THE THEORY AND APPLICATION OF THE STRUCTURE LIGHT ENGINEERING SURVEYING BASED ON A LASER THEODOLITE WITH THREE FREEDOMS OF ROTATION

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KEY WORDS structure light; engineering surveying; laser theodolite; three freedoms of rotation

ABSTRACT The concepts of "confining structure" and structure light are illuminated in this paper. A laser theodolite with three freedoms of rotation, which is aimed at "confining structure", is developed. Various scanning modes and their mathematical models based on laser theodolite with three freedoms of rotation are discussed. According to the features of a huge object, the structure light engineering surveying based on laser theodolite with three freedoms of rotation is determined as the main method in an actual application. The observation of four sound concrete posts and forced centering plates. Subsequently, it is transformed into the huge object coordinate system. The scanning mode with plumb plane is selected as the main mode in the whole work. And other assistant methods, such as close range photogrammetry and the method of using reflection sheet, are applied to the work of "scanning dead angle". At last, a surveying accuracy estimation of this method is done and a surveying accuracy test is finished. It can be concluded that the structure light engineering surveying based on laser theodolite with three freedoms of rotation is considered to be an effective and applied method, and has many superiority to some other surveying methods in the work of surveying "confining structure".

1 Introduction

In our country, the surveying work on industrial objects have gradually increased. Those industrial objects include railway and highway tunnels, various oil and gas cans, various aircraft, shell of cars, large military antenna used for scouting stealth plane, ship, internal structure of important building etc. The demand for precision is different from the general surveying, in addition, those objects still have some features that it lacks texture and it is hard to place a ruler and prism at them. Sometimes, there are some other disadvantages, such as narrow surveying space. Thus general surveying methods can not be used.

At present, there are not unified understandings to surveying method for those industrial objects in our country. General surveying methods have not only low precision but also low efficiency. Some advanced instruments from foreign countries are highly automatized, but their prices are also very high and the instruments belong to some trades, or even an enterprise, so the using efficiency is low, moreover, their functions may not be higher. According to the condition in China the authors consider the surveying method which has low investment and medium precision fit for various "confining structures" is based on the theory of structure light[3]. The structure light is a set of projection light whose location is known. The instruments that generate structure light can project grid, grating, stripe and
spot on objects surveyed. The instruments that survey structure light may be camera and video camera and some instruments surveying angles, which can survey the space locations of projection light and projection spot. Obviously, the structure light on confining structure lacking grain is beneficial to the surveying performance. Now, a huge number of instruments generating structure light in surveying field are general laser theodolites, which have two freedoms of rotation. A few years ago, it was used in the surveying task on confining structures[1].

Some shortcomings of general laser theodolite which has scanning dead angle of 90 degrees, unfit for the measurement of some vertical structures and the section surveying of coincidence between object space coordinate system and “global coordinate system” are the main reasons for developing the laser theodolite with three freedoms of rotation[2,4]. The studies, besides the study on instrument’s hardware, include mathematical models of laser light scanning forms and tests based on structure light photogrammetry. There are two kinds of instruments in “forward intersection”. One is laser theodolite, and the other, camera (or TV camera). After the single picture (or image) having the image of laser spot treated, the 3D model of the object surveyed can be obtained, then it undoubtedly, simplifies the surveying process and provides a better surveying plan for the object lacking veins. But sometimes, a plan based on structure light photogrammetry is not the best. According to precision, efficiency, work condition, equipment and manpower, the engineering surveying plan based on structure light is better. This paper develops the mathematical models and computation formulae in plane scanning mode, cone scanning mode and scanning mode with hyperboloid of one sheet using laser theodolite with three freedoms of rotation mentioned in theory, and the models and formulae are proved in an engineering surveying task.

2 The scanning theory of laser theodolite with three freedoms of rotation

2.1 The scanning modes of laser theodolite with three freedoms of rotation

General theodolite has two freedoms of rotation, they are the rotation freedom circling the vertical axis (primary axis) and the rotation freedom circling the horizontal axis (secondary axis). Besides the two freedoms of rotation mentioned above, the laser theodolite with three freedoms of rotation has the third rotation freedom circling collimation axis, which is called the third axis. Laser theodolite with three freedoms of rotation can perform various scanning modes according to different industrial objects. The sections of object whose own coordinate system is $D'-XYZ$ and axis Z is not vertical, as shown in Fig. 1 (a), can be surveyed using scanning mode with plane, and the scanning plane matches the $D'-X'Y'Z'$ coordinate system. If general laser theodolite is used for this kind of object in normal method, the object (even a huge airplane) must be placed in horizontal status strictly. In order to survey the shape or distortion of a symmetrical object (such as columnar oilcan), as shown in Fig. 1 (b), it is reasonable to place laser theodolite in the interior of the object and scan the object according to scanning mode with circular cone surface. When laser theodolite is placed on the top of the object and is used to scan it downward, the scanning mode

