities of manual operation are required, especially when there are a large number of piers. At the same time, many bridges and piers are located in special geographical environments, manual operation can also be risky. Therefore, the cost of manual measurement is very high using the existing measurement methods. Although automatic measurement robots have emerged on the market currently, they apply similar measuring methods with manual operation, and they are expensive and strict with working environments, which greatly restricts the application of such robots.

Considering the characteristics of the bridge piers built for high-speed rails and the specific requirements for settlement measurement, this equipment puts forward and realizes a highly automated and precise method of settlement measurement which has a great advantage over the traditional method. The equipment can achieve long-term unattended measurements with its accuracy reaching 0.1mm level and can upload real-time measurement data to the central server for further data processing. Compared with manual measurement methods, its operating cost is less than 2 percent of the cost of manual operation, but with better accuracy and character of real-time. This device fills the gap in automatic, high-accuracy, and low-cost equipment for measuring pier settlements, which significantly improves the efficiency of monitoring bridges and piers, and makes an important contribution to the construction process of high-speed railways in China.

3. Algorithm

In this system, each measuring device is equipped with a CCD sensor with high-precision, which can detect relative displacement between two adjacent piers accurately. However, the system is designed to monitor large-scale objects, for example, viaducts as foundations of high-speed railways which contain hundreds of piers. Under the influence of inevitable measuring noise, the distributed architecture of the system poses a challenge to the accuracy of the measurement of tiny absolute displacement. How to ensure the overall measurement accuracy under this system structure is an urgent engineering problem. In this section, we propose an algorithm based on data reconciliation to improve the precision of the absolute displacement of each pier, which is calculated using the measurement of relative displacements given by all the devices.

Assume that there are $n+1$ piers whose settlement levels need to be measured, and the absolute displacements of the first and the last one are assumed to be known. Let x_i indicate the absolute displacement of the i-th pier, $i = 1,2,...,n+1$. Without loss of generality, we assume that $x_{n+1} = 0$ and x_0 is already known. Let y_i indicate the output of the i-th device. According to the previous section, we have

$$y_i = x_i - x_{i+1} + \varepsilon_i, i = 1,2,...,n \quad \ldots\ldots \quad (1)$$

where ε_i indicates the zero-mean gaussian measuring noise.

Let

$$b = \begin{bmatrix} x_1 & x_2 & \ldots & x_n \end{bmatrix}^T$$

indicate the true value of settlement levels of each pier, and

$$y = \begin{bmatrix} y_1 & y_2 & \ldots & y_n \end{bmatrix}^T$$

denote the output of all devices. Define matrix

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

and noise vector

$$\varepsilon = \begin{bmatrix} \varepsilon_1 & \varepsilon_2 & \ldots & \varepsilon_n \end{bmatrix}^T$$

and assume that $\varepsilon \sim N(0,Q)$, where $Q = diag\left(\sigma_1^2, \sigma_2^2, ..., \sigma_n^2\right)$ is already known, we have the measurement equation

$$y = Db + \varepsilon \quad \ldots\ldots \quad (2)$$

and the constraint equation

$$x_1 = 0 \quad \ldots\ldots \quad (3)$$

In order to convert the constraint to the form of matrices, define

$$A = \begin{bmatrix} 1 & 0 & 0 & \ldots & 0 \end{bmatrix}$$

and

$$c = 0$$

so that the constraint can be rewritten as

$$Ab = c \quad \ldots\ldots \quad (4)$$

Our aim is to obtain the optimal estimation which satisfies the constraint and is as consistent with the measurement as possible. Therefore, we define the following optimization problem:

$$\min_{\hat{b}} \left(y - D\hat{b}\right)^T Q^{-1} \left(y - D\hat{b}\right)$$

$$s.t. A\hat{b} = c$$

where $\hat{b}$ indicates the estimation to be obtained. According to [12], the least-squares solution to the linear data conciliation problem under the constraint (4) is given as follows

$$\hat{b} = \hat{b}_0 + \left(D^T Q^{-1} D\right)^{-1} A^T \cdot$$

$$\left[A\left(D^T Q^{-1} D\right)^{-1} A^T\right]^{-1} \left(c - A\hat{b}_0\right) \quad \ldots\ldots \quad (5)$$

where

$$\hat{b}_0 = \left(D^T Q^{-1} D\right)^{-1} D^T Q^{-1} y \quad \ldots\ldots \quad (6)$$

is the unconstrained optimal solution.

