Positioning of Screw Holes Group Based on Digital Camera and Digital Control Drilling

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ABSTRACT  Positioning of screw holes is an important production procedure for steel construction connecting with bolts. In this paper, a new production method is presented, in which the digital camera is used for taking pictures of screw holes and other techniques are advanced. This paper also indicates that the pixels of CCD chip in photogrammetry should be chosen as all geometric units in an image, such as interior elements and all kinds of distortions. The measure can also simplify the camera calibration for determining the size of non-square pixel.

KEY WORDS  digital camera; screw holes; digital drilling machine; photogrammetry; multi-station photogrammetry; self-calibration; bundle adjustment

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Introduction

Hundreds and thousands of screw holes connects huge bridge, shipping and all kinds of larger tower structure with different parts such as steel beams. And on every linking part, many screw holes to be drilled are assigned whose accurate positions are to be confirmed. Manual methods are adopted during current operation. The production period is long, and the efficiency is low. This is a technical problem to be solved with modern technologies.

By consulting relevant documents we can learn that there are a lot of optional industrial measurement schemes, sensors and methods[1]. There are several kinds of plans that are suitable for measuring and locating screw holes considering the hole location numbers, different distribution and precision. It may be the plan of angle measurement based on industrial measurement control network[2]. It may be a semiautomatic measurement plan based on "robot". It may be the plan based on laser tracking system (such as Swiss SMART 310 type and LTD500 type threedimensional laser tracking system or API Tracker II of USA). It may be the plan of angle measurement based on the principle of structural light. It may also be a video recording plan based on certain video recording equipment[3].

By comparing and studying all the plans mentioned above, this paper puts forward a new plan. It is better than other plans on the overall indexes such as operability, precision, speed, input-output ratio, etc and has radically changed the production procedure. We began to study on the production of the beam of the third Yangtze River bridge of Wuhan from 1998. The bridge is linked by hundreds of steel beams (orthogonal beam of specialshaped board type). The body of each steel beam is about 38 m wide, 3 m high, 12 m to 16 m long, and several hundred tons in weight. Holes are drilled at bolts connection parts of neighboring steel beams. Fig. 1 shows that two neighboring steel beams are put in the openair. On the 38 m neighboring steel beam, there are thousands of screw holes in disorder. So we need to manufacture a series of hookup
board on which the precision of hole positions of board should be within ±0.35 mm.

![Fig. 1 Two neighboring steel beams in open air](image)

The quantity of bridge screw holes is enormous (about 1 million). The positions of screw holes are outside and on the whole on a "plane". Steel beam is bulky and is not suitable for indoor operation. Moreover, considering a lot of factors such as the operability of digital drilling holes and the use of a digital camera, the author puts forward a research approach based on screw holes positioning and digitally drilling holes with digital cameras.

1 Key technologies

The research of this part involves several key technologies including locking of the digital camera, processing unit of different geometrical parameter of image points, automatic determination on the center of round hole of the image, applications of bunch adjustment with additional parameter and multistation photogrammetry, etc.

1.1 Locking focus of the digital camera

The position of the point \((x_0, y_0)\) and the distortion are required to be equal in the photogrammetry, namely to keep the locking of the interior elements in a broad sense. But most digital cameras with the function of automatic focusing have different interior elements and optical distortion. So whether a camera has the "locking function" is an important index, which is suitable for photogrammetry. There are two kinds of methods for the locking of interior element and optical distortion. One is to adopt the manual mode, the other is to adopt method of locking focus. After having take in an image, we keep controlling expose button and take other images continuously, in order to implement multistation and multiimage photogrammetry. When examining the digital camera, we should give definite distance to examine the interior element and optical distortion coefficient too. The method is to annotate the accurate mark on the camera, or to resume the focus of adjusting while examining on the spot.

1.2 Processing unit of geometrical senses of image space

Usually, the unit of \(f\), image points \((x, y)\), principle point \((x_0, y_0)\) and unit of systematic error correction value which comes from optical distortion and etc. should be the long measure. Originally this paper proposes all these elements using the unit of pixel, and the accuracy is proved by practice.

