1 Introduction

The great Kwan-yin Statue with a height of 61.9 m in Xiqiao Mountain, Nanhui, Guangdong province is the highest sitting statue in the world. Seen from Fig. 1, the statue surface is forged with 3mm-thick copper sheets. The statue is supported with precise and rational steel structure from the inside. The close-range photogrammetric technique is the essential technical guarantee for the direct creation of the construction drawing. The creation of the statue has gone through three stages, which are the small model, the middle model and the real object with the heights of 0.619 m, 6.19 m and 61.9 m, respectively. By means of the close-range photogrammetric technique, 117 vertical sections and 190 transects were measured with almost 80 thousand collection points. On the basis of the collected data, the construction drawings to forge the statue copper surface was drafted and the quantity of the copper sheets to make the statue was calculated. In this project, an extra high precision industrial control network is established. On the analytical plotter, four stereopairs are processed and the surface processing is done, simultaneously. The copper consumption statistics, especially the direct creation of the construction drawing as well as design and creation of steel prop-up structure are the technical features of the project, too.

1.1 Technical requirements

According to the analysis, the allowed error for the 61.9 m high statue is ±2 cm. As a result, the allowed error of the middle model with the height of 6.19 m is ±2 mm, while the error of the coordinate of image control points is no more than ±0.7 mm. Moreover, in order to work out the spatial coordinates
Fig. 1  Kwan-yin Statue with a height of 61.9 m
of the image control points by means of forward in-
tersection (shown in Fig. 2), for example, to work
out the spatial coordinate of the image control
point $D_2$ between the survey stations $Z_4$ and $Z_3$,
the error of the spatial coordinate of the survey
station should be no more than ± 0.2 mm.

By synchronously processing the four stereopairs
in Fig. 2 on the analytic plotter, the spatial coordi-
nates of each point on the transect $H_1$ ($a, b, c, \ldots, h, i$) can be rapidly acquired and edited in
the same file. The fussy data edition can be omitted
and errors may be found in time.

Having been processed, the relevant data of tran-
sect $H_1$ and the adjacent transect $H_2$ can be pro-
vided directly to the factory as the construction
drawing.

2  Establishment of an extra high
precision industrial control net-
work

2.1 Establishment of an industrial measuring
control network

An industrial control network composed of four
surveying piers ($Z_1, Z_2, Z_3, Z_4$) was established
around the middle model. Compulsory alignment fa-
cilities were placed on each pier. The control net-
work was in a square shape with a sideline of
12 m. Two first-level Invar rod scales were placed
in the middle of the net nearly with the same height
as that of the total station. The prop of the range
finder prism was used as the observation symbol
between the stations. Paint the prop with a black
oil pen and let a peachblow plastic board be the
background for better observation conditions. Mea-
sure five times on each direction of the diagram
with TC2000 Total Station.

2.2 Side length mensuration

According to the relevant method \cite{1,2}, the precise
distance $B$ between two piers ($Z_1, Z_4$) is mensu-
rated with a precision of ± 0.03 mm.

2.3 Acquisition of the control network plane co-
dinates

Supposing the $Z_1$ coordinate (10,000, 10,000),
make the horizontal connection line between $Z_1Z_4$
be axis \(Y\). Establish the \(Z_1-XYZ\) coordinate. In terms of "geodetic quadrangle", implement error adjustment with \(B\) as the real value. After the adjustment, the rectified values of the azimuth angles on each station are \(\pm 0.22^\circ\), \(\pm 0.24^\circ\), \(\pm 0.42^\circ\) and \(\pm 0.39^\circ\), respectively. The RMS \((m_x, m_y, m_p)\) of the surveying piers \(Z_1\) and \(Z_4\) and factors of error ellipse are given in Table 1. The accuracy of directions and side lengths is shown in Table 2, in which the RMS of the direction takes \(\circ\) as the unit and RMS of the side length takes \(\text{mm}\) as the unit and the denominator of the sideline relative error is \(m_s\).

Obviously, the accuracy at this level is far beyond that by other methods.