In the case of our system, the problem can be further simplified because both A and D are known, and D is invertible. Therefore we have

$$\hat{b}_0 = D^{-1} y \quad \ldots\ldots \quad (7)$$

$$D^{-1} = \begin{bmatrix} 1 & 1 & 1 & \ldots & 1 & 1 \\ 0 & 1 & 1 & \ldots & 1 & 1 \\ 0 & 0 & 1 & \ldots & 1 & 1 \\ & & \ldots & & & \\ 0 & 0 & 0 & \ldots & 1 & 1 \\ 0 & 0 & 0 & \ldots & 0 & 1 \end{bmatrix} \quad \ldots\ldots \quad (8)$$

Based on this result, we will give an analysis of the performance of this algorithm. Define the sum of the last $n-k$ variance items as

$$\Sigma_k = \sum_{i=k}^{n} \sigma_i^2$$

and some matrices can be simplified as follows

$$\left(D^T Q^{-1} D\right) = \begin{bmatrix} \Sigma_1 & \Sigma_2 & \Sigma_3 & \ldots & \Sigma_{n-1} & \Sigma_n \\ \Sigma_2 & \Sigma_2 & \Sigma_3 & \ldots & \Sigma_{n-1} & \Sigma_n \\ \Sigma_3 & \Sigma_3 & \Sigma_3 & \ldots & \Sigma_{n-1} & \Sigma_n \\ & & \ldots & & & \\ \Sigma_{n-1} & \Sigma_{n-1} & \Sigma_{n-1} & \ldots & \Sigma_{n-1} & \Sigma_n \\ \Sigma_n & \Sigma_n & \Sigma_n & \ldots & \Sigma_n & \Sigma_n \end{bmatrix} \quad (9)$$

$$\left[A\left(D^T Q^{-1} D\right)^{-1} A^T\right]^{-1} = \frac{1}{\Sigma_1} = \frac{1}{\sigma_1^2 + \sigma_2^2 + \ldots + \sigma_n^2} \quad (10)$$

Let

$$K = \left(D^T Q^{-1} D\right) A^T \left[A\left(D^T Q^{-1} D\right)^{-1} A^T\right]^{-1}$$

we have

$$K = \begin{bmatrix} 1 \\ \Sigma_2/\Sigma_1 \\ \Sigma_3/\Sigma_1 \\ \cdots \\ \Sigma_{n-1}/\Sigma_1 \\ \Sigma_n/\Sigma_1 \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots (11)$$

and the optimal solution can be rewritten as

$$\hat{b} = D^{-1}y + K\left(c - AD^{-1}y\right) \quad \ldots\ldots\ldots (12)$$

This equation gives the least-squares estimation of the absolute displacement of each pier under the constraint and requires the statistical properties of the gaussian noise to be known. In the case of our system, compared with data reconciliation applied for chemical processes, there are no unmeasurable variables, but we only have one constraint condition. Therefore, the major factor that influences the precision is still measurement noise. Furthermore, if $\sigma_1^2 = \sigma_2^2 = \ldots = \sigma_n^2$, the result (12) can be further simplified, which is the same with data adjustment.

4. Application to Detecting Pier Settlements

In this section, we will consider the case of detecting pier settlements and compare the effectiveness and precision of the two methods, namely data reconciliation (equation (12)), inverted matrix (equation (7)).

Assume that $n = 50$, where the first and the last pier are both specially reinforced so that $x_0 = x_{n+1} = 0$. The real absolute displacement b is randomly generated on the premise that the relative displacement between any two piers will not be too large. Each item of $\sigma_i^2, i = 1,2,\ldots,n$ is also randomly generated, and Q is assumed to be known. In figure 6, the true value of the absolute displacement, the estimation $\hat{b}_0$ given by equation (7), and $\hat{b}$ given by the data reconciliation algorithm are illustrated. The corresponding estimation error is shown in Figure 7.