The collinear equation as Eq. (1) shows, for instance, the unit of object aspect as \((X, Y, Z; X_0, Y_0, Z_0)\) is expressed with the metric system. However, geometry quantities in image coordinates, such as \((f, x, y; x_0, y_0; \Delta x, \Delta y)\), using other units (such as inch, pixel), the formula keeps definitely correct because after both sides of the formula are divided by \(f\), there are no dimension.

\[
\begin{align*}
(x - x_0 + \Delta x) &= f \frac{a_1(X - X_0) + b_1(Y - Y_0) + c_1(Z - Z_0)}{a_0(X - X_0) + b_0(Y - Y_0) + c_0(Z - Z_0)} \\
y - y_0 + \Delta y &= f \frac{a_2(X - X_0) + b_2(Y - Y_0) + c_2(Z - Z_0)}{a_0(X - X_0) + b_0(Y - Y_0) + c_0(Z - Z_0)}
\end{align*}
\]

(1)

The important meaning of this inference lies in that we can use the existing photogrammetry software to deal with the digital image directly, and use pixel as the unit of all geometry quantity in image aspect. In addition, we can deduce a simple method for calibrating digital camera when all geometry quantities in image aspect are expressed with the unit, pixel. This method needs no calibration on the element size \((dx \times dy)\), but the approximate ratio \(a(dy/dx)\).

When there is no systematic error, the differ-
ence of distance between two neighbouring pixel in $x$ direction and the distance between two neighbouring pixel in $y$ direction within digital camera CCD chip do not influence the calculation results. But when there is systematic error correction ($\Delta x, \Delta y$), it is wrong when we calculate correction of $x$ and $y$ with $dx$ and $dy$. At this situation, we set $dy=adx$ and to the optics distortion of the radial direction $\Delta x$, we can get the formula of taking length as unit and that of pixel as unit respectively;

As to eccentric distortion $\Delta x_0$, we can list the formula of taking length as unit and that of pixel as unit respectively.

Obviously, the calculation of $a$ and determination of the precision of $m_a/a$ is very important.

If we express the size in $x$ direction with $\lambda_x$, express the size in $y$ direction with $\lambda_y$, the resolution in $x$ direction with $n_x$, the resolution in $y$ direction with $n_y$, therefore we have two formulas $\lambda_x = n_x dx, \lambda_y = n_y dy$. And we can calculate value of $a$ and $m_a/a$ with the following formulas:

$$a = \frac{dy}{dx} = \frac{n_x \lambda_x}{n_y \lambda_y} \tag{2}$$

$$m_a = \left[ \left( \frac{m_x}{l_x} \right)^2 + \left( \frac{m_y}{l_y} \right)^2 \right]^{1/2} \tag{3}$$

Approximately we set $\frac{m_x}{l_x} \approx \frac{m_y}{l_y} = \frac{m_l}{l}$, and then there is relation between $\frac{m_l}{l}$ and $\frac{m_a}{a}$:

$$\frac{m_l}{l} = \frac{1}{\sqrt{2}} \cdot \frac{m_a}{a} \tag{4}$$

In addition, depending on Eq. (2), within the main term ($k_1 x a^2 y^3$), the extra error $d\Delta x$ caused by the distortion error of $a(m_a)$ can be expressed as:

$$d\Delta x = 2k_1 x a y^3 m_a = \left( 2 \frac{m_a}{a} \right) \Delta x \tag{5}$$

So, according to following formula to determine the precision $\frac{m_a}{a}$, it can meet the demands;

$$\frac{m_a}{a} = \frac{1}{2} \cdot \frac{d\Delta x}{\Delta x} \tag{6}$$

If the condition $\Delta x = 5$ pixel and $d\Delta x = 0.1$, we can know precision $m_a/a$ up to 1% and it meets the demands well.

If we add $\frac{m_a}{a}$ of Eq. (6) to Eq. (5), we can know the precision of $\frac{m_l}{l}$:

$$\frac{m_l}{l} = \frac{1}{2 \sqrt{2}} \cdot \frac{d\Delta x}{\Delta x} \tag{7}$$

That is to say, with precision 1/140 to determining the length of chip ($l_x$ and $l_y$), we can calculate the value of $a$ according to Eq. (3), it meets the demand of precision.

