Research on Structural Deformation Monitoring Based on Digital Close-Range Photogrammetry Technology

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Abstract. Through the long-term and precise structural deformation monitoring of buildings to determine its health status is very important for their safe use and operation maintenance. At present, the traditional surveying measurement is mainly used to monitor the building deformation, which is not only labor-consuming and time-consuming, but also for some parts of the building that are not easy to reach, the observation becomes very difficult or even impossible to achieve. This paper compares and analyzes the advantages and disadvantages of several surveying technologies, including traditional measurement and the latest digital methods, e.g. 3D laser scanning technology, GNSS (Global Navigation Satellite System) technology, and digital close-range photogrammetry technology, in their application of structural deformation monitoring. The key technology and main steps of digital close-range photogrammetry in deformation monitoring is focused here. Unlike traditional surveying methods which are limited to discrete point monitoring, digital close-range photogrammetry can non-contactly obtain complete images of the monitored object at different times and spatial coordinates of the monitoring points, thereby obtaining comprehensive deformation data of the building. The additional stress variation law of the building can be quickly and accurately determined, which is beneficial to establishing a more detailed prediction system for building deformation. The example of digital close-range photogrammetry in structural deformation monitoring is carried out to demonstrate the improved algorithm. The result shows that the accuracy can reach millimeter level, which means it is comparable to traditional high-precision surveying methods, e.g. the total station measurement.

Keywords: digital close-range photogrammetry; structural deformation monitoring; building; multi-baseline photogrammetry

1 INTRODUCTION

With the rapid development of China's economy, especially for super-large cities like Shanghai, the number of buildings is increasing. From the perspective of existing buildings, there are a large number of buildings with a wide range of construction

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time and diverse types. As of 2022, the urban building construction area in Shanghai has exceeded 1.548 billion square meters, including about 742 million square meters of residential buildings and about 806 million square meters of non-residential buildings. Through the safety inspection of about 170 million square meters of old buildings in the city, it was found that about 17 million square meters of buildings have potential safety hazards. At the same time, in the process of urban construction, large-scale construction projects such as subways, tunnels, deep foundation pits, etc. also have a negative impact on the safety of surrounding buildings. It is of great significance to monitor the structural deformation of buildings in real time in order to give early warning when abnormal phenomena occur to prevent property losses and casualties caused by accidents. At present, the conventional ground survey[1-2] is mainly used to monitor the structural deformation, which is not only labor-consuming and time-consuming, but also for some parts of the building that are not easy to reach, or dangerous buildings, the observation becomes very difficult or even impossible to achieve. As a new digital surveying method with non-contact, high precision and multi-information, photogrammetry has a good development prospect in building structural deformation monitoring.

2 COMPARISON OF SEVERAL SURVEYING TECHNOLOGIES IN STRUCTURAL DEFORMATION MONITORING

2.1 Traditional Surveying Technologies

The traditional surveying method for monitoring structural deformation is mainly through setting up a large number of observation points on the target objects, and the deformation data are obtained through total station and level observation, its limitations include: First, the structural deformation can not be obtained as a whole, it can only be limited to discrete points; Second, the conventional instruments are inefficient and the field work is heavy, so it is impossible to obtain the three-dimensional coordinates of the monitoring points in a short period of time; Third, the internal parts of the building structure are difficult to reach, which can not be measured. Fourth, it is difficult to observe dangerous buildings.

2.2 Three-dimensional Laser Scanning Technology

Compared with the traditional measurement technology, the massive three-dimensional point cloud and coordinate values can more accurately reflect the real location and characteristics of the building. However, the disadvantage of three-dimensional laser scanning in deformation monitoring is also obvious. For example, for the massive three-dimensional point clouds with noise and lack of other auxiliary data coordinated processing, the accurate extraction of building-related feature lines and points is numerous and difficult. Moreover, because 3D points are the characteristics of cloud organization, it is difficult to judge photos and point cloud feature points only by visual inspection, and the error is large, so it is difficult to achieve accurate monitoring of specific range and target points[3].

2.3 GNSS Technology

GNSS (Global Navigation Satellite System) technology is a new method which has sprung up in the past decade, which can use the principle of static relative positioning to obtain high-precision three-dimensional coordinates of observation points. However, the limitations of GNSS in structural deformation monitoring still exist. Firstly, the observation points are very limited. For the engineering projects that need to carry out a large number of point monitoring, GNSS can not be installed at every point, and for the objects with complex structure and no obvious characteristic points, it is difficult to apply GNSS measurement method; Secondly, in the non-open environment, such as the dense building area in the center of Shanghai, the GNSS signal is affected, and the monitoring technology can not be applied normally.

