A Real-Time System for Monitoring Distant Dynamic Displacement of Structures

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Abstract  Based on digital image processing technique, a real-time system is developed to monitor and detect the dynamic displacement of engineering structures. By processing pictures with a self-programmed software, the real-time coordinate of an object in a certain coordinate system can be obtained, and further dynamic displacement data and curve of the object can also be achieved. That is, automatic gathering and real-time processing of data can be carried out by this system simultaneously. For this system, first, an untouched monitoring technique is adopted, which can monitor or detect objects several to hundreds of meters apart; second, it has flexible installation condition and good monitoring precision of sub-millimeter degree; third, it is fit for dynamic, quasi-dynamic and static monitoring of large engineering structures. Through several tests and applications in large bridges, good reliability and dominance of the system is proved.

Keywords  dynamic displacement; real-time monitoring and detecting; sub-pixel; system calibration; dynamic tracking

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Introduction

Measured dynamic displacement data of a structure is valuable in dynamic monitoring, detection and analysis [1-3]. However, at present, real-time monitoring and detection of dynamic displacement of large engineering structures is a difficult problem, due to the limitation of the existing measurement device and technique. According to detection results, existing detection methods for dynamic displacement can be divided into two kinds: the direct method and the indirect method [4]. For the former method, a datum point should be contained, which is fixed relative to the dynamic point, the relative displacement between dynamic and fixed point is detected by a sensor. Because of the less space occupied for the mini-structure, a fixed datum point can be found all the time. A high degree of measurement precision and dynamic response can be obtained, so automatic processing and real-time output can be carried out. It is difficult to find a fixed datum point around a dynamic point of the large structures, such as long-span bridges, high-rise structures and so on. Along with the increase of deformation of the measured object, the sensor can fail, which results in the failure of dynamic measurement. For the latter method, the measurement apparatus is small and convenient, but it has a fatal defect of lower measurement precision and lower reliability. As for monitoring and detecting dy-
dynamic displacement, because of the quantity of information, complexity of the measurement apparatus and data processing, expensive apparatus and strict working conditions of advanced and new technology, there are many problems in achieving automatic processing and real-time output. In the light of the foregoing, based on the direct method, a real-time system is developed to monitor and detect the dynamic displacement of large engineering structures. For this system, the untouched remote monitoring technique is adopted, the real-time processing data and output can be achieved, and it has flexible installation condition, good monitoring precision, lower cost, and convenient operation.

1 System structure

The real-time monitoring and detection system is divided into two parts: hardware system and software system.

1.1 Hardware system

The hardware system of the real-time monitoring and detection system is mainly made up of image grabbing equipment, a computer and system calibration board (Fig.1). An industrial CCD camera and image grabbing card are adopted by the image grabbing equipment. Different lenses can achieve different distant observations; especially, the long-focus lens can observe hundreds of meters. Generally, the image grabbing card can reach speeds in excess of 25 frames per second. Because of the frequency of large structures within a few Hz, it can meet the require ments of the low-frequency vibration detection for large structures. Because the overall performance of the PC has been greatly improved, and it has good universality, the PC is chosen in this system. The system calibration board can use a wooden clamp board, plastic board or thin metal board. There is a specially designed black and white geometry figure that is 25 square plot points on the board. It does not require an electronic device and electric source, and it is only fixed on the measured structure through the adapter.

1.2 Software system

The software system of the real-time monitoring and detection system is mainly made up of a real-time operating system and real-time image gathering and analysis system. At present, Windows XP is used and more mature as a platform, which is adopted for this system to run the software. In this platform, VC++ programming language is used to achieve image gathering. By using multithread programming technique, the pictures in the cache are processed. Also, automatic tracking and object recognition are achieved. Finally, the result is exported. It ensures that the system is in real time.

2 Working principle and realization flow

2.1 System installation

The system calibration board is fixed on the measured structure. The “X-Y” axis of the calibration board’s coordinate system parallels with the engineering system. For example, the “lateral-vertical-horizontal” of the large bridge is the “X-Y-Z” axis of the engineering coordinate system, the “principal-secondary” axis of high-rise buildings is the “X-Y” axis of the engineering coordinate system, and its plumb line direction is the Z-axis.

For monitoring the bridge, the equipment used for image gathering are set up along the bridge axis on a fixed point. The point may be on the ground, bridge pier or platform, where the camera can gather images of the systematic nominal board. The principal optical axis of the camera can be adjusted into facultative posture, such as angle of elevation, angle of depression and angle of deflection (Fig.2).

