Monitoring Instantaneous Dynamic Deformation of A High-rise Building by Digital Photography

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Abstract. In order to make up for the shortcomings of conventional measurement methods in measuring instantaneous deformation of high-rise buildings, in this paper, we propose the method of IS-PPT (Image sequence-photographic proportional transformation) based on digital photogrammetry to monitor the instantaneous Dynamic deformation information of high-rise buildings. The specific actions of this method are: Setting up the camera in the right position to make the monitoring object in the center of the image and setting five stable reference points in the vertical direction of the objective lens at the same time, then selecting feature points as monitoring points on high-rise building. According to the method of IS-PPT, the pixel variation of the monitoring point on the image plane is transformed into the actual amount of change in the object plane, thus, the actual instantaneous deformation value of high-rise building and its regulation of variation with time are obtained. This method can warn potential dangers in real time and provide data support for maintenance of high-rise buildings timely.

1. Introduction
With the development of global construction industry, the number of high-rise buildings are increasing in the whole world, and super-high-rise buildings are also springing up like bamboo shoots after a spring rain driven by new technology. The structure of core tube is widely used in super high-rise buildings in the world, core tube structure full name is center shear tube structure. That is, in the central part of the building, the central core tube is formed by elevator shaft, staircase, ventilation shaft, cable well, public toilet and part of the equipment, and an outer frame inner tube structure is formed with the outer frame to be poured with reinforced concrete. At present, the research on super high-rise buildings mainly focuses on the design method of the structure itself and the aspects of anti-tilting, wind resistance, earthquake resistance and so on. But there is relatively little research on the construction process of the structure. With the increase of building height, the deformation of construction and use stage has become a problem worthy of consideration[1]. Therefore, it is great significance to monitor the high-rise building in instantaneous dynamic state in construction and operation, and it is becoming more and more imperative.

The super high-rise building project is huge and the period of construction is long, the deformation
of the building is relatively complex during the period of construction and operation. A variety of monitoring instruments and methods are needed to monitor the settlement, tilt, cracks and other conditions of the building, then achieve the goal of controlling the quality of the building. A large number of observation data have been produced, as a result of the combination of a variety of observation techniques, it is difficult to analyze the multiple data sources.

At present, the precision leveling, surveying robot and other monitoring methods used for settlement observation, although the accuracy of high precision, but are limited by topographic and geological conditions, unable to monitor multiple deformation points at the same time[2]. Strain measurement and tilt measurement can monitor the deformation of the deformation body automatically, but only can monitor the local deformation information; The sensor measurement and the GPS technology can monitor, record and calculate automatically, but the GPS receiver or antenna is required to be arranged at each monitoring point, and the GPS receiver and the antenna must contact with the monitoring object directly, at the same time it is affected by the external environment more easily; 3D laser scanning can monitor multiple points at the same time, but the monitoring period is so long that it is difficult to realize the instantaneous dynamic deformation information of the monitoring object. To sum up, the current monitoring technology can not realize the characteristics of simple, fast, instantaneous, automatic, and non-contact monitoring at the same time of transient dynamic deformation of high-rise buildings[3].

With the rapid development of digital photography technology, we propose the method of IS-PPT in this paper. The data acquisition device is non-measurement digital camera. Setting reference points on the vicinity of high-rise buildings, making the camera is roughly perpendicular to the reference plane[4]. The system of monitoring and warning for building deformation is developed, it can obtain the instantaneous deformation information of the whole High-rise building continuously and transmit the data to the computer for data processing in real time. For the high-rise building under construction, it is easy to realize the periodic comparative analysis of the deformation for the building structure by non-contact measurement. Through experiments, the deformation and deformation law of each monitoring point of the tall building under complex load and external environment conditions are obtained, which provides reference data for the safe construction and operation of high-rise building. It solves the problems that the traditional measurement methods can not monitor multiple points at the same time and obtain the instantaneous deformation information.