2.4 Digital Close-range Photogrammetry

Digital close-range photogrammetry is to take digital images of the tested object within a certain short distance (usually within 300m), and then analyze the obtained images in order to directly describe the appearance conditions such as the shape and size of the object [4]. In the past ten years, digital close-range photogrammetry has been widely used in tunnels, bridges, dams, archaeology, cultural relic protection and deformation monitoring of high-rise buildings[5]-[7].

Compared with other digital surveying technologies, photogrammetry combines photographic pictures with control measurement, and it is convenient to obtain deformation monitoring data. Moreover, with the combination of image analysis and feature extraction, it can better restore the surface model and accurately extract related points, with high accuracy of post-processing results and good adaptability to the environment.

However, although there is less field work, photogrammetry requires to process a large amount of data of indoor work. And the parameter data of the camera itself needs to be processed, and there is a partial conversion and correction residual error, so for the monitoring with high precision, the camera and correction parameters, model parameters and related conversion accuracy need to be well studied.

2.5 Comparison and Analysis

The surveying technologies commonly used in structural deformation monitoring are analyzed from the main aspects of monitoring data acquisition efficiency, feature extraction accuracy, data analysis accuracy and working environment adaptability. The comparison is shown in Table 1.

Table 1. Comparison and analysis of the adaptability of digital surveying technologies in deformation monitoring

Comparison aspect	**3D laser scanning**	GNSS	Digital close-range photogrammetry
data acquisition	High	Average	High
feature extraction accuracy	Average	High	High
data analysis accuracy	Higher	High	Higher
working environment adaptability	Better	Poor	Good

According to Table 1, compared with other surveying technologies, photogrammetry has the following advantages: First, the information of the subject can be accurately recorded in an instant, and then the instantaneous point position relationship can be obtained; Second, the photo is of rich information and objective in display, so it is suitable for measuring regular or irregular objects, especially buildings; Third, it is a non-contact measurement method, which does not hurt the target, especially the deformation monitoring of dangerous buildings, historical buildings and other important buildings; Fourth, compared with the traditional ground survey, it can greatly reduce field work; Fifth, photos can be preserved for a long time, which is conducive to inspection, analysis and comparison. Sixth, it can provide a variety of products based on three-dimensional spatial coordinates, including all kinds of data, graphics, images, digital surface models and three-dimensional dynamic sequence images[8]. Thus, it can be seen that photogrammetry can measure the deformation of any point, provide complete and instantaneous three-dimensional spatial information without touching the target object, and can observe the state of the deformed body before and after through observation in different periods. Among them, the integration of hardware (e.g. unmanned aerial vehicle, common ordinary digital cameras), technology and measurement methods provides a platform for close-range photogrammetry to achieve high-precision and efficient deformation monitoring.

To sum up, in the field of deformation monitoring, three-dimensional laser scanning technology, GNSS measurement technology and photogrammetry technology are all involved. With the development of science and technology, the traditional discrete point data acquisition and single data analysis technology has become mature. Combined with the requirements of future digital and three-dimensional urban development, large-scale, high-efficiency, high-precision surveying and mapping, image detection, Internet of things map and other multi-source technology integration of modern deformation monitoring technology has been put on the agenda. Digital close-range photogrammetry monitoring has become a leader in the field of deformation monitoring, especially in structural deformation monitoring, because of its unique interdisciplinary and technical characteristics.

3 MAIN STEPS OF THE DIGITAL CLOSE-RANGE PHOTOGRAMMETRY IN STRUCTURAL DEFORMATION MONITORING

3.1 Layout Requirements for Deformation Monitoring Points

The layout for deformation monitoring points depends on many factors, such as the accuracy requirement of deformation monitoring, the shape and size of the building, the natural and social environment of the monitoring area, the conditions of imaging equipment and the processing of indoor work data, etc. The layout requirements for deformation monitoring points include:

(1) Settlement monitoring: the monitoring points should be set on the building where the characteristics of settlement and deformation can be reflected, such as column foundation, load-bearing wall, four corners of the building, midpoint, both sides of the expansion joint, the change of foundation form， geological conditions, and building load.

(2) Tilt monitoring：the monitoring points should be located on the outside of the building, near the centerline of the building, and in two directions perpendicular to each other.

(3) Overall deformation monitoring: the monitoring points should be fully covered and relatively evenly distributed on the surface of the building.

