Remote Measurement in Steel Grid Structure Based on Control Grid Network

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Abstract  Based on a control grid network and in combination with a remote total station and digital camera, the distribution of steel nodes and deflection curve of a steel grid structure can be obtained easily. The measurement result shows that this method is effective and utilitarian.

Keywords  steel grid structure; ball nodal point; control grid network; image coordinate; 3D digital model

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Introduction

The grid structure represented by the Bird’s Nest Beijing Olympic stadium presents a symbol of the building construction technology trend of the future. The construction survey of a steel grid structure with a large span is a necessary work for components installation and structure testing. For the practical survey, the tools such as level instrument and steel ruler generally are used in traditional surveying, due to constraints of the domain of ground and space that surround the steel grid structure building. However, the traditional methods are inconvenient to operate and cannot obtain enough data to reflect the whole condition of the steel grid structure. If we adopt remote surveying means to measure the steel grid structure, then it would be easy and able to effectively deal with these problems.

The test object is a steel grid structure building with spherical shape as shown in Fig.1. First, a space control network (or units of group) with 3D reference frame is constructed, and the coordinates of the control points in every control network unit are collected. The feature points distributed on the surface of the ball that link the rods of the steel grid structure as control points should be chosen carefully. The shape and number of each control network unit can be composed in the form of 3 points, 5 points and 9 points, etc., according to the figure and scale of the grid structure field. After rectifying the position of the ball nodal point, the coordinates of the spherical center can be obtained. Second, the coordinates of other ball nodal points located on the steel grid structure can be achieved from the grid structure image coordinates (x, y) shot by digital camera. This means that taking...
the geometry condition of the control network unit as grounds of image rectification and setting up the perspective collineation relationship between the image frame and the space control network frame, we can acquire the coordinates of the spheric center and establish a 3D model of the grid structure which can be used to provide some testing indexes such as span and deflection for structure evaluation.

1 Surveying with remote method

1.1 Construction of space control network

The upper part of the spheric steel grid structure is shown in Fig.1. Observing from outside the building, the grid structure takes a football shape, and from the internal point of view it is a sphere composed of many grid structure units with the shape of pentagon and hexagon, so we can take advantage of its regular geometric figure. The pentagon and hexagon shapes have been chosen as the units of space control network, and the control point is the ball nodal point.

According to surveying intention, the control network can be classified as two kinds: constraining network and checking network. The former can provide necessary known data used in the change of point coordinate from image frame to 3D space frame, or consists of constraining condition to take part observing data adjustment so as to obtain interior or exterior bearing element of image. The checking network provides the contrast data to check against the same point coordinate which is solved from the image and further to evaluate the precision of the result.

It has strong points as follows when these control networks are adopted:

1) The more the checking conditions are, the more the geometric strength of the network shape is.

2) No need to set a mark on the ball, so the observing time can be saved.

3) It is easy to match image pairs in the computer.

1.2 Data collection from control network

According to the location relationship between the building and steel grid structure, two stations on each floor with common reference frame were established, and every ball nodal point distributed on all control network units at these stations was measured. For the reliability of observation precision, the instrument based on two stations of \( A, B \) should be fixed during the surveying at the same floor spot. Because most of the ball nodal points are difficult to access by surveyor, a total station of Type TRIMBLE5600 is used as the surveying instrument which can survey the ball nodal point without reflection prism, and its surveying precision is \( \pm 3 \text{ mm+5 ppm} \).

Supposing the coordinate of station \( A \) is \((X_0, Y_0, H_0)\) and the bearing of directed edge \( AB \) is \( \alpha_{AB} \), therefore the point space coordinate of the control network unit can be obtained from the formula[4] (1):

\[
\begin{bmatrix}
X_i \\
Y_i \\
H_i
\end{bmatrix} = \begin{bmatrix}
X_o \\
Y_o \\
0
\end{bmatrix} + D_i \begin{bmatrix}
\cos \beta_{oi} \\
\sin \beta_{oi} \\
\tan \alpha_{oi}
\end{bmatrix}
\]

Where \( D_i \) is the horizontal distance between station point \( o \) and ball nodal point \( i, h_i \) is the height of instrument sight line, \( \beta_{oi} \) is the bearing of \( oi \).

