Monitoring dynamic deformation of communication tower using photography dynamic monitoring system

Yongquan Ge¹, Chengxin Yu² ∗, Xiaodong Liu³ and Ronghui Wang⁴

¹College of Surveying and Geo-Informatic, Shandong Jianzhu University, Jinan, China
²School of Business, Shandong Jianzhu University, Jinan, China
³College of Continuing education, Shandong Jianzhu University, Jinan, China
⁴Asset Management Office, Shandong Jianzhu University, Jinan, China

*Corresponding author e-mail: ycx1108@126.com

Abstract. With the advent of next-generation cellular mobile communication technology, the world ushered in a new communications tower construction boom to protect the safe operation of the communication towers without delay. In this paper, we monitored the dynamic deformation of the communication tower using the PDMS (photography dynamic monitoring system). Results showed that the tower is integrity and stability; The deformation is conform to the China national standard. The PDMS can monitor the tower in a non-contact, it has a characteristic of strong robustness, excellent flexibility and low cost.

1. Introduction
The communication tower is a kind of tall structure with communication antennas. It is characterized by high structure, small cross-section, and the transverse load plays a major role. It is a slender structure [1]. The antenna on the communications tower, there are mobile phone antennas or Other sectors antennas, generally. Figure 1 shows the four kinds of the communication tower. In recent years, infrastructure in China has improved steadily, all kinds of new communication technology constantly emerging, especially the latest generation of cellular mobile communication technology, 5th generation mobile networks, once again aroused the climax of communication tower construction in China.
Figure 1. Mobile phone base station communication tower

The most used cellular mobile phone base station communication tower is usually built at a certain distance due to the requirements of layout and coverage. The tower is about 30~60m high. There are 2~3 floors on the tower and 5~6 m apart from each other.

As such communication towers are widely distributed in urban and rural areas, their size is huge, and the number is astonishing. During the service life, due to long-term load action or sudden disaster [2], the steel tower structure will have potential safety hazards, which will seriously endanger the safety of human life and property. So it is necessary to carry out regular structural health monitoring for such steel tower structures.

Our country structure for structural monitoring foreign communications tower is relatively late, in recent years has been found in the relevant monitoring products, most of these products are based on the deformation sensors collect information, monitoring is a method of contact. Contactless monitoring methods will undoubtedly bring a lot of trouble and danger, such as workers need to climb the tower for maintenance of the instrument, the limited life of the sensor and monitoring costs higher. This paper introduces a method of monitoring the deformation of a non-contact, monitoring the deformation of steel tower structure using the PDMS (photography dynamic monitoring system).

This method not only overcomes all the obvious flaws of previous contact measurement, but also greatly reduces the cost of monitoring, the current method has been successfully applied to steel, masonry structures, bridges, dam structure, aircraft structure, and high-rise buildings the steel has a large venue [3-7] or the like deformation monitoring good effect.

2. Photography dynamic monitoring system

After about two decades of system development, all equipment in the information acquisition section is now flexible, as figure 2 shows. The camera we can choose a non-metric digital camera. The reference means stable instruments which have some marks easy to recognized, we can even replace it with a coat hanger full of marks. The diastimeter we can replace it with the total station if we do not have a diastimeter. However, we should choose some reliable instrument if the condition allows. Generally, we use a sony α350 camera, use a pair of tripods as the reference, use a total station as the diastimeter.

Figure 2. Photography dynamic monitoring system
2.1. The zero-centered motion parallax method

Initially, the calculating displacement method for a digital camera is mainly composed of two Time baseline parallax method, and the DLT (direct linear time), due to the relatively low requirement for the control points, the Time baseline parallax method is widely applied to the deformation monitoring using a digital camera [8]. However, the new method is still flawed by Chengxin Yu et al., 3D time baseline parallax method [9], IM-STBP (image matching-space time baseline parallax) method [10], the PST-IM-MP (photograph scale transformation-image matching-motion parallax) method [11] and the Z-MP (zero-centered motion parallax) method (Figure. 3). Each proposed method is based on the accumulation of a large number of tests, now the Z-MP method has been applied to the vast majority of monitoring the scene, and excellent monitoring results.

In Figure 3, If monitoring point on the object plane is moved from $A'$ to $B'$, its deformation $\Delta x$ and $\Delta z$ on the reference plane are:

$$
\Delta x = \frac{y}{f} \Delta P_x \\
\Delta z = \frac{y}{f} \Delta P_z
$$

(1)

Where $f$ is the principal distance of photo, where $y$ is the distance of image plane and reference plane. $\Delta P_x$ and $\Delta P_z$ are the horizontal and vertical deformations of monitoring point on the image plane. $\Delta x$ and $\Delta z$ are the horizontal and vertical deformations of monitoring point on the reference plane.