3.2 Main Steps of Digital Close-range Photogrammetry

Before deformation monitoring, the control network and photogrammetric station arrangement should be set up according to the characteristics of the monitoring object and the actual situation. The layout and survey of the control network is completed by the traditional high-precision conventional ground survey, and the length of the baseline should be controlled when the photogrammetric stations are arranged. In order to find and eliminate errors in processing the data of indoor work, it is also necessary to set up checkpoints. At the same time, before formal photography, a small amount of trial work needs to be carried out in order to grasp the better exposure time and various photography technical parameters needed to obtain a clear image[9]. The specific process of implementing digital close-range photogrammetry is shown in Figure 1.

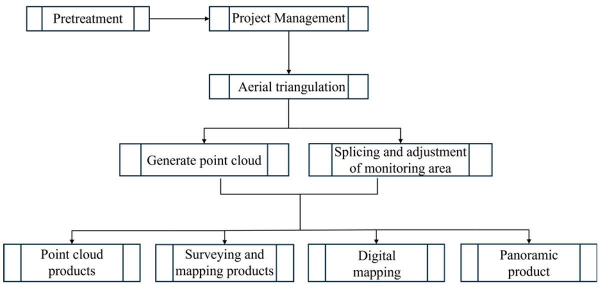

Fig. 1. The specific process of implementing digital close-range photogrammetry

4 EXPERIMENTAL ANALYSIS AND VERIFICATION

In order to verify the accuracy of digital close-range photogrammetry in structural deformation monitoring, this paper compares the monitoring results of photogrammetry, high-precision and traditional total station through experiments. In the experiment, close-range photogrammetry is used to photograph the structure, which deforms under known stress conditions. And the deformation extent of local deformation points can be accurately measured by the set sensor, but the number of points that can be measured is limited. In comparison, photogrammetry can deal with any number of target point coordinates that need to be determined. In this paper, "improved multi-baseline digital close-range photogrammetry self-calibration beam adjustment algorithm" [10] is adopted in order to improve the accuracy.

4.1 Experimental Method

The workflow of the improved multi-baseline digital close-range photogrammetry with self-calibration bundle adjustment is shown in Figure 2.

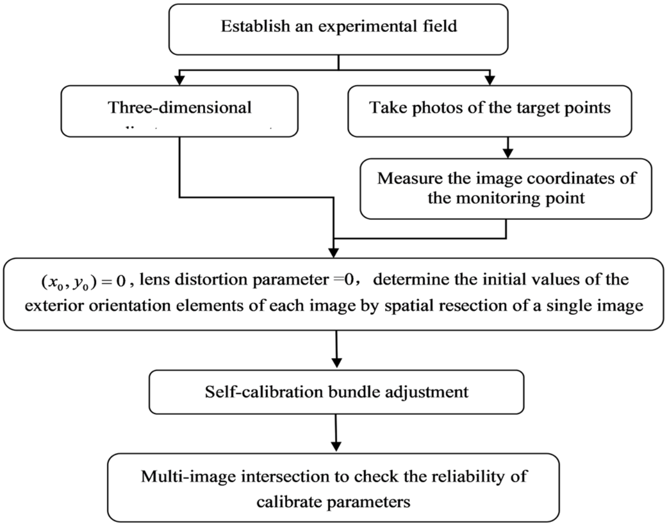

Fig. 2. Flow chat of the improved multi-baseline digital close-range photogrammetry with self-calibration bundle adjustment

4.2 Experimental Process

The experimental object is a steel structure, which is connected by seven brackets fixed on the base. The steel structure before and after deformation is shown in figure 3 (a) and (b) respectively by adding force on the top of jack to deform the structure. From the figures marked with the yellow line, we can see that the experimental board is obviously deformed after adding force.

There are three types of points in figure 3: 20 control points distributed on the stable support platform; 40 unsolved points whose coordinates are unknown and are evenly distributed on the upper and lower sides of the steel structure experimental plate and on the stable columns in the middle; six checkpoints were set to check the external accuracy of photogrammetric experimental results.

Fig. 3. The set-up of the experimental site

The three-dimensional coordinates of the control points and checkpoints are determined by the SOKKIA NET1200 total station with angle measurement accuracy of 1 "and ranging accuracy of 0.6mm+2ppm. As the measuring distance is less than 100m, the accuracy of control points and checkpoints is in the millimeter level.

In photogrammetry, the ordinary digital camera is used to photograph the structure before and after deformation, and in the self-developed close-range photogrammetry software, the coordinates of the target points to be measured are calculated based on the improved multi-baseline digital close-range photogrammetry algorithm to realize the deformation analysis of the structure. The camera model Nikon D200 was taken with an image of 23.6mm × 15.8mm (3872 x 2592 pixels) and an initial focal length of 50mm (8500 pixels). Before and after the deformation, 3 photogrammetry stations were set up, and 2 pictures were taken at each station, with a distance of 10 to 20 m.