![Fig. 1](image_url)
2.2 Scanning mode with plane

When the collimation axis of general laser theodolite circles the horizontal axis, the scanning mode with plane is formed. The point of forward intersection between the straight and the plumb plane is the solution to the unknown point. To a certain point, it is the forward intersection of two straights, as shown in Fig. 2. In order to measure the coordinates of unknown points, it is feasible to select two kinds of original directions.

2.2.1 Scanning mode with plumb plane according to the original direction paralleling the X axis of object coordinate system

As shown in Fig. 2, it is obvious that:

\[
\begin{align*}
(Y - Y_T)/(X - X_T) &= \tan H \\
(Y - Y_L)/(X - X_L) &= \tan A
\end{align*}
\]

(1)

So, the plane coordinates \(X, Y\) are respectively:

\[
\begin{align*}
X &= (X_T \tan H - X_L \tan A + Y_L - Y_T) / (\tan H - \tan A) \\
Y &= (X_L \tan H \tan A - (Y_L - Y_T) \tan H) / (\tan H - \tan A)
\end{align*}
\]

(2)

and furthermore, the two solution equations of elevation \(Z\) are

\[
\begin{align*}
Z &= Z_T - \tan(90^\circ - V_T) [(X - X_T)^2 + (Y - Y_T)^2]^{1/2} \\
Z &= Z_L - \tan(90^\circ - V_L) [(X - X_T)^2 + (Y - Y_T)^2]^{1/2}
\end{align*}
\]

(3)

2.2.2 The line between total station \(T\) and laser theodolite \(L\) as the original direction of horizontal angle

Here, the plane coordinates of point \(P\) can be solved using general forward intersection. The equations are shown as follows.

\[
\begin{align*}
X &= (X_T \cot A - X_L \cot \beta - Y_T + Y_L) / (\cot A + \cot \beta) \\
Y &= (X_L \cot \beta + X_L \cot A + Y_T - Y_L) / (\cot A + \cot \beta)
\end{align*}
\]

(4)

Certainly, the collocation (two surveying stations and the measured point) must be noticed. The sequence order must be anticlockwise and the internal angles \(\alpha\) and \(\beta\) should be adopted.

2.3 Scanning mode with circular cone surface

When the collimation axis of general laser theodolite circles the vertical axis, the scanning mode with cone surface is formed. The point of forward intersection between straight and cone surface is the solution of unknown point, and a certain point is the forward intersection of two straights. The taper of cone surface depends on the zenith distance of collimation axis, as shown in Fig. 3.

The coordinates of point \(L\) are assumed as \((B_X, B_Y, B_Z)\) in the coordinate system \(T-XYZ\) with \(T\) as the origin point, the coordinates of point \(P\) are \((X, Y, Z)\) in coordinate system \(D-XYZ\) and \((\Delta X, \Delta Y, \Delta Z)\) in coordinate system \(T-XYZ\).
So, there are three equations as follows to solve the coordinates \((\Delta X, \Delta Y, \Delta Z)\) of point \(P\):

\[
\Delta Y/\Delta X = \tan H = \sigma \tag{5}
\]

\[
\Delta Z^2/\Delta X^2 + \Delta Y^2/\Delta X^2 = \tan^2(90^\circ - V_T) = 1/\delta \tag{6}
\]

\[(\Delta X - B_x)^2 + (\Delta Y - B_y)^2 = (\Delta Z - B_z)^2 \tan^2 V_L = e(\Delta Z - B_z)^2 \tag{7}
\]

From Eqs. (5) and (6), we have

\[
\Delta Z = [(1 + \sigma)^2/\delta]^{1/2} \Delta X = \eta \Delta X \tag{8}
\]

According to Eqs. (5), (7) and (8), we can get

\[(\Delta X - B_x)^2 + (\alpha \Delta X - B_y)^2 - e(\eta \Delta X - B_z)^2 = 0\]

or

\[
(1 + \sigma^2 + e^2 \eta^2) \Delta X^2 - (2B_x + 2\alpha B_y + 2e\eta B_z) \Delta X + (B_x^2 + B_y^2 + \eta^2 B_z^2) = 0 \tag{9}
\]