We can imitate the above theory to examine eccentric distortion, to examine radial distortion coefficient caused by object lens, to examine radial distortion without same focus. All data processing are digital image, so it is no use of taking into account whether camera has optical zoom caused by condenser lens, of course we need not take into account whether the image we deal with has digital transforming focus, and we need not determine the value of $dx, dy$.

### 1.3 Mobile control shelf

Tube material of aluminum alloy is portable and plane type, and durable, it has over ten control points whose diameters are about 20 mm, control point mark like ☀️, so that it can be identified by computer. The spatial coordinate of each control point is obtained with the precision nearly ±0.07 mm in every direction. Coordinates $D-XYZ$ of mobile control system is defined to be a objective coordinate system. While taking a photo, put control shelf set around screw holes to be determined. The function of control shelf is to offer the control of objective space, in order to offer exterior element approximate value for back intersection, and is used to check the precision of photogrammetry.

1. **Determination of exterior element approximate value**

In control shelf system $D-XYZ$, the purpose of determining the element approximate value includes two points; one is for rectification of image, the other is providing the initial value of the image for bunch adjustment. When we implement multistation and multiimage photogrammetry, every image has different orientation in objective space coordinate system $D-XYZ$ in common,
its angle $\varphi$ and angle $\omega$ can be up to several dozen degrees, and the straight negative sign differs; its angle $\kappa$ can change in the range of $(0^\circ - 360^\circ)$.

1.5 Automatic survey of screw holes center

We take 100% photography cover to joins part of steel structure, as Fig. 2 shows, there are more than one hundred screw holes on joins part of steel structure, all screw holes total amount reach one thousand. So, accurate and automatic survey of screw holes center is an important technology to guarantee measure precision and speed. To determine image pixel value of screw holes center, we use two values in pattern processing, subpixel position of round boundary and antinoise round fit technology. We adheres to "from outside to inwards", instead of the tactics "from inside to outwards" while searching for the boundary. We can construct a cone with photography center and the round that is surveyed. This cone is truncated by the image surface, so "horizontal image" of round is still a round, but "slope image" of round turns into oval. It is verified that the deviation between center of round and the center of oval can be neglected. Moreover, the size of ovals and major axis direction of ovals are not the same on the image.

![Fig. 2 Crescent image processing](image)

Main technologies adopted in image processing include:

1. Adjust sloping photo to horizontal photo to avoid elliptic detection and obtain central coordinates of circle on sloping photo by inverse operation.
2. Get elliptic equation or circular equation through binary and fitting and further get geometrical center of ellipse or circle.
3. Determination of the value of ellipse center $M_0$.

According to general representation of conic formula:

$$a_1 x^2 + 2a_{12} x y + a_2 y^2 + 2a_1 x + 2a_2 y + a_0 = 0$$

where

$$a_1, a_2, a_{12}, a_0 \neq 0$$

The invariants $(l_1, l_2, l_3)$ in the above formula under horizontal and rotary transformation are:

$$l_1 = a_{11} + a_{12}, l_2 = \begin{vmatrix} a_{11} & a_{12} \\ a_{12} & a_{22} \end{vmatrix}, l_3 = \begin{vmatrix} a_{11} & a_{12} \\ a_{12} & a_{22} \end{vmatrix}$$

We can consider this conic as ellipse if the following condition can be meet in calculating

$$l_2 > 0, l_1 \neq 0, l_1 l_3 < 0$$

and the coordinates of elliptical center $M_0(x_0, y_0)$ can be calculated with the following formula:

$$a_{11} x_0 + a_{12} y_0 + a_1 = 0$$
$$a_{12} x_0 + a_{22} y_0 + a_2 = 0$$

(10)

Obviously, all calculations listed above need not to know the initial value of all unknown quantity.