1.3 Rectification of coordinate to spheric center

As can be seen from Fig.3, if the crosshair on the collimating telescope is distributed symmetrically, and the image of the ball nodal point is located on the plane of crosshair, we can ensure that the sight that crosses the collimation axis is also through the ball nodal center. It is the same case when measuring the image coordinate. If we have found the center point of the circle of the ball image, the point coordinate should be the image coordinate of the spheric core too.

Setting the radius of the ball nodal point as \( r \), then the rectified coordinate of the spheric core is:
2 Solving space coordinate of ball nodal point based on image

2.1 Collection of image coordinate

At the same time, using a digital camera in two known stations we can acquire two or more images that cover the same area of the steel grid structure, and then transfer these images to a computer. After the rotation processing and scale-fitting in images to obtain revised images, we can measure the image coordinate \((x_i, y_i)\) in each image. Usually, the coordinate of ball nodal points in each image should be orthocenter following Eq. (3).

\[
x_i = x_i - x_{ab}
y_j = y_j - y_{ab}
\]

(3)

Where \(x_{ab}, y_{ab}\) are barycentric coordinate of the image \(k\).

When the position of the grid structure compared to the station is very high and the photography distance is limited at the same time, the declivity photography manner has to be used to guarantee that each image contains at least one complete control network unit figure.

2.2 Settlement of image orient element

As to the same image point, its image coordinate and space should meet the need of collineation condition. The collinear image equation is shown in Eq. (4).

\[
\begin{bmatrix}
X_i \\
Y_i \\
Z_i
\end{bmatrix}
= \begin{bmatrix}
m_{11} & m_{12} & m_{13} \\
m_{21} & m_{22} & m_{23} \\
m_{31} & m_{32} & m_{33}
\end{bmatrix}
\begin{bmatrix}
x_i \\
y_j \\
f
\end{bmatrix}
+ \begin{bmatrix}
X_S \\
Y_S \\
Z_S
\end{bmatrix}
\]

(4)

Where \(m_{ij}\) bears the element function of the transformation matrix from the image-plane reference frame to the object-space one and \(k\) is scaling scalar.

With regard to Eq. (4), there are many methods that can be used to solve the image coordinate; one is the image exchange solution such as space intersection (SI) and space resection (SR). First, SR model is selected to obtain the orientation elements of each image, including linear element \((X_S, Y_S, Z_S)\) (camera station coordinate) and bearing element \((\phi, \omega, \kappa)\). Then the image coordinate of the same points that come from different images such as L and R is used. Adding the orientation elements of L and R images, we can solve the space coordinate of every ball nodal point with the SI model. The computing process is described as follows:

1. SR model is usually used to obtain camera station. The linearised functional model based on SR can be written as

\[
v_j = a_j X_S + b_j Y_S + c_j Z_S + \cos(ii) - \cos(LJ)
\]

(5)

In the case

\[
\cos(LJ) = \frac{(X_j - X_i)(X_j - X_i) + (Y_j - Y_i)(Y_j - Y_i) + (Z_j - Z_i)(Z_j - Z_i)}{S_iS_j}
\]

Where \(s_j\) and \(s_i\) are the distances between image point \(i\) and \(j\) to image main point, \(f\) is focus of camera, \(S_i\) and \(S_j\) are the distances between ball nodal point \(I\) & \(J\) to camera station. When the adjustment with least squares is carried out, the coordinate of camera station could be obtained.

\[
X_i = X_0 + \Delta X_i, Y_i = Y_0 + \Delta Y_i, Z_i = Z_0 + \Delta Z_i
\]

(6)

It should be solved in iteration between Eq. (5) and Eq. (6) until \(\Delta X_i, \Delta Y_i, \Delta Z_i\) are close to zero.