After solving \(\Delta X\) according to Eq. (9), we can solve \(\Delta Y\) and \(\Delta Z\), and finally obtain the coordinates of point \(P\) in object coordinate system \(D-XYZ\):

\[
\begin{align*}
X &= X_T + \Delta X \\
Y &= Y_T + \Delta Y \\
Z &= Z_T + \Delta Z
\end{align*} \tag{10}
\]

2.4 Scanning mode with hyperboloid of one sheet

The coordinates of point \(L\) are assumed as \((B_x, B_y, B_z)\) in the coordinate system \(T-XYZ\) and those of scanned point \(P\) are \((\Delta X, \Delta Y, \Delta Z)\). In coordinate system \(L-XYZ\), the coordinates of point \(P\) are \((\Delta X - B_x, \Delta Y - B_y, \Delta Z - B_z)\), as in Fig. 4.

According to the scanning mode with hyperboloid of one sheet\(^{[2, 4]}\), the mathematical model is

\[
(\Delta X - B_x)^2/a^2 + (\Delta Y - B_y)^2/a^2 - (\Delta Z - B_z - c)^2/b^2 = 1 \tag{11}
\]

where

\[
\begin{align*}
a^2 &= \frac{R^2 \sin^2 \kappa}{\sec^2(90^\circ - V_L) - \cos^2 \kappa} \\
b^2 &= \frac{R^2 \sin^2 \kappa \cos^2 \kappa}{\left[\sec^2(90^\circ - V_L) - \cos^2 \kappa\right]^2} \\
c &= \frac{R \sec(90^\circ - V_L) \tan(90^\circ - V_L)}{\sec^2(90^\circ - V_L) - \cos^2 \kappa} \tag{12}
\end{align*}
\]
Considering Eqs. (5), (8) and (11), we obtain
\[
(\Delta X - B_X)^2/a^2 + (\sigma \Delta X - B_Y)^2/a^2 - \\
\left(\frac{\sigma \Delta X - B_Y - c}{b}\right)^2/b^2 = 1 \quad (13)
\]
or
\[
b^2(\Delta X - B_X)^2 + b^2(\sigma \Delta X - B_Y)^2 - \\
a^2(\sigma \Delta X - B_Z - c)^2/a^2b^2 = 0 \quad (14)
\]
So, we have
\[
(b^2 + b^2a^2 - a^2\eta^2)\Delta X^2 - (2b^2B_X + \]
\[2b^2aB_Y + 2a^2\eta B_Z + 2a^2\eta \Delta X + \\
(b^2\Delta X^2 + b^2B_Y^2 + a^2B_Z^2 + a^2c^2 + \\
2a^2B_Zc - a^2b^2) = 0 \quad (15)
\]
According to Eq. (15), \(\Delta X\) can be solved, then \(\Delta Y\) and \(\Delta Z\) can also be solved. Thus, the coordinates \((X, Y, Z)\) of unknown point \(P\) in object space coordinates system \(D-XYZ\) can be obtained.
The truth of scanning mathematics modes has been proved by the tests in which simulative data have been used.

3 Application and precision analysis

The appearance of a huge metal object (45 m x 50 m x 14 m) is measured with 184 profiles and 3300 points surveyed. The scanning mode with plumb plane is the main surveying method.

3.1 The evidence of choices surveying method
When the appearance of the huge metal object is measured outdoors, it will lead to some problems, such as the deformation caused by the change of the temperature or caused by the difference in temperature on the basis of the different directions of each component and the shaking of the component caused by the wind. Because of these environmental factors and the low efficiency in the course of surveying the few points on the profile in the way of close-range photogrammetry, the structure light engineering method at night has been chosen as the main surveying method. The way of close-range photogrammetry has been applied only on the upper surface of the huge metal object. The impact brought by the possible deformation of control points in the survey has been considered specially.

3.2 The establishment of observation post coordinate system and the transformation to the huge metal object coordinate system
The observation post coordinate system \((C_1-X'Z')\) is established, which is composed of four sound concrete posts and forced centering plate. The "half total station" composed of Distomat Wild DI2000 and theodolite Wild T2 is used to measure horizontal angles three rounds and distances ten rounds. After strict "braced quadrilateral" adjustment, the mean square error of the weakest point of four observation posts is about approximately ±0.2 mm, for side the relative mean square error of the weakest edge is approximately 1/120 000, and the largest correction of the length of side is 1 mm, as shown in Fig. 5.