4. Determine the circle center.

Similarly according to Eq. (8), if the condition $a_{11} = a_{22} = a > 0$ is meet and $a_{12} = 0$, then

$$x^2 + 2 \frac{a_1}{a} x + y^2 + 2 \frac{a_2}{a} y + \frac{a_0}{a} = 0$$

or

$$\left(x + \frac{a_1}{a}\right)^2 + \left(y + \frac{a_2}{a}\right)^2 = \frac{1}{a^2} (a_1^2 + a_2^2 - a a_0)$$

(12)

that is to say, the coordinates $(x_0, y_0)$ of circle center $M_0$ and radius of circle are:

$$x_0 = -\frac{a_1}{a}, y_0 = -\frac{a_2}{a}, r = \frac{1}{a} \sqrt{a_1^2 + a_2^2 - a a_0}$$

5. Another strategy is scanning the whole image with given interval of row according to the mode of TV scanning, then, measure all screw holes automatically.

After the measured method and algorithm mentioned in ②,③,④ and ⑤, the measuring results are shown in Fig. 3.

6. About crescent image

In some cases, crescent highbrightness region is generated at one side of screw hole because of lateral sunlight (see point 19 and point 20 in
Fig. 3 Measurement results with edge matching

...and the gray level of the region is equal to that of armor plate surface. Fitting the boundary of black region and remove the boundary points whose error is greater than limitation, then calculate the center of circle.

1.6 Multi-photogrammetry

Multi-photogrammetry, i.e., multistation photogrammetry, is a technology used in close-range photogrammetry generally to improve precision and reliability of measurement. In narrow sense, multiPhotogrammetry is symmetrical cross photogrammetry for several times. Seeing Fig. 4, different from 2 times of vertical aviation photographic cover. According to some scholars' early research, in a broad sense, multi-photogrammetry stands for a photogrammetry method which has multistation, multicontrol, multirecords, multimarking and multifunctional program support. Multistation photogrammetry of close-range photogrammetry makes a photogrammetry recording nearly 100% objects many times, to obtain high accuracy, best even precision of threedirectional coordinate and higher dependability.

1.7 Application of light bunch adjustment method

After having obtained pixel coordinates of screw holes group at all images, we use light bunch adjustment method with additional parameter to process them. And during this procedure, the following details are to be noticed.

We use half of resolution ratio $x$ (1 000) and resolution ratio $y$ (1 280) as the approximate value of the principle point coordinate $x$ and $y$, namely $x_0 = 640$ pixel, $y_0 = 500$ pixel.

Approximate value $f$ of principle distance is determined by use of photogrammetry distance $H$, objective diagonal length $D$ and diagonal pixel number $d$.

$$f = d \cdot \frac{H}{D} = 1624 \text{ pixel} \cdot \frac{2.84 \text{ m}}{2.14 \text{ m}} = 2155 \text{ pixel}$$

The approximate values of exterior elements are determined by consulting the control point on the control shelf, and are solved with space resection of single image.

2 Simulated test and optimization design

We have implemented simulated test and optimization design in the laboratory, our purpose is to choose exactness and scheme of inspection method, overall arrangement, additional choice of parameter to seek optimum design in photog-
2.1 Principle and method of operation

The method of simulated test and optimization design is to set up a standard grid, to implement many kinds of photogrammetric schemes and evaluate quality of every scheme with true error of a large number of check points.

When we spray a little water to drawing desk glass of AVIOTAB type coming from the Leica Company, smooth polyester membrane with thickness of 0.1 mm on the glass, and fix it with the sticky tape paper all around. Depending function of computer graphics, control grids of area as 1.1 m × 0.9 m are drawn and grids interval is 5 cm, at the same time circle with the diameter of 15 mm at every intersect point of grid as the black round solid are drawn, amounts to 399, as Fig. 5 shows. It can be seen that the coordinate error of the sign center is not greater than ±0.05 mm. Taking the E2N type digital camera from NIKON company as example, by symmetrical cross photogrammetry method, namely with multiphotogrammetry way, we carry on 100% photographic cover to standard grid from several different angles many times, so we get 100% overlap images. Overall 9 stations are arranged as Fig. 4 shows, we have 9 times photogrammetry overlap cover to standard grid. Here, the 9 stations are marked as $S_0, S_1, \ldots, S_8$, among them main optical axis of $S_0$ is perpendicular to standard grid on the whole, other symmetrical stations (such as $S_1$ and $S_2$), including their photographic direction, are symmetrical in shape to the center of the standard grid.