During dynamic displacement monitoring, once the system is calibrated, the principal optical axis of the
camera should be fixed.

![Fig 2 Diagram of system installation](image)

### 2.2 System calibration

System scalar is creating the correspondence relationship between the image coordinate system of the CCD camera and the engineering system. By using the centroid method of the sub-pixel technique, the data of object points are abstracted. First, the image is changed into binary. Then, the object region will be identified. Because of the existence of noise in the image, it may bring some errors when the image is changed into binary. Also, the boundary of the object region will have a blur. To eliminate its impact on the algorithm precision, object points are preprocessed with turn-on and closing. If the object region is chosen properly, the precision of 0.2-0.5 pixels can be achieved[5-7].

Finally, the centroid of the plot point \((x_0, y_0)\) will be solved by Eq.(1).

\[
x_0 = \frac{\sum_{i,j \in S} i I(i,j)}{\sum_{i,j \in S} I(i,j)}
\]

\[
y_0 = \frac{\sum_{i,j \in S} j I(i,j)}{\sum_{i,j \in S} I(i,j)}
\]

The image is gathered by a CCD camera, which is a mapping of the image in the calibration board. The mapping function depends on the geometrical relationship of the image coordinate system of the camera and the engineering system. This is a linear relationship for the ideal optical system. However, there are complex errors in the practical optical system, such as image errors, distortion errors, influence of ragged register plane and so on. They result in a complex nonlinear relationship\[^{[8,9]}\]. In this study, the cubic polynomial fitting method is adopted to establish the corresponding relationship between the two. That is:

\[
X = \sum_{i=0}^{3} \sum_{j=0}^{3} a_{ij} u^i v^j, \quad Y = \sum_{i=0}^{3} \sum_{j=0}^{3} b_{ij} u^i v^j
\]  

where \(X, Y\) are the engineering coordinates of the object point; \(u, v\) are the corresponding image coordinates; \(a_{ij}, b_{ij}\) are the coefficients of the polynomial. There are 25 points in the demarcation board composition square dot matrix spacing. Their engineering coordinates are known, and the image coordinates of the corresponding points in the images can be obtained. According to least squares method, it demands the error sum of squares \(\varepsilon\) of 25 plot points being smallest. \(\varepsilon\) is given by:

\[
\varepsilon = \sum_{i=0}^{24} \left( X_i - \sum_{j=0}^{3} \sum_{i=0}^{3} a_{ij} u^i v^j \right)^2
\]

That is:

\[
\frac{\partial \varepsilon}{\partial a_{ij}} = 2 \sum_{i=0}^{24} \left( X_i - \sum_{j=0}^{3} \sum_{i=0}^{3} a_{ij} u^i v^j \right) u^i v^j = 0
\]

The solution of Eq.(4) is:

\[
\sum_{i=0}^{3} \sum_{j=0}^{3} a_{ij} \left( \sum_{l=0}^{3} u^l v^l \right)^{s+t} = \sum_{i=0}^{3} X_i u^i v^j
\]

By substituting \(b_{ij}, Y\) for \(a_{ij}, X\) in Eq.(5) gives:

\[
\sum_{i=0}^{3} \sum_{j=0}^{3} b_{ij} \left( \sum_{l=0}^{3} u^l v^l \right)^{s+t} = \sum_{i=0}^{3} Y_i u^i v^j
\]

where \(s=0,1,2,3; \quad t=0,1,\ldots,3-s; \quad s+t \leq 3\). There are two groups of linear system of equations that is composed of 10 equations, and each system contains 10 unknown numbers. The equations are solved separately, and then the parameters \(a_{ij}\) and \(b_{ij}\) can be obtained. That is to say, coordinate conversion between the two systems is achieved.

To ensure the real-time nature of the system, region growing algorithm is adopted, which can mark the control points and calculate cancroids of pixels. Then automatic calibration is achieved between the engineering coordinate and image coordinate. In general, by using a camera to capture a picture of the calibration board, it can complete the system calibration before dynamic measurement. That is, the relationship of the two coordinates is established.
2.3 Automatic tracking of moving object in image series

The purpose of moving object tracking is to analyze the image series screened by the sensor and account for the location of objects in each image. The reliability and precision are two important indexes during the tracking process\[^8\]. In the near distance, the object has a certain area, so windows center tracking or matching tracking are used to assure the stability and precision of tracking. The windows center tracking based on sub-pixel is introduced in this study, so the tracking windows can hitch the object and account the object center in windows\[^10,11\]. Noise disturbance during tracking is the main factor that affects the tracking precision. During object tracking, the noise mainly originates from two ways: one is the inherent noise of the system and the sensor; the other is the surroundings disturbance around objects, which will bring errors when accounting the center of the object. The precision of estimating the object center is very sensitive to the center position of the object window. When images and division arithmetic and the dimension of the object window are certain, the average error of estimating the object center has a direct ratio to the difference of the real position of the object center and windows center. That is to say, the more the object windows center is near to the object center, the more average error is small. Based on this property, while estimating the object center, the distance between the windows center position and object center can be used as feedback to revise the position of the windows center. This allows us to approach the object center and close nearest to the discrete value of the object center to reduce error. Fig.3 shows the process of the tracking recursion calculation.