After the transformation from the observation post coordinate system \((C_1-X'Z')\) to the huge metal object coordinate system \(I-XYZ\), we obtain the coordinates of each observation post in the huge metal object coordinate system. The reflector of "definite position" is placed on the fifth observation post. The "elevation" \(Y\) of the reflector in the huge metal object coordinate system \(I-XYZ\) is measured accurately, so it can pass "elevation". The height of the fifth observation post is close to the average work height.

During the surveying course, the basic control composed of the five observation posts mentioned above plays an important role.

On the ground of the metal object, the precise planimetric grid with precision above 1mm is set. The planimetric grid offers certain referenced help to the whole course of surveying the metal object.
3.3 The theory of the structure light engineering surveying based on laser theodolite

3.3.1 The main hardware and software
1) Laser theodolite
2) The rotated pentagonal prism and its bracket
3) Total station and portable computer
4) The software of complete functions

3.3.2 Surveying theory

The laser ray whose space direction is known is used not only as a direction of forward intersection, but also as an aimed target of another direction (from total station). Thus, the complex procedure of arranging profile mark points is omitted, and two surveyors can be reduced to one, and the operation procedure is simplified in order to obtain the 3D coordinates of surveyed points at once.

If the cross sections are measured, the laser theodolite LT is set to parallel X-axis (laser beam parallel X-axis). Then the rotated prism RP can scan some cross section, and the total station TS connected with portable computer PC aims some laser point and records its horizontal angle and vertical angle as shown in Fig. 6. After the 3D space coordinates of RP and TS have been surveyed, the 3D coordinates of laser point P can be surveyed at once.

The main advantages of the surveying technology applied to survey the huge object are as follows.
1) It is fit for surveying the profile. The density of the surveying points can increase or decrease whenever possible with the difference of the curvature of the profile.
2) It increases the precision of surveying on the basis of the method, forward intersection and trigonometric leveling, and avoids the process of measuring the distance.
3) It speeds surveying course greatly because the 3D coordinates can be measured on the spot and the profile figure can be shown by the online work supported by the advanced software.
4) The whole process of survey is easy to understand, which is good for the communication between surveying workers and operating workers.

3.4 The usage of other surveying technology

Some other new surveying methods are used in order to supplement the structure light engineering surveying method based on laser theodolite.

3.4.1 The function of online total station

During the course of surveying the appearance of the huge metal object, the total station Set2C is used. Communicative conductors make the total station and the portable computer work on line. The data from the whole process can be input into the computer and be processed in time. Some main functions are as follows:

1) The rate of making mistakes is very low thanks to the rare man-made record of data during the whole work course.

2) During the surveying course the points on the profile and setting out, the position and the 3D coordinates of the point surveyed can be displayed on the screen.

3) The general operation of the common engineering surveying including the forward intersection, the setting out of planimetric points, the measurement of trigonometrical leveling and so on can be done in time. These functions are very important in some aspects such as calculating the 3D coordinates of the points on the profile, calculating point A indicated by laser ray, setting out grids and controlling the quality in the surveying course (checking precision to find faults in time).

4) The surveying results of each profile, including figures and data, can be shown whenever possible. That improves the comprehension of the whole surveying process and provides chances for those amateur surveyors to take part in the discussion on some surveying problems.

5) The distance between surveying station and the profile is surveyed right away. With the aid of the function, the displacement of surveyor's pole and the height difference between the reflection sheet surveyed and some horizontal section known are reported in time.

3.4.2 The surveying method used on the belly

The belly of the huge metal object is long, and it is about 0.8 m high to the ground. It is not suitable to use photogrammetry. A special surveyor’s pole is shown in Fig. 7. Its basic structure is a tribrach with a level 4, a staff 3 which can be protracted and contracted with a sharp point, a reflection sheet 2 (3 × 3 pieces, the square of each piece is about 1 cm × 1 cm). Before surveying, the "object height" \( V_2 \) is measured accurately. During surveying, the online total station Set2C is used to survey the 3D coordinates of point \( P \) on the profile one by one.