2.1.1. Correction of system errors in The Z-MP method on the reference plane. On the reference plane, if corresponding monitoring points in the zero image and successive image are $(x_1, z_1)$ and $(x_2, z_2)$, compared with the prefect image which without errors of camera external and internal parameters, systematic errors of corresponding monitoring point are $(dx_1, dz_1)$ and $(dx_2, dz_2)$, respectively. The equations can be expressed as Equation (2):

Figure 3. Principle of the Z-MP method

Figure 4. Layout of points
\[
\begin{align*}
(x_2 - x_1) + (d_2 - dx_1) - \Delta x &= 0 \\
(z_2 - z_1) + (d_2 - dz_1) - \Delta z &= 0
\end{align*}
\] (2)

If there are errors of camera external and internal parameters between the zero image and successive images, the control points located on the reference plane will generate parallax \( \Delta x_p \) and \( \Delta z_p \) as Equation (3):

\[
\begin{align*}
\Delta x_p &= (x_2 - x_1) - (d_2 - dx_1) \\
\Delta z_p &= (z_2 - z_1) - (d_2 - dz_1)
\end{align*}
\] (3)

The parallax \( \Delta x_p \) and \( \Delta z_p \) of the control point must be caused by the errors of camera external and internal parameters in successive zero images. For convenience, we selected the linear part of the parallax \( \Delta x_p \) and \( \Delta z_p \) for processing. We take parallax \( \Delta x_p \) for example, it can be expressed as Equation (4):

\[
\begin{align*}
\Delta x_p^0 &= \Delta x_p^0 + \delta x_p \\
\Delta x_p^0 &= \left[ -\frac{dy_s}{Y} - \frac{\Delta f}{f} \right] x_1 + z_1 \Delta \kappa + \left[ -\frac{f}{Y} \Delta X_s - f \Delta \phi - \Delta \chi_0 \right] - \frac{x_1^2}{f} \Delta \phi - \frac{x_1 z_1}{f} \Delta \omega \\
\delta x_p &= \left[ \frac{2 \Delta x_p Y_s}{f} \right] \frac{dy_s}{Y} - \frac{\Delta X_s}{f} \Delta \phi - \frac{\Delta \chi_0}{f} \Delta \omega - \frac{\Delta x_p}{f} \Delta \phi - \frac{\Delta z_p}{f} \Delta \omega + \frac{d_2}{f} \Delta \phi \\
&= \left( 2 \Delta x_p x_1 \right) \frac{dy_s}{Y} \frac{dy_s}{Y} + \frac{\Delta X_s}{f} d \phi_2 - \frac{\Delta \chi_0}{f} d \omega_2 - \frac{\Delta x_p}{f} d \omega_2 - \frac{\Delta z_p}{f} d \omega_2 + \frac{d_2}{f} \Delta \phi \\
&= \frac{2 \Delta X_s}{f} d \phi_2 - \frac{\Delta \chi_0}{f} d \omega_2 - \frac{\Delta x_p}{f} d \omega_2 - \frac{\Delta z_p}{f} d \omega_2 + \frac{d_2}{f} \Delta \phi
\end{align*}
\] (4)

Because motion \( \Delta p_x^0 \) is caused by the change of camera external and internal parameters \( (\Delta X_s, \Delta Z_s, \Delta \phi, \Delta \omega, \Delta \kappa, \Delta f, \Delta \chi_0) \) in the successive and zero images, we can correct \( \Delta p_x^0 \) with a sufficient number of control points, we only discuss \( \Delta x_p^0 \) as follows, it can be expressed as Equation (5):

\[
\Delta x_p^0 = ax + bz + c + dx^2 + ez
\] (5)

If there are more than five control points, each unknown coefficient \( (a, b, c, d, e) \) can be obtained according to their \( \Delta x_p^0 \). For convenience, we selected the linear part of the Equation (5) for processing, \( \Delta x_p^0 \) and \( \Delta z_p^0 \) as Equation (6) shows:

\[
\begin{align*}
\Delta x_p^0 &= ax + bz + c \\
\Delta z_p^0 &= a'x + b'z + c'
\end{align*}
\] (6)