4.3 Analysis of Test Results

After obtaining the control point and image point information, the coordinates and deformation extent of the deformation point are calculated according to the process of "image point information extraction - relative orientation - forward intersection - model connection - absolute orientation - bundle adjustment", the result is shown in Table 2.

Table 2. The deformation coordinates of some monitoring points calculated by photogrammetry

Point No.	Deformation（mm）			Point No.	Deformation（mm）		
	$\triangle X$	$\triangle Y$	$\triangle Z$		$\triangle X$	$\triangle Y$	$\triangle Z$
1	-4.6	10.2	-8.6	10	0.2642	4.0544	1.1514
2	-4.9	5.9	-18	11	0.0969	4.0825	1.4023
7	-6.2	1.2	-66.6	12	-0.2676	4.0992	1.4106
8	-6.2	1.2	-72.2	16	-1.4643	4.1355	1.3983
9	-3.7	5.5	-73.4	19	-1.7308	4.1401	1.0405

It can be seen that after adding the force, the structure has obvious deformation in the three directions of X, Y and Z, especially in the Z direction. And the deformation in the middle part of the upper beam and the lower beam is the most significant.

At the same time, in order to ensure the accuracy of the results and evaluate the external accuracy, in the experiment six checkpoints were selected to be measured before and after adding forces, but in the process of calculating the unsolved points, the six checkpoints are not used as control points, but also involved in the adjustment as unsolved points. Finally, the calculated values are compared with the measured values, as shown in figure 4. As can be seen from the figure, after deformation, the difference between coordinates calculated by photogrammetry and coordinates measured by total station is within 1mm. The mean values of checkpoint results were (0.25,0.23,0.38) mm, and the root mean squares were (0.30,0.31,0.36) mm, respectively.

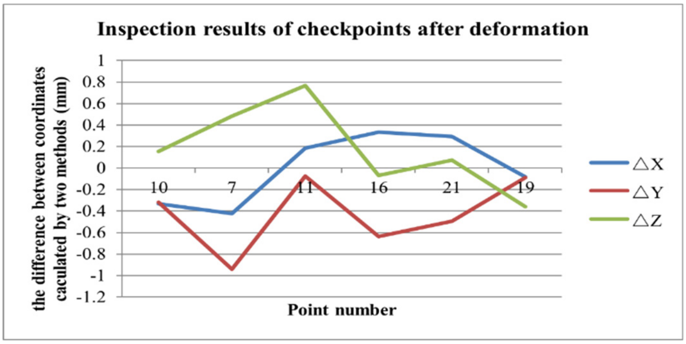

Fig. 4. Inspection results of checkpoints after deformation

4.4 Discussion

According to the analysis of the deformation extent of the checkpoints, the difference between the calculated value and the measured value of the checkpoint is within 1mm. Therefore, through this experiment, the following conclusions can be drawn:

(1) By means of close-range photogrammetry, the structure can be photographed, and the coordinates of any number of interested target points can be calculated, thus the deformation of the structure can be analyzed.

(2) From the comparison of the deformation extent of the checkpoints obtained by traditional high-precision total station and photogrammetry, it can be seen that the difference between the coordinate and deformation extent of the point to be obtained by close-range photogrammetry and that measured by total station is within 1mm. It can be seen that the coordinates of the objects obtained by photogrammetry are correct, and the accuracy is not lower than that of the total station.

5 CONCLUSIONS

In order to ensure the safety of the building, especially in the process of large-scale underground projects, it is necessary to carry out continuous precision deformation monitoring to determine its deformation state. The traditional surveying technologies are mostly limited to the displacement and settlement analysis of discrete monitoring points, which can not reflect the deformation law of structure in detail.

Compared with traditional structural deformation monitoring methods, the digital close range photogrammetry technology studied and improved in this paper has the characteristics of fast, high accuracy, non-contact, etc. It can not only survey without damaging buildings, but also improve the efficiency and accuracy. This method can not only obtain images and dimensions of monitoring objects, but also further determine the difference of the spatial coordinates of deformation points in different periods. The deformation analysis is carried out via the calculated data, so as to realize the structural deformation monitoring with high precision and high resolution, analyze the spatial information intuitively, and obtain the comprehensive structural deformation data. thus, the law of additional stress change of the building facade can be determined quickly and accurately, which is helpful to establish a more detailed prediction system of structural deformation.

The monitoring method presented in this paper can provide new ideas, methods, and technological guidance for structural deformation monitoring in Shanghai and even across the country.

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