2.4 Dynamic observation

A camera is used to continuously gather images of the calibration board, which is vibrating with the structure. By processing the pictures, the image coordinates of the point is obtained, then the object coordinate of the dynamic point are solved. According to the speed of image gathering, the two-dimensional displacement data of the dynamic point and time interval curves are exported. Considering the time interval between the image series, the structure velocity, acceleration and other parameters can be obtained\[^12\]. Fig.4 shows its operating flowchart.

3 Tests and engineering instances

To evaluate the system detection precision, we have carried out several multi-distance static and dynamic field tests.

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Fig.3 Diagram of the recursion calculation of the object tracking window center

Fig.4 Flowchart of systematic data processing
3.1 Static tests

In the distance 50 m and 70 m, 25 coordinate known points are designed on the calibration board. Then, the image processing results are compared with given values and measurement error can be obtained. 50 m distance measuring error is ±0.194 mm, and 70 m distance is ±0.226 mm.

3.2 Circular motion tests

The motor takes the object point making circular motions at different speeds. Fig.5 and Fig.6 show the displacement locus diagrams of two kinds of 50 m distant circular motions.

3.3 Engineering instances

3.3.1 Bridge detection

In recent years, traffic and transportation have developed rapidly in China. The bridges built in different years take on ever-increasing car flow in traffic. The safety detection of the bridge is of universal concern. Several bridges are detected by this system. Fig.7 and Fig.8 show the dynamic displacement time-travel curves of two bridges racing and jumping tests separately.

3.3.2 Icing test detection of high-voltage cables

Along with the development of the electric industry, the 750 kV and 1 100 kV extra high voltage projects have been enforced in China. In winter, the high-voltage cables often suffer icing hazards in the north and mid-west of China. Ice accretion will induce a violent motion of the cable, which causes a tensile force to the insulator string, electric substation fitting and tower. This may lead to failure. When the cable is jumping, the gap between cables is reduced. It may cause flashover between phases. Therefore, the ice accretion jump of the cable is considered by transmission line design in heavy ice zone. Its relevant theory is studied at home and abroad, and the empirical formula is achieved. However, there are no precedents to follow for high voltages of 750 kV and above.
parameters are obtained by simulated test. It is very important for verifying the theoretical analysis. In a Wuhan research institute, we put to a series of simulated ice accretion tests a large-span cable in a large outdoor test ground. The dynamic displacement data of the jumping cable are obtained by this system, including the biggest jump amplitude, the displacement time-travel curves, cycles, attenuation process, and insulator string movement and so on. Fig.9 shows the dynamic displacement time-travel curves of the midpoint of a 320-m span cable unloading at 100%.

4 Conclusions

1) To detect the displacement of a specific point, the practical calibration and dynamic tracking method this system adopts not only controls linear distortion but also effectively overcomes the problem brought inevitable between the image plane and object plane due to influences of obliquity and deflection angle and the atmosphere. Without using a power supply, the system calibration board is so simple and convenient to setup fast that it is widely applied in many complex practical engineering instances.

2) Two-dimensional and remote-distance dynamic displacement is detected by untouched monitoring techniques. Measuring distance, precision and speed of response can meet requirements of low-frequency vibration detection methods for large structures. Real-time data can be processed and digital information, data table and time-travel curve would be obtained simultaneously.
3) Except for our independently developed software, other equipment, such as the camera, lens, and image grabbing card adopt general standard products. The following advantages are obtained: ① ensure high reliability of the system; ② according to engineering requirements, it can choose corresponding equipment and develop new programs to extend application range; ③ greatly reduces the cost of this integrated system, to setup simply and conveniently.

4) Current data gathering speed is 25 frames per second, which is due to our video CCD camera. First-order vibrating information of large structures would be obtained completely. In future studies, to get high-order information, data capturing speed should be improved and a high-speed image grabbing card or camera should be used. Finally, information of velocity and acceleration would also be obtained.

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