CONTROL WORK IN CLOSE RANGE PHOTOGRAMMETRY

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KEY WORDS close range photogrammetry; control work; high accuracy; industrial control net

ABSTRACT The purpose, classification, required accuracy and surveying methods of control work for close range photogrammetry have been briefly stated. The different methods for definition of space object coordinate system are also reviewed. It is suggested that the habitually-practised rotation angle system for aerophotogrammetry in China should be used for the future teaching and researching work in the close range photogrammetry, and that the rotation angle system for terrestrial deformation photogrammetry should be left out in order to avoid the confuse and reduce the amount of expense for making softwares. It has been emphasized that there are three important aspects in the close range control work with high accuracy using the conventional method of engineering surveying: the use of standard scale for measurement of distance between two general stations, the accurate determination of start direction line between two general stations and the handling method of influence of 2C change. A method for setting up industrial surveying control net with extra-high accuracy $\pm (0.05-0.20)$ mm is presented by the author. This kind of industrial control net is necessary for batch process of large industrial components with purposes of measurement, inspect and lofting. There are some special methods of control work in the close range photogrammetry, including two methods presented by the author.

1 Introduction

By virtue of the control points and/or relative control work, the main objective of control surveying in close range photogrammetry is to bring the close range photogrammetric net under the specified object space coordinate system. Besides the selection of object space coordinate system, the design of control points and relative control work, the methods for control surveying and the selection of surveying apparatus, the content for control work includes the methods for establishing indoor control system and moveable control system.

2 A Summary of control work in close range photogrammetry

There are three objectives to implement control work in close range photogrammetry: 1) bringing the close range photogrammetric net under the specified object space coordinate system, 2) by means of redundant control work (including control points or relative control work), enhancing the intensity for photogrammetric net, 3) by means of the redundant control work or relative control work, inspecting the accuracy and reliability for photogrammetry. Control points and relative control are two classes of control in close range photogrammetry. Control points are generally identification marks with known coordinate on or around the object to be measured. Relative control is a certain known geometric relationship among the unknown points in...
photogrammetric processing, e.g. the known length between two unknown points in object space. Although relative control is comparatively less used, when unable or inconvenient to lay control points, it is the only choice.

In close range photogrammetry, the determination of 3D control points in principle adopts the routine surveying method. However, as the demands for determination accuracy of control points is very high (reaching the submillimeter level or even higher), certain specific details of the operational considerations are different from those of the routine method. Besides using the routine methods, the layout for 2D control points may use 2D coordinate measurement apparatus. This kind of 2D control may be applied for simulating test of optimal design as well as calibration on different cameras including digital cameras. Besides using the routine methods, the layout for 1D control points may use a certain standard scale, such as Invar Scale, Levelling Rods of different grades, lengths engraved on glass or metal in micrometering, and even some microorganism with standard lengths.

In close range photogrammetry, only the shape and size but not the absolute location of the object is necessary. According to this demand, for determining an object space coordinate system including a close range photogrammetric net in it one can adopt one of the following methods or use them comprehensively, which is shown in Fig. 1.

1) After the object space coordinate system being initiated, the close range photogrammetric net according to the laid control points is included. Set an object space coordinate system D-XYZ near the object. According to a group of measured control points in the coordinate system (at least two 3D control points and one 1D control point are needed e.g. \( P_1, P_2 \) and \( P_3 \)), the established photogrammetric net is included, as Fig. 1 shows. This method is the same as the routine aerophotogrammetry.

2) After the exterior orientation element for a certain photo to define object space coordinate system being assigned, the photogrammetric net according to the known lengths of the object space is included.

Assign values for a certain photo in the close range photogrammetric net. For example, assign values for photo \( P_1 \) in Fig. 1 (\( X_1 = 1000 \), \( Y_1 = 0 \), \( Z_1 = 3000 \), \( \varphi_1 = 45^\circ \), \( \omega = \kappa = 0^\circ \)), so as to determine the origin and coordinate axial direction for D-XYZ. Then include the photogrammetric net according to the known lengths (at least one known length).

The known lengths for object space can be selected as: (1) the known length measured on or around the object, including the standard scale, e.g. MN, (2) measuring the distance between two photographic centers, i.e. photobase, e.g. \( B_{12} \), (3) measuring the distance between a certain photographic center and an object space point, e.g. \( D_1 \).

3) Assign values for an object space point to define the object space coordinate system. Then according to the relative control of object space line, the photogrammetric net is included.

Assign values for object space points (for example, assign value for the 3D coordinate of Point \( M \). Set point \( M, N \) and \( Q \) of the same height and assign value for \( a \) in \( MN \) direction.) to define the object space coordinate system D-XYZ. Measure \( MN = L \) on the spot and include the photogrammetric net.