### Table 1 RMS of surveying piers and factors of error ellipse/mm

| Point | \(m_x\) | \(m_y\) | \(m_p\) | \(E\) | \(F\) |
|-------|---------|---------|---------|-------|-------|
| \(Z_2\) | \(\pm 0.029\) | \(\pm 0.039\) | \(0.048\) | 0.039 | 0.029 |
| \(Z_3\) | \(\pm 0.029\) | \(\pm 0.039\) | \(0.048\) | 0.039 | 0.029 |

### Table 2 Accuracy of directions and sidelengths

| Station~Station | \(m_{ps}/\circ\) | \(m_s/\text{mm}\) | \(1/m_s\) |
|----------------|-----------------|-----------------|----------|
| 1~4            | \(\pm 0.00\)    | \(\pm 0.000\)   | 1/999 999|
| 1~3            | \(\pm 0.41\)    | \(\pm 0.034\)   | 1/498 688|
| 1~2            | \(\pm 0.50\)    | \(\pm 0.039\)   | 1/310 991|
| 3~4            | \(\pm 0.50\)    | \(\pm 0.039\)   | 1/509 998|
| 2~4            | \(\pm 0.41\)    | \(\pm 0.034\)   | 1/497 338|
| 2~3            | \(\pm 0.54\)    | \(\pm 0.032\)   | 1/380 567|

#### 2.4 Precision measurement of surveying station elevation

In order to reach the precision of \(\pm 0.2\ \text{mm}\), the method combining vernier caliper with automatic level can be used for the precision measurement of surveying station elevation.

#### 2.5 Determination of the spatial coordinates of image control points

Inversely stick the color thumb pins to the appropriate position on the statue. Treat the tips of the thumb pins as the control points. Each stereopair has more than seven symbols such as \(D_1, D_2, D_3\) and \(D_4\) in Fig. 2. Compute the object spatial coordinates from the corresponding surveying piers in the way of forward intersection and indirect elevation.

According to the estimation equation of RMS \(m_p\) in the forward intersection plane coordinate, assume its weakest direction is taken, then we can obtain \(m_p = \pm 0.11\ \text{mm}\).

According to the estimation equation of RMS \(m_h\) of the indirect elevation method, and taking the weakest status, we can obtain \(m_h = \pm 0.12\ \text{mm}\).

Set some symbol points in different parts of the control network. Determine their spatial coordinates in terms of different surveying piers combination. The coordinate differences are all smaller than \(\pm 0.25\ \text{mm}\). This process is used to inspect the quality of the network.

It is obvious that the real precision of the control points is prior to the proposed requirement which is \(\pm 0.07\ \text{mm}\), which seems to suggest losing the requirement in the real operation.

#### 2.6 Establishment of statue model coordinate system \(M-XYZ\)

By confering with Party A, the plane coordinate origin of \(M-XYZ\) should coincide with the plumbing central line of the column (lotus stand) on the statue bottom. The elevation coordinate origin should coincide with the upper surface of the column.

1. Determine the two dimensional coordinates \((X_i, Y_i)\) of the 96 points on a round of the lotus stand in \(Z_1-XYZ\);
2. Compute \((X_i, Y_i)\) and the radius \(R\) according to the following relational expression

\[
(X - X_o)^2 + (Y - Y_o)^2 = R^2
\]

The observation equation of the fitting round is

\[
[(V + V_x) - (X_{C_o} + dX_c)]^2 + [(Y + V_y) - (Y_{C_o} + dY_c)]^2 = (R_0 + dR)^2
\]

Thus, the condition equation with the unknown number \(AV + BX + W = 0\) has the following form with the rectified number \(dX_c\) of the approximation:

\[
[(X - X_{o})(Y - Y_o)] \left[ \frac{V_x}{V_y} \right] + [(X - X_{o})(Y - Y_o) - R_0] \left[ \frac{dX_c}{dY_c} \right] + [(X - X_o)^2 + (Y - Y_o)^2 - R_o^2] = 0
\]
2.6.2 Transformation between $Z_1$-XYZ of surveying pier coordinate system and $M$-XYZ of model coordinate system

According to the computed values of $(X_c, Y_c)$ and the origin position of the elevation, the three dimensional conformality transformation from $Z_1$-XYZ to $M$-XYZ, especially the transformation of the coordinates of each control points, is realized. During the course of the transformation, the connecting line between the two earlobes is treated as axis $X$ of $M$-XYZ. Assign $(50.00 \text{ m}, 50.00 \text{ m})$ for the central axis of the lotus stand.

In addition, in $M$-XYZ, check and fit the second round $(Z = 1.23 \text{ m})$ and the third one $(Z = 6.58 \text{ m})$ on the lotus stand. The coordinates of the circle's center $(X_c, Y_c)$ are obtained as Table 3 shows.

| $Z$  | $X_c$ | $Y_c$ |
|------|------|------|
| 1.23 | 50.09| 49.96|
| 6.58 | 49.98| 49.93|

### 3 Photographic and some relative problems

#### 3.1 Surface Treatment

The intensity of GRP texture of the middle model is very good. However, the surface is offwhite with few veins. To assure the three-dimensional correctness, manual processing, e.g., using the black oil pen to draw the lines by hand, has been carried out on the surface.