3.4.3 The surveying method for the top and the part where laser ray can not scan

The special surveyor’s pole, shown in Fig. 8, is applied to surveying the top of the huge metal object and its part laser ray can not scan. There is a level on the special pole whose bottom is a staff 3 with a sharp point, the distance between the reflector or reflection sheet is about 10 cm. Before surveying, the "object height" \( V_1 \) is measured accurately. During surveying, the online total station Set2C is used to survey the 3D space coordinates of point \( P \) on the profile one by one.

3.4.4 The surveying method for horizontal profile

The progressive approximation using large reflection sheet (4 pieces × 6 pieces) is adopted to survey
the horizontal profile at an arbitrary height. When some surveying result does not accord with the height of the profile, the reflection sheet should be moved or another height should be read directly.

3.4.5 The close-range photogrammetry process

The close-range photogrammetry method is used for surveying the profiles on the top surface of the huge object.

1) Photograph and photogrammetric process

The photo theodolite UMK10/1318, made in Germany, is used to normally photograph the top surface at the height of 14 m from the height of 19 m. The photographic distance \( Y \) is about 4.5 m, the photographic baseline \( B \) is about 1.8 m. Three pairs of photos are taken in order to survey three vertical sections, three horizontal sections, four horizontal sections on the special part and several character points.

2) How to process the surface

Man-made texture is made on the surface where the close-range photogrammetry method is used. The transparent adhesive plaster (6 cm in width, 15 cm in length) is attached to the surface every about 10 cm. Man-made texture is portrayed on it with oil pen. Man-made texture strengthens the stereo-felling and assures the precision of indoor surveying.

3) The surveying of picture control point

All picture control point’s mark is made of steel bead with 2 mm diameter. Its 3D space coordinates are surveyed using forward intersection and trigonometric level and its precision outclasses 1 mm. The average of circle readings between two sides of steel bead is the last result.

4) The indoor process

The analytical plotter BC2 is used to process the stereo pair, and the residual error of absolute orientation point is less than 1 mm.

3.5 Accuracy estimation

3.5.1 Accuracy estimation of forward intersection

The planimetric coordinates of hundreds character points on the huge object, each branch station, the total field picture control points and the profile points surveyed by structure light engineering surveying method are all surveyed by engineering surveying. Its accuracy estimation is based on the equation as below:

\[
m_p^2 = m_A^2 + m_B^2 + \frac{m_v^2(a^2 + b^2)}{\rho^2 \sin^2(a + \beta)} \tag{16}
\]

According to angle mean square error \( m = \pm 2\sqrt{2} \), the average distance of sides \( a = b = 30 \text{ m} \), the average angles sum \( a + \beta = 150^\circ \), there are two cases as follows.

a. When forward intersection from two observation posts, according to this test result, \( m_A = m_B = \pm 0.2 \text{ mm} \) and Eq. (16), the \( m_p \) is given by

\[
m_p = \sqrt{0.2^2 + 0.2^2 + 1.16^2} = 1.19 \text{ mm}
\]

(16a)

b. When forward intersection from an observation post and a branch station, \( m_A = \pm 0.2 \text{ mm} \) and the accuracy of branch station according to Eq. (16a) with \( m_B \) that is equal to \( \pm 1.19 \text{ mm} \),

\[
m_p = \sqrt{0.2^2 + 1.19^2 + 1.16^2} = \pm 1.67 \text{ mm}
\]

(16b)

3.5.2 Accuracy estimation of trigonometrical leveling

During the course of surveying the appearance of the huge metal object, there are two methods for surveying altitude in terms of trigonometric leveling: one is by the vertical angle after computing the planimetric coordinates according to forward intersection, the other is directly computing the 3D coordinates of unknown points according to slope, horizontal angle and vertical angle.

According to the accuracy estimation of trigonometric level, we get

\[
m_h = \sqrt{\tan^2 a \cdot m^2_i + \frac{s^2 m_a^2}{\cos^2 a \cdot \rho^2} + m_v^2 + m_v^2}
\]

1) Computing altitude after forward intersection from two observation posts

When \( a = 1^\circ, \ m_{s(max)} = m_p = \pm 1.19 \text{ mm} \) [according to Eq. (16a)], \( s = 30 \text{ m}, m_a = \pm 4^\circ \) and assuming \( m_i = \pm 0.2 \text{ mm}, m_v = 0 \), then

\[
m_h = \pm 0.61 \text{ mm}
\]

(16c)

2) Computing altitude after forward intersection from one observation post and one branch station