From the above arguments, there are diversified methods to define photogrammetric object space coordinate system and to include the photogrammetric net. Making the right selection may decrease the workload of control and result in more suitable outcome for the demand of specific objects.

A concise analysis about the determination accuracy of control points can be made as follows. Supposing the RMSE of undetermined point \( m \) consists of the RMSE of control point \( m_{\text{control}} \) and the
RMSE of $m_{\text{photogrammetry}}$

$$m = \sqrt{m_{\text{control}}^2 + m_{\text{photogrammetry}}^2}$$  (1)

In order to make $m_{\text{control}}$ have no effect on $m$, set $m_{\text{control}} < m_{\text{photogrammetry}}/3$ to define the determination accuracy requirement for control points. As $m_{\text{photogrammetry}}$ can be pre-evaluated, the determination accuracy for control points may be set in advance.

For the relative control, e.g., relative control of length, the similar methods can be used to propose reasonable demands for the determination accuracy.

3 General measurement methods for close range control points

In actual measurement of close range photogrammetry, the coordinates of control points $(X, Y, Z)$ are measured and calculated with the common methods. With regard to the close range photogrammetry control at submillimeter level, first calculate the plane coordinates $(X, Y)$ using forward intersection method, then calculate the elevation $(Z)$ with indirect elevation method.

To make the determination accuracy reach the submillimeter level, there are three problems to be considered during the operation.

3.1 Determine the distance between two general stations with “the standard scale method”

The distance between two general stations $A$ and $B$ is $s'$, as Fig. 2 shows. Only when the accuracy reaches a high level (such as $+0.1$ mm), will the accuracy of control points reach the level of submillimeter. Comparatively speaking, “the standard scale method” is the most suitable way. Former Wuhan Technical University of Surveying and Mapping adopted this method for the latest determination of the indoor control field. Other methods, including using distance finder such as ME5000 or Invar rod, can hardly determine the distance between two stations simply with high accuracy (e.g., $+0.1$ mm).

3.2 Determination of initial direction of horizontal angle

For the determination of the initial direction of horizontal angles, the following methods may be selected and used according to different situations.

1) Method of collimator. When using two theodolites simultaneously, adjust their focuses to infinite distance and make them see each other’s cross wire. At that time, the two axes of collimation are parallel but not coincided. As Fig. 3 shows, the two axes both have an included angle $\theta$ with the connecting line of $A$ and $B$. Readjust the focus, aim at the mark $m$ on the other objective lens system to shorten $\epsilon$. With this method, the accuracy may reach about $0.1^\circ$. However, the requirement towards the ID location of $m$ is restricted, which is not easy to operate.

2) Method of rotating the measuring theodolite. When determining the initial directional line from Station $A$ to Station $B$, select or set the plumb object on the theodolite on Station $B$. Read the horizontal angles on the left and right pans of Station $B$. Rotate the apparatus in Station $B$ by $180^\circ$ around the vertical axis. Then observe the originally selected object in Station $A$. Before and after the rotation, the average angle value to this object is the reading number of horizontal initial directional line from Station $A$ to Station $B$. The selection of two objects may check or increase the determination accuracy.

3) Method of selecting symmetric objects. When determining the initial direction from Station $A$ to Station $B$, select an accurate symmetric object on a certain accessory (such as prism rack post of distancer) in Station $B$. 
With the method 2) or 3), the determination accuracy of initial directional line may reach ± (1-2)°.

3.3 2C change caused by focus adjustment

Apparent 2C change exists in the short distance observation. Generally, the method of circle measurement is used to counteract the effect of 2C. In special circumstances, the changing law of 2C should be measured in advance. Adopt the online operations and pre-estimate whether the effect value of 2C is tolerable.

4 Methods for establishing extra-high accuracy control net in industrial

4.1 Measurement

An industrial control net with high accuracy at submillimeter level is necessary for batch process of large industrial components with purposes of measurement, inspect and setting out. In terms of the size of components, the control net is composed of several to tens of measurement pillars with the control coverage to nearly hundreds of square meters. The coordinate accuracy of the measurement center should reach the level of (0.1-0.2) mm.

In industrial measurement, the method for establishing such an industrial control net with high accuracy was proposed in 1996 by the author and started its application. In 1999, the method was published\[j\]. The following are the supplementary materials.

4.2 Method for determining the baseline length between two general stations

Suppose that there is a control net as Fig. 4 shows, the angle between each pair of stations as $S_1, S_2, \cdots, S_6$ can be measured accurately. In order to determine $S_1 S_2$ and $S_3 S_4$, standard scales of $MN$ and $OP$ are set in the appropriate places of the intersection angle. After obtaining the approximate plane coordinates of each station, restricted error adjustment may be carried out according to the related geodetic net. Thus the plane coordinate values for each station after adjustment can be obtained.