#### 3.2 Photographing

Photographing the four major stereopairs is made in the manner of vertical image frame with Swiss P31 video camera. The photographing distance is about $7 \text{ m}$, while the base line is about $1.7 \text{ m}$ and the photographing height is about $3.5 \text{ m}$ (distance to the ground). The purpose to select the above data is to cover the whole statue from one side without any significant blind angle. Moreover, estimate the photographing error on the weakest direction according to the following equation, the error value will not surpass the specified limit value as $\pm 2.5 \text{ mm}$, 

$$m_Z = \frac{Z^2}{B_f} \sqrt{\frac{2}{y_2}} m_{X,Y} = \frac{(7000)^2}{1700 \times 100} \sqrt{2} \times 5 \mu \text{m} = 2 \text{ mm}.$$

Check the real lengths in a photogrammetric way with the Invar rod scale laid in the control network. The length differences are smaller than $\pm 1.5 \text{ mm}$. The RMS $m_X, m_Y, m_Z$ of the residual error of the absolute directional object spatial coordinate is smaller than $\pm 1 \text{ mm}$, from which the real accuracy of the photogrammetric work in this project can be obtained.

The four stereopairs are straight photographed ones, whose main optic axes face the front side, left side, right side and back side of the statue, respectively.

The natural light indoors is the main illumination source with some kinds artificial light as the auxiliary. In the process of photographing, the collimating mark imaging quality and symbol imaging are paid special attention to. The secondary illumination measure collimating mark is adopted when necessary. Some specific symbols are matched with necessary backgrounds for a clearer visual effect.

Some straight stereopairs of comparatively large scales are photographed for complementarity for the hidden and important parts.

### 4 Photogrammetry

#### 4.1 Synchronous processing of the four stereopairs on the analytic plotter

Place the eight photographs of the four stereopairs on the left and right photograph plates to carry out the synchronous processing on the $BC_2$ analytic plotter, as shown in Fig. 3.
opair processing, this method has the following advantages:

1) The four stereopairs all use inner orientation, relative orientation and absolute orientation so that the united orientation quality can be assured.

2) The four stereopairs cover the whole statue from the front, back, left and right. As a result, with support of special software, it is unnecessary to exit the program when doing data collection. Select the current data model for model (stereopair) transformation. Record all the data of a certain section into the same file. We can use the front and back stereopairs (11-12 and 31-32) to record all the data of a certain section into the same file. We can also use the front, back, left and right stereopairs (11-12, 21-22, 31-32 and 41-42) to record all the data of a certain section in to the same file. This method has an apparent effect on assuring achievement quality, reducing fussy data editing workload and enhancing the production efficiency. It is also one of the important reasons for the rapid accomplishment of the project.

4.2 Orientation quality

The results of inner orientation, relative orientation and absolute orientation of the four major pairs are listed in Table 4. The data illustrates the feasibility and precision level of the high precision control survey and synchronous processing of the four pairs.

The \( m_x, m_y, m_z \) in the absolute orientation volume in Table 4 represent the RMS of the object spatial coordinate residual error of each orientation point.

| Stereopair | Inner orientation/mm | Relative orientation | Absolute orientation/mm |
|------------|----------------------|----------------------|-------------------------|
|            | \( m_x \) \( m_y \) \( m_x \) \( m_y \) \( m_x \) \( m_y \) \( m_x \) \( m_y \) \( m_z \) | Total of points | RMS of vertical parallel line \( m_x \) \( m_y \) | Total of points | \( m_x \) \( m_y \) \( m_z \) |
| 11-12      | \( \pm 0.002 \) \( \pm 0.001 \) \( \pm 0.002 \) \( \pm 0.001 \) | 21 | \( \pm 0.002 \) | 12 | \( \pm 0.518 \) \( \pm 0.482 \) | \( \pm 0.560 \) |
| 21-22      | \( \pm 0.003 \) \( \pm 0.000 \) \( \pm 0.002 \) \( \pm 0.003 \) | 25 | \( \pm 0.001 \) | 7 | \( \pm 0.950 \) \( \pm 0.422 \) | \( \pm 0.536 \) |
| 32-32      | \( \pm 0.003 \) \( \pm 0.007 \) \( \pm 0.001 \) \( \pm 0.007 \) | 32 | \( \pm 0.001 \) | 9 | \( \pm 0.365 \) \( \pm 0.376 \) | \( \pm 0.510 \) |
| 41-42      | \( \pm 0.003 \) \( \pm 0.003 \) \( \pm 0.003 \) \( \pm 0.003 \) | 18 | \( \pm 0.001 \) | 7 | \( \pm 0.532 \) \( \pm 0.225 \) | \( \pm 0.505 \) |

4.3 Section surveying

According to the producing necessity, let the space between the sections of the common parts be 5 cm and the space between the sections of the important parts 2.5 cm. This project has drawn 190 transsects and 117 vertical sections. There are 78,289 collection points in the section surveying. Including the interpolation points, there are more than 140,000 three dimensional spatial coordinate points.