In this case, we only need three or more reference points to obtain \( (a, b, c) \) and \( (a', b', c') \). Take \( \Delta p_x^0 \) as an example. When \( \Delta p_x^0 \) contains only occasional errors, Equation (6) can express as Equation (7):

\[
\begin{align*}
p_x' + V &= ax' + bz' \\
V &= ax' + bz' - p_x'
\end{align*}
\] (7)

Where, \( p_x' \) is the differential coefficient of \( \Delta p_x^0 \), the error equation is:

\[
V = ax' + bz' - p_x'
\] (8)

The equation of the composition method is:
\[
\begin{align*}
    a \sum x' + b \sum x'z' - \sum x'p' &= 0 \\
    a \sum x'z' + b \sum z' - \sum z'p' &= 0
\end{align*}
\] (9)

Calculate barycentric coordinates by control points on the reference plane.

\[
\begin{align*}
    x_i &= x - \frac{\sum x_i}{n} \\
    z_i &= z - \frac{\sum z_i}{n}
\end{align*}
\] (10)

Because coordinates of control points are barycentric coordinates, \( \sum x_i \sum z_i = 0 \) and the parallax coefficient in the \( X \) direction as Equation (11) shows:

\[
\begin{align*}
    a_x &= \frac{\sum z_i^2 \sum x_i p_i - \sum x_i z_i \sum z_i p_i}{\sum x_i^2 \sum z_i - \sum x_i z_i \sum x_i z_i} \\
    b_x &= \frac{\sum x_i^2 \sum z_i p_i - \sum x_i z_i \sum x_i p_i}{\sum x_i^2 \sum z_i - \sum x_i z_i \sum x_i z_i}
\end{align*}
\] (11)

Where, \( a = \tan \phi \) and \( b = \tan \omega \). Similarly, we can obtain the parallax coefficient \( a_z \) and \( b_z \) in the \( Z \) direction. Finally we can obtain \( \Delta x^0 \) and \( \Delta z^0 \).

2.1.2. Obtain the deformation of monitoring points on the object plane

\[
\begin{align*}
    \Delta X &= Y - \Delta x \\
    \Delta Z &= Y - \Delta z
\end{align*}
\] (12)

Where, \( \Delta X \) and \( \Delta Z \) are the horizontal and vertical initial deformations of the monitoring point on the object plane. Equation (12) is also the core of the PST-IM-MP method.

2.1.3. Zero-centered motion parallax of monitoring points on the object plane.

\[
\begin{align*}
    \Delta X' &= \Delta X - \frac{\sum \Delta X}{n} \\
    \Delta Z' &= \Delta Z - \frac{\sum \Delta Z}{n}
\end{align*}
\] (13)

Where, \( \Delta X' \) and \( \Delta Z' \) are the horizontal and vertical final deformations of monitoring point on the object plane. Because we obtained \( \Delta X' \) and \( \Delta Z' \) their mean are zero, named zero-centered.

3. Monitoring test of communication tower

As figure 4 shows, set up a camera station at a suitable position on the test field, set up a reference plane. Continuous photographing of the monitored structure attention, camera station avoid vibration during shooting. After obtained the relative distances among the camera station, reference plane and monitored plane, solve data, analysis results, and predictive deformation use a computer with photography dynamic deformation software.
3.1. Results and analysis

Import photos to computer, preprocessing photos optionally using photography dynamic monitoring software. The preprocessing of photos include image distortion correction, image cropping, image binarization, etc. Furthermore, calculate the deformation of each monitored point. Finally, we obtained some available information like pixel value before and after error correction, the real deformation value before and after error correction, scale transformation value. Because the software can give the intermediate data, we can easily process the data twice.

Part of the data of this test are shown in Table 1 ~ 2:

| Time/s | U0 | U1 | U2 | U3 | U4 | U5 | U6 | U7 | U8 | U9 |
|--------|----|----|----|----|----|----|----|----|----|----|
| 1      | 111.29 | 116.60 | 93.87 | 92.20 | 91.73 | 97.70 | 53.40 | 59.49 | 30.53 | 63.47 |
| 2      | -26.71 | -40.74 | -23.63 | -44.86 | -18.84 | -32.39 | -19.78 | -18.25 | -4.23 | -20.12 |
| 3      | 74.71  | 60.27 | 65.50 | 43.60 | 27.81 | 42.53 | 28.12 | 42.57 | 29.53 | 25.98 |
| 4      | 45.63  | 31.11 | 37.78 | 45.23 | 31.03 | 30.87 | 32.80 | 32.42 | 20.99 | 2.65 |
| 5      | -11.56 | 0.43  | -10.41 | 8.56  | 7.04  | -11.25 | 3.94  | 0.09  | 2.45  | 9.96  |
| 6      | -80.30 | -69.45 | -70.08 | -67.15 | -28.42 | -47.46 | -21.40 | -55.40 | -27.11 | -20.00 |
| 7      | -8.94  | -9.63  | -23.82 | -17.24 | -22.35 | -8.50  | -11.91 | -12.91 | 14.70 | -4.01 |
| 8      | -33.51 | -34.77 | -15.44 | -23.95 | -24.84 | -26.19 | -10.74 | -26.71 | -24.29 | -28.42 |
| 9      | -111.02 | -96.26 | -72.12 | -64.44 | -75.34 | -74.75 | -69.24 | -53.33 | -46.23 | -47.56 |
| 10     | 40.41  | 42.48  | 18.34  | 28.05  | 12.22  | 29.41  | 14.77  | 32.04  | 3.69  | 18.05 |

![Table 1. Deformation of U0~U9 in X direction/mm](image)

| Time/s | U0 | U1 | U2 | U3 | U4 | U5 | U6 | U7 | U8 | U9 |
|--------|----|----|----|----|----|----|----|----|----|----|
| 1      | -169.60 | -182.81 | -149.00 | -142.21 | -113.53 | -120.61 | -98.04 | -86.06 | -70.93 | -56.05 |
| 2      | 18.97  | 15.78  | 27.90  | 13.86  | 20.43  | 20.55  | 21.75  | 9.42  | 18.45 | 6.93 |
| 3      | 18.00  | 4.12  | 11.44  | 16.72  | 17.87  | 8.44  | 3.58  | -2.95 | -0.60 | -5.71 |
| 4      | -97.76 | -88.09 | -72.90 | -88.82 | -48.69 | -64.92 | -44.67 | -58.16 | -29.59 | -41.84 |
| 5      | -10.21 | 19.88  | 13.85  | 33.72  | 6.86  | 12.06  | 8.62  | 16.75 | 5.85  | 0.74 |
| 6      | 31.32  | 46.97  | 38.25  | 14.30  | 0.70  | 34.11  | 13.09  | 21.38 | 7.53  | 17.21 |
| 7      | 86.40  | 98.95  | 71.74  | 73.42  | 54.81  | 55.80  | 60.95  | 49.39 | 32.66 | 36.37 |
| 8      | 104.53 | 93.74  | 74.38  | 97.62  | 85.94  | 80.00  | 47.16  | 58.84 | 32.63 | 45.86 |
| 9      | -92.29 | -110.59 | -94.40 | -108.40 | -82.14 | -96.15 | -60.41 | -71.33 | -27.53 | -36.83 |
| 10     | 110.65 | 102.07 | 78.75  | 89.82  | 59.18  | 70.70  | 47.95  | 62.68 | 31.49 | 33.34 |

According to the Table 1 ~ 2, the visualization results are shown in Figure 5 ~ 7:

![Figure 5. Deformation of U0~U9 in the X direction](image)
As shown in Figure 5 ~ 7, the deformation curves with cold color represent the deformation of left points, the deformation curves with warm color represent the deformation of right points. Figure 7 is a split violin figure, which the fitting method of curve is kernel smooth. As Figure 5 ~ 6 shows, it is elastically deformed in regular monitoring of the overall structure, indicating that the steel column had excellent elastic properties. The deformation trend of the points which have the same height is similar, the monitored structure of each part showed strong integrity, each connecting rod is integrity, security, and reliable structure. As Figure 4 and Figure 7 shows, the deformation of the monitored points its elevation is a positive correlation, in other words, with increasing elevation of monitoring position in communication tower, which is increasingly severe dynamic deformation, this is accord with the rule of the steel deformation. To this test, the maximum deformation of the communications tower occurs in the part I, it is 216.8232mm. The deformation is conform to the China national standard [12].

4. Conclusion
In this paper, we completed the dynamic deformation monitoring steel tower using the PDMS, and got the following conclusions:

(1) With the arrival of the construction boom of the communications tower, it is instant to protect the safe operation of such a large number of the communications tower, the PDMS can complete the dynamic deformation monitoring of the tower, to protect the safe operation of the tower, and to overcome the contact measurement of defects. Meanwhile, a large number of points can be monitored, high flexibility, strong robustness, outstanding economy.

(2) The deformation law of the monitored structure communication tower is stable, and the deformation is conform to the China national standard.
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