When \( a = 20^\circ, \ m_{s(max)} = m_p = \pm 1.67 \text{ mm} \) [according to Eq. (16b)], \( s = 30 \text{ m}, m_a = \pm 4^\circ, m_i = \pm 0.61 \text{ mm}, m_v = 0 \) [according to Eq. (16c)], thus
3) Computing altitude according to the distance surveyed by electromagnetic wave

Using reflector or reflection sheet to obtain the slope, when \( a = 20^\circ, m_s = \pm 3\sqrt{2} \text{ mm}, s = 30 \text{ m}, m_o = \pm 4^\circ, m_i = \pm 0.61 \text{ mm}, m_r = 0 \), \( [\text{according to Eq. (16c)}] \), then

\[
m_h = \pm 1.16 \text{ mm} \quad (16d)
\]

4) Accuracy estimation of position

According to Eqs. (16b) and (16d), the synthetic accuracy of the planimetric coordinates and the altitude of the weakest point on profile is

\[
m = \sqrt{m_h^2 + m_n^2} = \sqrt{1.67^2 + 1.16^2} = 2.03 \text{ mm} \quad (16f)
\]

3.5.3 Accuracy estimation of close-range photogrammetry

The vertical sections and cross sections are surveyed using photogrammetry. The accuracy estimation of the weakest direction is

\[
m_y = \left[ \frac{Y^2}{(Bf)} \right]^{1/2} \cdot m_y = \pm 0.83 \text{ mm} \quad (17)
\]

3.6 Accuracy test

In order to examine the accuracy of the engineering surveying method based on structure light, each point on a profile is surveyed in two ways. One is that the space coordinates of laser point are computed according to forward intersection from two observation posts and trigonometric level and considered as true value. The other is that the space coordinates of laser point are surveyed according to structure light scanning method. Statistically, the mean square error of point position is less than 0.6 mm. The values are shown in Table 1.

4 Conclusion

All kinds of scanning modes and relevant formulae of structure light engineering surveying on the basis of laser theodolite with three rotation degrees is deduced in this paper. The truth of the theory mentioned is proved by simulative test, especially by the application of surveying the appearance of huge metal objects. The method of structure light engineering surveying has many incomparable advantages with comparison to other ones in surveying confining structures even in many other cases.

| No. | Forward Intersection/m | Structure Light Engineering Surveying/m | \( \Delta X/\text{mm} \) | \( \Delta Y/\text{mm} \) | \( \Delta Z/\text{mm} \) |
|-----|------------------------|----------------------------------------|----------------|----------------|----------------|
| 1   | 20.790 6               | 20.791 9                              | -2.020 5       | 3.019 2       | +1.3           | +0.2           | +0.8           |
| 2   | 20.791 5               | 20.791 9                              | -1.941 4       | 3.144 5       | +0.4           | -0.7           | +0.1           |
| 3   | 20.792 2               | 20.791 9                              | -1.605 6       | 3.316 4       | -0.3           | +0.7           | -0.1           |
| 4   | 20.793 3               | 20.791 9                              | -1.505 7       | 3.315 9       | -0.4           | +1.0           | -0.4           |
| 5   | 20.792 8               | 20.791 9                              | -1.397 4       | 3.291 0       | -0.9           | -0.4           | -0.7           |
| 6   | 20.791 2               | 20.791 9                              | -1.259 9       | 3.220 1       | -0.2           | -0.6           | 0.0            |
| 7   | 20.792 6               | 20.791 9                              | -1.109 9       | 3.084 3       | -0.7           | +0.1           | -0.6           |
| 8   | 20.792 0               | 20.791 9                              | -1.008 9       | 2.981 5       | -0.1           | +0.3           | 0.0            |

\[
\text{Accuracy} \quad m = \pm \left[ \frac{[\Delta \Delta X]/(3n)]}{2} \right] = \pm 0.57 \text{ mm}
\]

Table 1 Accuracy test table

References

1 Feng W H, Bai F, Li X, et al. Light section photogrammetry and its application. Journal of Wuhan Technical University of Surveying and Mapping, 1992, 17(4): 48～56
2 Feng W H, Fan Q B, Li X. An investigation into the principles of structured-light photogrammetry based on laser theodolite, Acta Geodaetica et Cartographica Sinica, 1995, 24(1): 71～76
3 Feng W H. An expound concerning the surveying of confining construct, Acta Geodaetica et Cartographica Sinica, 1996, 25(2): 156～160
4 Feng W H, Li X. A structure light photogrammetry system based on laser-theodolite, optical 3D measurement techniques. Vienna, 1995. 445～453