5 Solution of the intersection point coordinate of cross and vertical sections

The fiducial mark of the intersection point of the cross and vertical sections on the given axis \( Y \) is necessary in the producing process. As shown in Fig. 4, the cross section line \((1, 2, 3, 4, 5)\) on the given axis \( Y \) cannot intersect at the same point, which is caused by the photogrammetric error. Let the coordinates of the two points be \( A_1(17,000, 29, 247, 45,000) \) and \( A_2(17,000, 29, 253, 45,000) \). Get the mean value of \( Y \) values as the final result, that is, \( A(17,000, 29, 250, 45,000) \). The condition for the mean value is that the difference of the two

Fig. 4 Solution of intersection point coordinate of the cross and vertical sections
point's Y values do not surpass ±2 cm (on the real statue).

6 Direct creation of interpolated point and statue construction drawing

The objective to produce the interpolation points is to improve the working efficiency. Take a certain cross section as an example. As shown in Fig. 5, the Arabic numeral annotations are the collection points, and the signals “×” are the interpolation points. It is obvious that using the interpolation points for lofting is rapid and convenient.

The total of the construction drawing pieces for the statue surface forging is just 307. Each drawing is composed of three parts:
- the sketch drawing of the section with the name. Beside the major inflection points of the section, mark the inflection points as \((A, B, C, \ldots)\);
- the accurate enlarged drawing of the curve between two interpolation points, e.g., \(B\) and \(C\), with the marked number 18, 19, ..., 30;
- the two dimensional coordinate of each point.

The workers carry out the lofting process according to the data mentioned above.

It should be emphasized that with the data the steel structure experts design and produce the complicated steel prop structure inside the statue. All the required data for the construction drawing is stored in four floppy disks. In addition, the choriso-pileth of the middle model is specially drawn for reference.

7 Statistics of surface area and volume of the statue

The surface of the Kwan-yin Statue is made of 3 mm-thick copper sheet with a gross consumption of 700 t. According to the management requirement, the surface area is computed in terms of the triangle area method for the total consumption of the copper sheet.

Set the vertex coordinates of the triangle as \(A(X_A, Y_A, Z_A), B(X_B, Y_B, Z_B), C(X_C, Y_C, Z_C)\), the triangle area is

\[
S_{ABC} = \frac{1}{2} | \begin{vmatrix} AB \cdot AC \end{vmatrix} = \frac{1}{2} | (X_B - X_A) \cdot (X_C - X_A) + (Y_B - Y_A)(Y_C - Y_A) + (Z_B - Z_A)(Z_C - Z_A) |
\]

Fig. 6 shows that collection data points on the two adjacent cross sections, \(Q\) and \(R\), can form a series of “tiny” triangles. The sum of the tiny triangle areas is considered as the consumption of the copper steel between two sections.

When the sample points on the high and low curves are different, especially when the collection point density on the opposite positions is of great difference, the Lagrange point interpolation method and manual point rejection method are adopted to solve the problem. A special program is designed to calculate the surface area. The total surface area of the copper sheet is about 7,000 m².

8 Conclusion

1) This study is an example of direct creation of
construction drawings in mechanical industry. In the process of forging objects with complicated configurations, the close-range photogrammetry and the matching technologies are fit for the requirements of multiple survey points, high precision and so on.

2) The synchronous processing of four stereopairs on the analytic plotter is an effective measure to assure the higher speed for close-range photogrammetry and to decease the frequency of errors and mistakes during the data processing.

3) The establishment of extrahigh precision industrial control network and the high quality of the image control points are the technical guarantee of this project.

4) The surface treatment technology, which is short of texture objects, is essential.

5) The computation and statistics of other geometric senses based on spatial coordinate are the common requirements. This study has searched for methods to compute the surface area and volume of the industrial objects.

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Notes to Contributors

Contributions are welcomed on one of the following subjects or in related areas:

- GIS
- Geodynamic
- Physical geo-surveying
- GPS
- Geo-surveying
- Engineering surveying
- RS
- Photogrammetry
- Mapping apparatus
- Cartology
- Graphics

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