2. The system of high-rise building instantaneous deformation monitoring

2.1. The Elimination of objective lens aberration in non-measurement digital camera

When photographed in a non-measuring digital camera, the inner and outer azimuth elements are unknown. At the same time, the inner and outer azimuth elements of the image sequence change slightly influenced by the noise of the camera itself, therefore the inner and outer azimuth elements are different at different times[5]. At this time, the algorithm suitable for measuring digital camera is no longer applicable. In order to solve the problem of strict requirements for internal and external azimuth elements in the process of calculation, the method suitable for non-measurement digital camera is direct linear transformation method (DLT). The method is an algorithm that converts the image coordinates into spatial coordinates directly. The formula is as follows:

\[
\begin{align*}
L_1X + L_2Y + L_3Z + L_4 &= 0 \\
L_5X + L_6Y + L_7Z + 1 &= 0 \\
L_8X + L_9Y + L_{10}Z + L_{11} &= 0
\end{align*}
\]

In formula (1): x, z are the coordinate of the image point with any point as the origin; X, Y, Z are the spatial coordinate of the object point corresponding to the image point, Li (i=1, 2, …,11) are unknown coefficients to be calculated. In this way, the spatial coordinates of the object can be calculated directly from the image coordinates, the transformation from image coordinate system to
image space auxiliary coordinate system is avoided.

All optical lens exist distortion problems, it belongs to geometric distortion of imaging, it is a distortion and deformation phenomenon caused by the different magnification of the image in different regions of the focal plane, the degree of this deformation is increased from the center of the picture to the edge of the picture gradually which is reflected more clearly at the edge of the picture. The problem is especially serious for zoom lenses, generally speaking, when shooting at the wide angle end, the edge of the picture tends to protrude outward, which is called bucket distortion; When shooting with a remote camera, the edge of the picture is often concave inward, which is called pillow distortion [6]. For common digital cameras, the distortion should be taken into account. In this paper, in order to eliminate the distortion difference of the camera, the corresponding mathematical model is established.

$$\Delta x = (x - x_0)r^2K_1$$
$$\Delta z = (z - z_0)r^2K_1$$
$$r = [(x - x_0)^2 + (z - z_0)^2]^1/2$$

In formula (2): Δx, Δz are the correction terms of objective lens distortion difference; x₀, z₀ are coordinate of the main points of the image; r is radius vector.

Through calculation, the image coordinate after correcting the distortion difference can be obtained:

$$x + \Delta x = x + (x - x_0)r^2K_1$$
$$z + \Delta z = z + (z - z_0)r^2K_1$$

(3)

2.2. Calculation of actual deformation of deformation points by Time Base Line parallax method(TBP)

The principle of Time Base Line Parallax method (TBP) is: In order to ensure that the internal and external azimuth elements remain unchanged, the monitoring station is fixed. The same time the image plane is parallel to the object plane. At the beginning of the experiment taking a piece of image as a reference photo, then taking a set of image sequences at the same time interval, measuring the size and direction of the displacement of each deformation point on the image at the same time interval, to points where no deformation occurs, there is no displacement at the point[7]. When the deformation point is deformed from A to B, the formulas of the actual deformation ΔX and ΔZ are as follows:

$$\Delta X = \frac{Y}{f}\Delta P_x = A\Delta P_x$$
$$\Delta Z = \frac{Y}{f}\Delta P_z = A\Delta P_z$$

(4)

In formula (4): Y is the distance from the photography center to the object plane; f is The distance from the photography center to the reference plane; ΔPₓ, ΔPᵧ are Horizontal and vertical deformation values of monitored points on the image plane; ΔX, ΔZ are Horizontal and vertical deformation values of monitored points on the object plane;

In theoretical, the value of coordinate variation of reference point should be zero in the process of deformation monitoring, but it cannot be guaranteed to be zero due to the existence of environmental impact and man-made error. The error of deformation points is corrected by calculating the barycenter coordinates of multiple reference points. According to the coordinate value of image points of reference points Calculate the barycenter coordinates[8]. the formulas are as follows:

$$\Delta P_x = P_{xm} - P_{x0}$$
$$\Delta P_z = P_{zm} - P_{z0}$$

(5)
3. The test of instantaneous dynamic deformation Monitoring on High-rise building

3.1. The process of testing

(1) The deformation monitoring data of high-rise buildings is collected by digital camera according to the theory of photographic measurement. In order to ensure the stability of the internal and external azimuth elements in the measurement process, the camera is fixed with a tripod, and the same time make sure the position of the monitoring object is in the center of the image [9].