The first level Invar rod scale has score mark errors (about ± (9-14)μm) and other errors. The error of the first level Invar rod scale after rigorous calibration may reach about ± 1 μm. However, the error of the first level Invar rod scale without calibration may reach 20 μm or even larger. In this method, the standard scale only needs to inspect the coordinates of the two endpoints but the others. As a standard scale, other standard lengths, such as horizontal baseline scale and various kinds of precise rulers with the length of 1 m, 2 m or even longer, can be selected or designed. After the inspection, if it is necessary to consider the temperature change effect, the scales of (1-3) m can be utilized to lay control nets of diversified shapes and sizes with the side length ranges from 3 m to 10 m or even longer.

Place the two endpoints of Scale $MN$ on a round with $AB$ as the diameter, as Fig. 5 shows. Make $MN$ and $AB$ approximately parallel, then the intersection angle is around 90°, and the distortion of image is smaller as well. At the same time, according to the rough-estimation formula of forward intersection of two points, ignoring the error on $X$ direction, the error of $M$ on $Y$ direction may be

$$m_y^2 = \left(\frac{S \cdot \sin \sin a_{AM}}{\sin^2 (a + \beta)}\right)^2 m_\beta^2 + \left| b \cos a_{AM} - \frac{S \cdot \sin \beta \cos (a + \beta) \sin a_{AM}}{\sin^2 (a + \beta)} \right|^2 m_a^2$$

(2)

Because $\cos (a + \beta) \approx 0, \sin (a + \beta) \approx 1$, then we have

$$m_y^2 = (S \cdot \sin a_{AM})^2 m_\beta^2 / \rho^2 + (b \cos a_{AM})^2 m_a^2 / \rho^2$$

(3)
Suppose that \( m = m_a = m_b \). The measured point accuracy on \( MN \) is the function of \( a \),

\[
m_{Y_M} = \frac{m_s}{\rho} \sqrt{\sin^2 a \cos^2 a + \cos^2 a \sin^2 a} = \frac{\sqrt{2} m_s}{\rho} \sin 2a
\]

(4)

and

\[
\tan a_M = \sqrt{S^2 - L^2} / (S - L)
\]

\[
\tan a_N = \sqrt{S^2 - L^2} / (S + L)
\]

(5)

thus, the relational expression of RMSE of scale \( L \) can be written as:

\[
m_L = \sqrt{m^2_N + m^2_M} = \frac{\sqrt{2} m_s S}{\rho} \cdot \sin 2a + \frac{m_s S}{\rho} \sin 2a
\]

(6)

Suppose \( S = 9 \) m, \( L = 3 \) m, \( m_a = \pm 1^\circ \), then there is \( a_M = 60^\circ, a_N = 30^\circ \),

\[
m_M = \pm \frac{\sqrt{2}}{2} \frac{1}{206} 265 \times 9000 \sin 120^\circ = \pm 0.026 \text{ mm},
\]

\[
m_N = \pm 0.026 \text{ mm}, m_L = \pm 0.036 \text{ mm}, m_s = \pm 0.11 \text{ mm}
\]

Several plied projects have proved that the above theory is accurate as a whole\(^1\). For example, a control net is composed of eight measurement pillars in a steel-organized workshop, the plane RMSE is swinging from 0.00 mm to 0.12 mm. The apparatus is Power Set 2010 Total Station at 2" level.

4.3 Precise method to determine the elevation of measurement pillar

In industrial measurement, the accuracy of the elevation of each measurement pillar of the extra-high accuracy control net should correspond to the accuracy of its plane coordinate. When the accuracy of plane coordinate reaches \( \pm 0.10 \) mm, the height vernier caliper and automatic level can be adopted to determine the elevation. Elevation RMSE may reach an accuracy of \( \pm 0.05 \) mm\(^2\). Before the determination, the levelness of the compulsive alignment apparatus's plane should be guaranteed within 1°.

The objective and method for establishing an indoor control field and creating a 3D moveable control system have been described generally by many researchers\(^{3-6}\).

5 Some specific methods for control

There are some specific methods for establishing the object space control in close range photogrammetry. They are listed as follows.

5.1 Control of measured distances

When the object space is sure to have a plane, but no IDs (such as plane frescos) are allowed to be attached, apparent points on the plane can be selected to compose a polygon of a certain shape. As Fig. 6 shows, measure the side lengths and diagonals with a precision steel ruler, then, carry out digital processing according to the routine side-measurement net to obtain the coordinates of each point with a certain point as the origin. This method is only applicable to control with low accuracy.

5.2 Control of special geometric features of measured objects

When the objects to be measured have obvious geometric features, such as obvious parallel line sets, groups of right-angle relations among lines, equidistance relations or proportional relations between line segments (for example, outer frames of windows and doors of ancient or modern buildings, rails in workshops in plants), they can be used for control work with analog method or analytical method in close range photogrammetry.