For making all images from different stations have the same principle distance value, and the same condition of exposing, we use focusing lock key AFL (Auto Exposure Lock) and automatic exposing locking key AEL (Auto Exposure Lock).

The chip diagonal of E2N type digital camera from NIKON Company is \(\frac{2}{3}\) inches (16.9 mm) long, and this kind of camera has only a resolution ratio of 1 300 000 pixel (1 280×1 000 pixel). In this research, the offline way (depending on PCMCIA card) and data of JPEG compression are adopted.

2.2 Multi-Photogrammetry test

Refering to Fig. 4, we carry on extensive simulated test in the laboratory.

2.2.1 Influence of number and position of stations on the precision of photogrammetry

Six group tests are implemented, and from 4 to 9 stations are adopted, respectively. The area is 50 cm × 50 cm, altogether we have 121 given points, we fetch 9 among them as control points to count true errors and mean errors ($M_x, M_y, M_z$) of other 112 points and the mean square error $\sigma$. You can pay respects to Table 1:

- If increasing the number of stations, the precision of $M_x, M_y$ will be improved (from 0.69 mm to 0.44 mm);
- Increasing the number of stations improves precision of $M_z$ (from 0.32 mm to 0.25 mm), while the relative precision of elevation is about 1 : 5 000.

2.2.2 Influence of number of images on the precision under the condition of without control shelf

We adopt the method of “opposite angle photogrammetry” on four stations. Take one photo and two photos of each station respectively. It is noticed that we can economize time and improve the precision when we take two images at the same direction on one station. For example, $M_x, M_y$ is improved from 0.58 mm to 0.48 mm; $M_z$ is improved from 0.91 mm to 0.83 mm. It is expected to have better result if we take more images on one station.

2.2.3 Influence of times of photogrammetry on the precision with having control shelf

In order to examine the performance of control shelf, we adopt the above mentioned photogrammetry way, but having “lower flying heights relatively”. It is noticed that we can get higher precision to take two images than one. For example, $M_x, M_y$ is improved from 0.55 mm to 0.37 mm; and $M_z$ is improved from 0.52 mm to 0.33 mm.
Table 1  Relationship between the accuracy and photography mode

| Photogrammetric way | Graph of photogrammetry way | $M_r$/mm | $M_s$/mm | $M_{r,s}$/mm | $M_{s}$/mm | $\sigma$/pixel |
|--------------------|-----------------------------|----------|----------|-------------|-------------|--------------|
| “four edges”       | $\cdot S_1 \cdot S_5 \cdot S_6$ | 0.48     | 0.50     | 0.69        | 0.32        | 1.0          |
| “four corners”     | $\cdot S_1 \cdot S_4 \cdot S_6$ | 0.38     | 0.31     | 0.49        | 0.37        | 0.9          |
| “four corners and centre” | $\cdot S_1 \cdot S_4 \cdot S_5 \cdot S_7$ | 0.37 | 0.24 | 0.44 | 0.38 | 0.9 |
| “four edges and centre” | $\cdot S_1 \cdot S_4 \cdot S_5 \cdot S_7$ | 0.45 | 0.51 | 0.67 | 0.33 | 0.9 |
| “four corners and four corners” | $\cdot S_1 \cdot S_4 \cdot S_5 \cdot S_7$ | 0.32 | 0.28 | 0.43 | 0.24 | 1.0 |
| “four corners, four corners and centre” | $\cdot S_1 \cdot S_4 \cdot S_5 \cdot S_7$ | 0.32 | 0.30 | 0.44 | 0.25 | 0.9 |

2.2.4 Influence of the number of control points and their distribution on the precision

We can learn from the following 7 groups of tests. Within the specific limits, the more of control points is the higher precision will be, but when control points obviously exceeding 6, the efficiency is not obvious yet.

