Instantaneous Dynamic Deformation Monitoring on Jiaozhou Bay Cross-sea Bridge with LVR-GPS Technology

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Abstract. Intend to get and process the monitoring data of the instantaneous dynamic deformation of Jiaozhou bay cross-sea bridge sufficiently, the paper makes application of the long visual range and the global positioning system (LVR-GPS) monitoring model in the experiment. The deformation monitoring experiment is conducted with horizontal distance exceed more than 2.2 kilometers. With the LVR-GPS model we can monitor multiple points, draw real-time curve image, and obtain the synchronous results. Thus, we can provide a creative deformation monitoring technology on the similar large-scale bridges.

Keywords: Deformation monitoring; LVR-GPS technology; Instantaneous dynamic; Cross-sea bridge.

1. Introduction

At present, the digital camera is mainly used in the near range in Digital Close-Range Photogrammetry (DCRP). However, when the human eye cannot see the LVR of artificial signs, there is no case of using digital cameras for deformation monitoring. This is determined by the digital camera's ability to capture data [1,2]. The monitoring of transient dynamic deformation of large bridges (such as Jiaozhou cross-bay bridge) with long visual distance needs to be further studied and perfected, which is a difficult problem to be solved. The problems to be solved are mainly the following five: First problem is whether the ordinary digital camera also be applied in the case of long visual range. In digital close-range photogrammetry, it is generally required that the distance from the photographic station to the target is no more than 300 meters. When the distance is longer than 300 meters or even several thousand meters, how to use digital photogrammetry technology? Second problem is the difficulty of setting reference points. In DCRP, it is generally required that the reference plane and the deformation plane should be in one plane or the parallel distance should not exceed about 0.55m. However, in many engineering sites, it is often unable to meet the requirements of reference point layout, so a new model is needed to determine the location of reference baseline. Third problem is the digital photogrammetric calculation model needs to be further improved. Though many models have been verified in actual production and practice. But when the corresponding monitoring environment and parameters are changed, the original model will face the problem of modification, which requires a new attempt in the process of research. Fourth problem is three high-precision receivers were used to observe the deformation of the large-span Jiaozhou bay cross-sea bridge in the form of GNSS static control network, to get the coordinates of the deformation and also the change in elevation and the measured accuracy, so as to verify the feasibility of high-precision monitoring of the bridge with GNSS static control network. Fifth problem is analyze the deformation quantity obtained by the static control network of GNSS and...
compare it with the instantaneous deformation observation and measurement results of digital camera in the state of LVR, so as to verify the accuracy and reliability of photogrammetry of LVR digital camera, achieve the effect of mutual checking and complementing each other.

Many theories and methods have already been proposed to monitor the long-span bridges, and good results also have been achieved recently. Xiao G.W., Xiong Y.Y. and Wang X.M. and Zhu Y. et al. [3-6] respectively used the automatic total station system, laser scanning and GPS technology and the real-time monitoring system based on GPS to monitor the long-span bridges. These methods cannot offer the instantaneous dynamic and overall monitoring of the bridge. Yu C.X., Zhao Y.Q. et al. [7-11] applied DCRP technology to obtain the real-time dynamic deformation curve of the Huang-tai dock bridge. They make the success in getting the accuracy information of multi-points.

Here we will establish an LVR-GPS model by using the uniform proportional pseudo-parallax algorithm and GPS technology. And the model will be used to monitor the instantaneous dynamic deformation in Jiaozhou Bay Cross-sea Bridge with horizontal distance exceeded 2100 meters. The monitoring precision will reach 3.11‰ approximately.

2. The LVR-GPS Technology

As the distance is much more than 300 meters, we construct the LVR-GPS model with using the uniform proportional pseudo-parallax algorithm creatively [12, 13]. By setting points and adjusting method in the experiment, we get the information of the deformation monitoring on the bridges [14-15]. Then we have

\[
\begin{align*}
    x - \lambda_1 X + \lambda_2 Y + \lambda_3 Z + \lambda_4 \varepsilon &= 0 \\
    -\lambda_5 X + \lambda_6 Y + \lambda_7 Z + \lambda_8 \psi &= 0 \\
    z - \rho_1 X + \rho_2 Y + \rho_3 Z + \rho_4 \varepsilon &= 0
\end{align*}
\]  

Make the capable weight to the monitor elements, we have

\[
\begin{pmatrix}
x_s \\
y_s \\
z_s
\end{pmatrix} = \begin{pmatrix}
\lambda_1 & \lambda_2 & \lambda_3 \\
\lambda_5 & \lambda_6 & \lambda_7 \\
\lambda_9 & \lambda_{10} & \lambda_{11}
\end{pmatrix}^{-1} \begin{pmatrix}
\lambda_4 \\
\lambda_8 \\
\psi
\end{pmatrix}
\]  

Where \( \delta x_{pr}, \delta z_{pr} \) [16] will satisfy

\[
\begin{align*}
\delta x_{pr} &= x_{2r} - x_{ir} = \varepsilon x_{2r} - \varepsilon x_{ir} \\
\delta z_{pr} &= z_{2r} - z_{ir} = \varepsilon z_{2r} - \varepsilon z_{ir}
\end{align*}
\]  

Accordingly [17-18], we have

\[
\begin{align*}
\delta X_{sdl} &= \Phi \cdot \mu \cdot \delta x_{cpl} \\
\delta Z_{sdl} &= \Phi \cdot \mu \cdot \delta z_{cpl}
\end{align*}
\]  

\( \delta X_{sdl}, \delta Z_{sdl} \) are the real deformation, and \( \Phi \) is the proportional value.