5.3 Grid and raster

Grids and rasters of different sizes (large in 1-2 m, and small in scores of \( \mu \)m) can be used for control work in close range photogrammetry and even micro photogrammetry.

5.4 Control using fixed length of microorganism

In micrometering or electronic micrometering, when it is difficult to handle with control of a too small size manually, the geometric size of a certain...
5.5 Establishment of control net using method “standard ruler”

When it is required to establish a control net with medium and low accuracy in a very narrow space, the method “standard ruler” presented by the author can be adopted. Suppose that the side length of a quadrangled control net MNOP is about 3 m. Put a 1 m standard ruler in the central part of the control net, as Fig. 7 shows. The operation steps are as follows:

1) Determine that the edge of score lines is the axis Y of the object space coordinate system. The axes X and Y are on the same horizontal plane. The plumb line is the axis Z.

2) Take some graduations as the known plane control points (endpoints and the center respectively). The Y coordinates of the points can be determined by Y graduation while their X coordinates are equal.

3) Place a general station in sequence on M, N, O, P respectively. The selection of the points’ positions should take backward intersection angles and forward intersection angles into consideration.

4) Carry out backward intersection according to the selected point position on the standard ruler. Determine the plane location of the vertical axis of the theodolite. The RMSE of point position of backward intersection can be calculated as follows:

\[ m_p = \frac{mb}{\rho \sin(\gamma + \delta)} \cdot \sqrt{\frac{(a_1}{s_1})^2 + \left(\frac{a_2}{s_2}\right)^2 - \left(\frac{a_1}{s_1}\right)\left(\frac{a_2}{s_2}\right)\cos(\gamma + \delta)} \]

(7)

It is noted that the known points A, B, and C are on the same line, as Fig. 8 shows. The relational expression is:

\[ a_1 \approx a_2 \approx b, \quad s_1 \approx s_2 \approx s, \quad a + \beta = 180^\circ - (\gamma + \delta) \]

Thus,

\[ m_p = \frac{mb^2 \sqrt{2 + \cos(a + \beta)}}{\rho s \sin(\gamma + \delta)} \]

(8)

Suppose \( s = 0.5 \) m, \( b \approx 2.0 \) m, \( a + \beta = 30^\circ \), \( m = \pm 2^\circ \), then the RMSE of the point position of backward intersection is

\[ m_p = \pm \frac{2.0}{206265} \cdot \frac{2000}{0.5} \cdot \frac{\sqrt{2 + 0.87}}{0.5} = \pm 0.26 \text{ mm} \]

Take several groups of outcome of backward intersection, the accuracy of the plane position of the general station point is expected to increase.

It is not easy to determine the distance between two general stations and reach such an accuracy by means of routine methods. The advantage of this method is that it is unnecessary to determine the angle of control net and to set the corresponding alignment objects. Only an apparatus is used for determination.

5.6 3D coordinate determination based on the theory of microscope depth of field

The theory to determine control points in a moveable 3D control system is based on the depth of filed relational expression of optical microscope, i.e.

\[ 2d_x = \frac{250 \pi \varepsilon}{\tan \alpha} \]

(9)

where \( 2d_x \) is the depth of filed with mm as the unit; \( \varepsilon \) is the degree of arc of limiting angle (about 2.75' of the blur circle, whose value is 0.000 8 which equals to the 0.2 mm on the visibility distance. \( n \) is the optical refraction index with the value of 1. \( N_A \) is the numeric aperture of the microscope with a value of 0.5, that is, \( n \cdot \sin \alpha = 0.5 \),
where $\alpha$ is 30°; $\Gamma$ is the total enlargement factor of the microscope.

If $\Gamma = 100, 2d_{e}$ will only be 0.004 mm. Even if the ability of adjustment and adaptability of the human eyes is taken into consideration, the depth of field will only be 0.01 mm.

According to the above theory, with regard to an apparatus with functions to determine 3D coordinates, a microscope can be fixed on an appropriate part of its vertical direction. With the aid of movement of the microscope on three directions, whenever the ID image is clear with naked eyes and is aiming at the center, its 3D coordinate values can be read.

5.7 Functions of relative control

Length relative control, especially several known lengths laid in object space, is the most commonly used relative control. According to the object space coordinate system defined in Fig. 1, in terms of several standard scales or known lengths with IDs on the two endpoints, a close range photogrammetric net with high intensity can be established. Having a close relationship with the net intensity, the layout of length relative control includes the quantity, length, accuracy, position and location, which should be designed optimally.

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It can be concluded that if a higher resolution digital camera is used and strict control is taken over the data, the PhotoModeler-AutoCAD-DSM method will achieve better results and may be applied in other fields for high precision 3D survey on objects with complex surface.

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