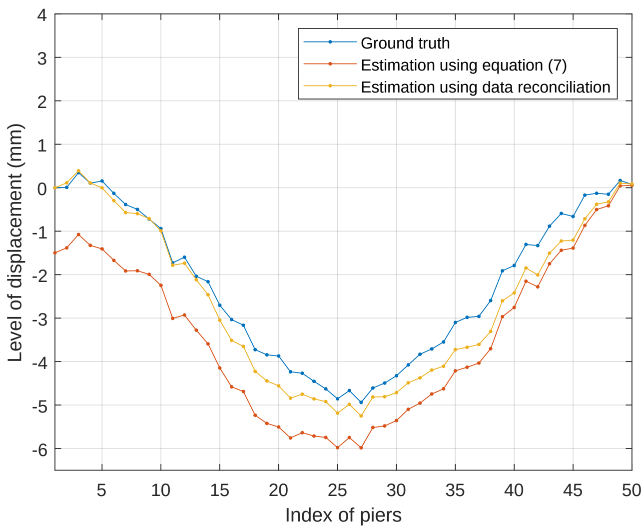

Fig. 6. True value and estimation of absolute displacement

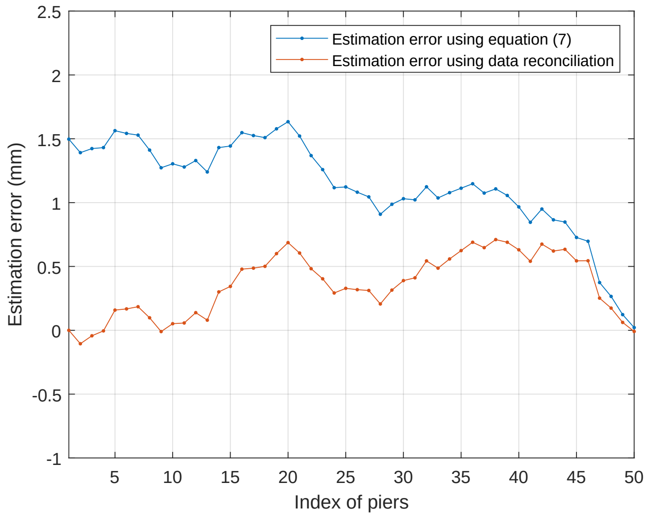

Fig. 7. Estimation errors of different methods

It is shown in the results that the influences of measurement noise accumulate and cause large estimation errors. Although there is only one constraint, it still significantly reduces the estimation error when data reconciliation is applied. In this case, piers in the middle have relatively large displacements, but measurements of relative displacements provided by each device are tiny and will not trigger the alarm.

Index	Overall MSE		Error reduction
	eqs. 12	eqs. 7	
1	0.152	0.445	65.8%
2	0.045	0.075	40.0%
3	0.042	0.265	84.2%
4	0.249	0.384	35.2%
5	0.050	0.181	72.4%

Table 1. Overall performance of the two methods

Using mean square error (MSE) as a numerical index that represents the overall error, we conducted the simulation experiment a few more times with randomly generated measurement noise. A comparison of the performance of the two methods is shown in Table 1. The overall MSE can be reduced by 35% $\sim$ 85% using data reconciliation (equation (12)) instead of the inverted matrix (equation (7)), which validates the effectiveness of our method.

With the application of this algorithm, the absolute displacements of all piers can be calculated with relatively high precision, so that potential danger can be effectively detected.

5. Conclusions

Aiming at satisfying the urgent need to estimate the absolute displacements accurately and automatically, we have proposed a distributed measuring system that is composed of our Laser Linear CCD Displacement Meters. The structure of the system, the functions of the devices as well as the workflow of the system have been introduced in this paper, illustrating its capability to resolve such engineering problems. To fully utilize the reference measurement points, an algorithm has been developed on the basis of linear data reconciliation to reduce the loss of accuracy. Finally, a simulation example based on the estimation of pier settlements has been proposed, illustrating the effectiveness of the algorithm. In summary, our system has filled the gap in the field of automatic instruments for displacement measurements, which provides a high-precision, automated solution for monitoring key objects. This system can be widely applied to monitor high-formworks, foundation pits, stages, tunnels, and bridges, which satisfies the need for automated displacement measurement instruments, reduces the cost, and improves the reliability of monitoring.

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