2.2.5 Influence of the cross angle on the precision of photogrammetry

Several tests above mentioned are implemented under the condition of a little cross angle $\gamma$ (about 30°). Now we adopt two different cross angle (nearly as 30° and 60°), with photogrammetry way of “four corners” and takes 2 images on each station and uses 8 control points to carry on a test for comparing optimization design. It can be concluded that precision with 60° is higher than that with 30 obviously, among them $M_{r,s}$ is improved from 0.44 mm to 0.34 mm; it is more outstanding that $M_r$ is improved from 0.33 mm to 0.18 mm.

The above optimization tests proves that using digital camera with solution of 1 million pixel, within a photography distance of 1 500 mm, with photogrammetry way of “four corners” and takes 2 images on each station and with cross angle about 60°, hole positioning precision reaches ±0.35 mm. These important optimization tests will be the foundation for carrying on positioning screw holes and digital control drilling hole in factory.

3 Production testing

On the basis of the research in this paper, the authors used the technology successfully in the testing production of steel beam of the third Yangtze River bridge of Wuhan and get the praise of manufacturer’s leadership and technical staff. At that time, we use Nikon E2 digital camera with a resolution of (1 280×1 000) pixel, a (50×50) cm² movable control shelf and a portable computer. From above result, we adopt 4 stations with each station making two images. The image of screw holes group on-the-spot is as Fig.5 shows. We use 8 control points, with remaining 8 control points as check points. Results of calculation of check points are listed in Table 2, mean residual error in x direction and y direction ($M_r$ and $M_s$) are about 0.2 mm. The mean error of the hole center coordinate of the image is about 0.6 pixel.
Table 2 Residual errors of check points on control system/mm

| No. | X    | Y    | Z    | DX  | DY  | DZ  |
|-----|------|------|------|-----|-----|-----|
| 1   | 100.703 | 229.004 | 100.106 | 0.273 | -0.181 | 0.540 |
| 2   | 100.682 | 502.145 | 100.584 | 0.078 | -0.216 | 0.085 |
| 3   | 231.129 | 626.294 | 100.442 | 0.206 | 0.256 | -0.161 |
| 4   | 501.250 | 624.257 | 100.442 | 0.009 | -0.283 | -0.040 |
| 5   | 631.425 | 480.695 | 100.115 | 0.032 | -0.183 | 0.150 |
| 6   | 628.585 | 232.840 | 100.055 | -0.236 | -0.039 | 0.276 |
| 7   | 499.310 | 98.060 | 99.773 | -0.289 | 0.248 | 0.044 |
| 8   | 254.750 | 99.835 | 99.597 | 0.259 | -0.147 | 0.290 |

$M_x = 0.203, M_y = 0.197, M_z = 0.177$

2) This paper reports one group test result of the optimization design, offers experience and basis for screw hole positioning and photogrammetry including the number and overall arrangement of multi-station photogrammetry, photographing times on each station, number of control point and the influence of the cross angle size on the precision of photogrammetry, etc. Depending on original experimental condition, precision of laying-out screw holes group is better than $\pm 0.35$ mm, relative precision of elevation is about $1 \pm 5000$. It is estimated that the precision will be improved by a large degree if a higher resolution digital camera is used and the number of stations and times of photogrammetric survey in one station increases.

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Fig. 5 Test photo

It takes 25 minutes from surveying to obtain the final result of calculation. With the equipment of magnetic disc which has result of calculation and FABRICATOR 3500 type digital control drilling machine of FARLEY Company in Australia, we get good precision of holes drilled to match stencil plate on-the-spot.

4 Conclusions

1) Screw hole positioning is important production procedure in steel construction using bolts connection. In this paper a new production method is presented, in which the digital camera for hole positioning is used and other techniques are advanced, which are rapid center determination for images of screw holes, multi-station photography, self-bundle adjustment and drilling holes by using digital drilling machine. This procedure have such advantages as high in precision of orientation on screw hole positioning, little consuming time, little fund input, low labour intensity, high adaptability.