Figure 1. The experiment scene, JC01/JZ01/JZ02 points and the deformation curve map
When monitoring the deformation points, the cameras should be set at the proper position and perpendicular to target. The internal and external azimuth elements are always changing when the experiment is conducted. According GPS measurement specification GB18314-2009, we set two reference points with two GPS. The first point-JZ01 is located near a beach 1.5km to the west of south of the interchange of Licun river, and the second point-JZ02 is located near a beach 1km to the northeast of the interchange of Licun river, see figure 1. And the distance between the two cameras and the bridge respectively are 2110.65m and 2109.31m. The Hi-Target Geomatics Office (HGO) data processing package was used for baseline solution and control network adjustment.

3. Experiment Process of Deformation Monitoring

3.1. Overall Design
Before the experiment, we made all the preparations. Including the positioning of the camera station, the placement of cameras, the erection and layout of GPS, the paste of deformation points and reference points, distance measurement, communication coordination and field command, etc. Then we take photos at the sparse traffic occasion from 9:04 to 11:04, and at the dense traffic occasion from 11:20 to 13:25.

3.2. Distance Measuring
First step is to measure the distance of every two points in the scene and take graphs record. Then input the zero image and subsequent images into the software and measure the screen coordinates. Establish data solution group, input reference baseline data, solve the data, and draw a deformation curve.

3.3. Data Processing
Three cameras simultaneously took series of photos when the traffic is sparse, and the first clearest one is zero photo. Forty-eight photos are taken at five second intervals when the vehicles are dense as the subsequent images. Input the zero image and subsequent images into the software and measure the screen coordinates. Then establish a data solution group, input reference baseline data, solve the data, and draw a deformation curve.

The first period was observed synchronously from 9:04 to 11:04, Beijing time, and the second period from 11:20 to 13:25, according to the technical requirements of C-class GPS control network. Before the observation, the instrument height was measured in three different directions, and the manual of external observation was recorded in detail.

4. Data Analysis

4.1. Data Analysis of the LVR Technology
The pixel coordinates of reference and deformation points contribute to generate motion curves of each deformation points. It is obvious that the points U0-U6 are elastic. As the 14-megapixel digital cameras are used in the experiment, it is too far away to clearly see the artificial signs. Some clear fixed characteristic points on the bridge are also selected as reference points for data processing. The obtained deformation curve is consistent, but there is a big gap when the change value of pixels is converted into the actual displacement value. From the data we can obtain graphs, which reflect the deformation status when the traffic is dense on the bridge. The trend of the curve is conformed to the deformation principle of the bridge structures.

4.2. Data Analysis of the GPS Technology
In the first period, 3D free network was used to conduct 3D unconstrained adjustment to obtain the coordinates of JZ01, JZ02 and JC01. The weakest edge of the baseline vector is JC01-JZ02, with an accuracy of 1/4744071. The relative closure difference of JZ01- JZ02-JC01- JZ01 tri-sided synchronous ring is 0.18 ppm, that is, 1.8/1000000. The point median error of the weakest point JZ02 is ±0.3mm.
In the second period, let the coordinates of JZ01 and JZ02 of the first period as known coordinates, conduct 3D constraint adjustment, and obtain the coordinates of JC01 in the second period, so as to compare with JC01 in the first period, and calculate the 3D deformation value of JC01 in key parts of the bridge. The weakest edge of the baseline vector is JC01-JZ02, with an accuracy of 1:27,3047. The relative closure difference of JZ01-JZ02-JC01-JZ01 tri-sided synchronous ring is 0.18 ppm, that is, 1.8/1000000. The point median error of the most vulnerable JZ02 is ± 5.7mm.

5. Main Conclusions
According the deformation curve map of the points in the right part of figure 1, we have the following conclusions: First, the points fluctuating around the equilibrium points slightly and the maximum relative displacement of each point does not exceed 10mm. Second, the bridge is in elastic status and the bridge is good with the increase of load. Third, the deformation curves map at different positions and spans show the good bending resistance of the bridge. Though the deformation of the bridge has occurred continuously on and on, but eventually regain to the original status. This shows the excellent stability of the bridge.

From the GPS data, we get the JC01 coordinate change law: south change 7.4 mm, west change 0.8 mm, up change 15.5 mm. The change of vehicle load makes the plane position of key parts of the bridge change little, while the elevation direction changes greatly. The higher elevation can show the reduction of vehicle load and the numbers of vehicles. In the second period that the time for lunch and rest, the number of vehicles crossing the bridge will greatly reduce, the detection results are consistent with the actual situation. The Starfish iRTK2 GNSS receiver can make the plane accuracy better than ±3mm and the elevation accuracy better than ±6mm for high-precision deformation monitoring of key parts of the bridge, which can monitor, analyze and predict the operation safety of the bridge.

Finally, the data analysis result shows the highly deformation accuracy up to 3.11‰ by using the digital LVR-GPS photogrammetry model with using the uniform proportional pseudo-parallax algorithm. The monitoring method will beneficial to the country's large-scale transportation facilities such as the large-span bridges, the elevated bridges, tall buildings, and so on. This also conducive to the healthy use and safety of the bridges that come into service.

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