2. Model of solving image bearing element using SR.

\[
\begin{bmatrix}
x_i \\
y_j \\
z_i
\end{bmatrix}
= \begin{bmatrix}
m_{11} & m_{12} & m_{13} \\
m_{21} & m_{22} & m_{23} \\
m_{31} & m_{32} & m_{33}
\end{bmatrix}
\begin{bmatrix}
X_i - X_S \\
Y_i - Y_S \\
Z_i - Z_S
\end{bmatrix}
\]

(7)

Based on Eq. (7) with known data, \(m_{ij}\) can be acquired, then the bearing element \((\phi, \omega, \kappa)\) can be done with Eq. (8).

\[
\begin{align*}
\phi &= \arctan(-\frac{m_{23}}{m_{13}}) \\
\omega &= \arcsin(-\frac{m_{12}}{m_{11}}) \\
k &= \arctan(-\frac{m_{23}}{m_{22}})
\end{align*}
\]

(8)

3. Equation of solving ball space coordinate \((X_p, Y_p, Z_p)\) using SI is shown in Ref. [2] which is based on the method of direction cosine with the known station coordinates \(A, B\) (which have been mentioned above and are equal to the coordinates of camera station L and R).

The surveying task of the steel grid structure had been fulfilled by means of a Panasonic MEGA digital camera and total station of Type TRIMBLE- 5600[5].
Each ball nodal point (including control point and image point) obeys the unified standard referenced as before and had been measured. The total number of surveyed ball nodal points is 765. The Eqs. (2), (5), (7), (8), (9) are utilized to compose the solving program, and the point space coordinate of all grid structures have been obtained.

### 3 Result analysis

To evaluate the point precision that relates to the survey instrument and solving model, some 3D points coordinate solved from the image are obtained and compared with the coordinate of the same 3D points that come from the checking network. The result is shown in Table 1:

**Table 1 Different result compared between checking point and image point**

| No | X     | Y     | H    | No | X     | Y     | h    |
|----|-------|-------|------|----|-------|-------|------|
| 1  | -0.007| -0.001| -0.001| 59 | -0.008| -0.003| .013 |
| 2  | -0.004| -0.012| .009 | 60 | .001  | -0.005| .003 |
| 3  | -0.010| .003  | .011 | 61 | .005  | -0.003| .004 |
| 4  | -0.007| -0.002| -0.003| 62 | -0.004| -0.022| -0.003|
| 5  | -0.007| -0.022| .010 | 63 | -0.008| -0.023| -0.003|
| 6  | -0.007| -0.005| -0.009| 64 | .002  | -0.007| .010 |
| 7  | -.012 | -.008 | .005 | 65 | .000  | -.012 | .004 |
| 8  | -.004 | .001  | .002 | 66 | -.001 | -.005 | .005 |
| 9  | -.003 | -.001 | -.003| 67 | -.009 | -.008 | .005 |
| 10 | -.016 | -.012 | -.010| 68 | .004  | -.006 | .002 |

From Table 1, the mean square error of the ball nodal point is obtained with position precision is ±14.8 mm. On the other hand, the difference of coordinate in X, Y and H direction at most points are less than 10 mm. The whole checking data show that the precision of the upper grid structure part is better than the lower part. This case is attributed mostly to the observation environment and not the method itself, so we can say that this method used in the surveying item meets the need of structure testing.

Beginning from the base of the grid structure, the united number of observation ball points have been given according to ball height, then the 3D digital spatial model is built, which can generate a 3D grid structure graph.

Fig. 4 and Fig. 5 are the perspective representations of the upper and lower part of the grid structure respectively. With these perspectives, we can find out the grid structure dynamic from different angles.

### 4 Conclusion

Combining the observation data of total station with digital image data, the distribution of steel nodes and deflection curve of a steel grid structure can be acquired easily. The testing data show that the precision of the solving result reached the aim of demand by means of this method.

Meanwhile, through the surveying on a similar building object, this method is easy and efficient, and can be used in the work of checking and accepting steel grid structures.

Based on the space-coordinate of steel nodes, the 3D model of the steel grid structure has been established and may be observed in different viewing angles. By way of changing the viewpoint S position, the perspective drawing of a three-dimensional spheroid can be demonstrated on the screen in an all-round visual angle.

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