(2) Arranging the layout of the experimental site according to the surrounding geographical environment. A reference plane is arranged at a distance of 4.1 meters away from the camera, and kept parallel to the monitored object plane. Make sure that the photographic beam is perpendicular to the object plane. Selecting reference points C0, C1, C2, C3, C4 on the reference plane. It is difficult to close to building during the construction process, then the deformation points are not posted on the building itself, but select the obvious signs U0, U1, U2, U3 as the deformation monitoring points on the image[9](the position of the deformation points is shown in figure 1).

(3) Taking a zero photo as reference photo at the beginning of the experiment, and taking one photo every 3 seconds, then we obtained a set of image sequences for data comparison. A total of 15 photos were taken in this experiment.

![Figure 1. The monitoring site of High-rise building.](image)

3.2. Analysis of test data

Reference points and deformation points are measured by the mouse on the screen. There will be some error in the position measurement of the reference point and the deformation point because of the clarity of the image and the ability of human eyes. The pictures in JPG format are compressed, in order to improve the accuracy of monitoring position, the original image is enhanced and converted into BMP format. The converted image sequence is loaded into the deformation monitoring software system to measure the position of the points. Then save the pictures into LCP format. The reference base line data is inputted into the system of deformation monitoring software for calculation, and the The error of the reference point, Deformation value of monitoring points, time-displacement curve of the deformation point is obtained as Table 1, Table 2 and Figure 2.

| Reference point | X    | Z    | X    | Z    | X    | Z    | X    | Z     |
|----------------|------|------|------|------|------|------|------|-------|
| C0             | +0.007 | -0.415 | -0.088 | -0.067 | 0.026 | -0.648 | 0.352 | -0.537 |
| C1             | 0.415  | 0.012  | 0.648  | 0.642  |

Table 1. The accuracy of Reference point /mm.
Table 2. Relative displacement of deformation points/mm.

| Test | U0   | U1   | U2   | U3   |
|------|------|------|------|------|
|      | DX0  | DZ0  | DX1  | DZ1  | DX2  | DZ2  | DX3  | DZ3  |
| 1    | 0.18 | -0.84 | 0.22 | 0.37 | 1.25 | -0.61 | 0.31 | -1.56 |
| 2    | -0.58 | -2.35 | 0.48 | -1.46 | 0.55 | -1.59 | -0.38 | -2.71 |
| 3    | 0.67 | 0.06 | 0.8  | 0.17 | 0.91 | 0.1  | 1.07 | -0.96 |
| 4    | 0.24 | -0.63 | 1.33 | -0.75 | 1.38 | -0.08 | 0.48 | -1.42 |
| 5    | -0.19 | -0.72 | -0.17 | 0.24 | 0.82 | -0.04 | 0.86 | -0.28 |
| 6    | 0.24 | -0.37 | 1.33 | -0.51 | 1.38 | 0.14 | 1.49 | -1.22 |
| 7    | -0.15 | -0.47 | 0.91 | 0.43 | 0.91 | 0.08 | 0.98 | -0.24 |
| 8    | 0.82 | -0.37 | 0.84 | -0.51 | 1.83 | -0.88 | 0.86 | 0.81 |
| 9    | 0.77 | 1.14 | -0.21 | 1.08 | 0.79 | 0.81 | 0.85 | 0.55 |
| 10   | 0.76 | -0.81 | 0.75 | 0.09 | 0.7  | -0.24 | 0.7  | -0.55 |
| 11   | 1.69 | -0.52 | 1.74 | -0.59 | 1.75 | 0.12 | 1.83 | -0.15 |
| 12   | 1.65 | -1.4 | 1.68 | -0.48 | 1.67 | -0.81 | 0.71 | -1.1 |
| 13   | -0.42 | 0.37 | -0.43 | 0.26 | 0.53 | 0.94 | -0.48 | 0.63 |
| 14   | 0.82 | -0.93 | 0.84 | -0.01 | 1.83 | -1.35 | 0.86 | -1.64 |
| 15   | 1.92 | -1.16 | 0.99 | -1.31 | 2.05 | -0.68 | 2.16 | -2.05 |
| min  | 0.18 | 0.06 | 0.21 | -0.01 | 0.53 | 0.04 | 0.31 | 0.28 |
| max  | 1.92 | 2.35 | 1.74 | -1.46 | 2.05 | 1.59 | 2.16 | 2.71 |

Figure 2. Time-displacement deformation diagram of each deformation point.

4. Conclusions

The relative deformation value of the deformation point in the object plane is calculated by the image sequence-photography proportional transformation method. Through the data analysis we obtained the following conclusions.

(1) It is an effective method to set up a reference surface within a certain distance of the camera when monitoring the deformation. The reference points C0, C1, C2, C3, C4 are located in the vertical direction of the camera about 4.1 meters away from the camera, the accuracy of the reference points is
within 0.7 mm. The error of barycenter coordinate is within the limit value.

(2) According to the file of displacement correction calculated by the software system of High-rise building monitoring, we can obtain the deformation value of each deformation point. According to the distance relationship between the photography center, the reference plane and the monitoring object, the photographic proportional coefficient is calculated to be 180. According to the proportion coefficient of photography, the instantaneous deformation of each deformation point can be calculated. The points with large deformation is U3, and the point with smaller deformation is U0, U1 and U2. This High-rise building belongs to central tube structure, the steel frame around the center tube is being built during the time of monitoring, in the process of construction, the construction of beam and column and the filling of the structure improve the overall mechanical performance of the structure, and at the same time increase the transverse shear force of the central tube. So the deformation of U0 point is larger than that of U1 point; Point U1 is in the middle of the building, the external force generated during the construction of the steel structure outside the building is relatively reduced compared to the point of U0, then the amount of deformation of the point of U1 is relatively reduced; U3 is on the 65th floor of the building. At this time, the tower is in operation on the top floor. The operation of the tower foundation is also one of the reasons for the large deformation at the point of U3; The point of U2 is located in the middle of the building and is relatively closer to the point of U3, the deformation is slightly lesser than the point of U3, but greater than points of U0 and U1;

(3) According to the experimental data, it is judged that the High-rise building is in the period of safe construction. The minimum deformation value of the deformation point is 0.29mm on the diagram, that is, 53.64mm on the ground, the maximum deformation value of the deformation point is the 2.98mm on the diagram, that is, the field 536mm on the ground. It is far less than the limit value of interstory displacement of frame structure under wind load of High-rise building1/450 [11]. Therefore, according to the experimental results, it can be judged that the High-rise building is in the elastic stage and the building has good safety.

(4) In the system of monitoring can generate the deformation curve of the deformation point according to the image sequence quickly. The instantaneous deformation value and relative change of deformation points can be seen intuitively, and the deformation values of different points can be obtained at the same time. It is easy to judge the deformation trend of each part of the building and the deformation law with time Intuitively, thus, provide the data analysis for the structural optimization of High-rise buildings.

The system is simple to operate, does not contact the monitoring object, does not affect the normal construction and use of the project, can avoid potential hazards, can monitor instantaneous deformation, the monitoring accuracy up to 3‰, can carry out real-time, rapid and intuitive analysis of building deformation. It provides data support for the healthy use and later operation and maintenance. it is easier to popularize in projects.

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