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Abstract

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Error compensation method of large size steel sheet measurement based on control field

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Abstract. Aiming at the problem of low accuracy of large size sheet edge, a method of sheet size error measurement based on control field is proposed. Firstly, an error compensation model of the measuring system based on control field is established by analyzing the causes of the errors of the measuring system. A grid standard plate is designed and the error distribution on the grid line is obtained by using the measurement results of the standard plate. Secondly, the error curve is established according to the distribution, and the trig function theorem is used to project the curve into the image pixel coordinate system. Finally, the control field of the whole measurement area is reconstructed by linear interpolation, and the measurement results are compensated and corrected. The steel sheet is measured in the measuring area of 1.2m× 2.6m on the basis of these theories and technologies. The experiment shows that the precision of the measuring system can reach 1mm per meter, which satisfies the accuracy and speed requirements of large-size steel sheet measurement in industry, and has high application value.

1. Introduction

In recent years, large-size sheets have been widely used in large-size equipment such as airplanes and ships. In the manufacture and assembly of major equipment, accurate measurement of plates is a key step to ensure the accuracy of equipment manufacturing. The wrong size of the plates will seriously affect factory production efficiency and product quality. Traditional detection method measures the size of the tested plate by a micro-meter. This method can not obtain accurate dimensional deviation, and has a slow detection speed. Based on the above considerations, the measurement of large-sized plates based on machine vision has become a research hotspot.

At present, a coordinate measuring machine is used to measure large-size turbine blades. The measurement error of a 550 mm blade of is within 0.04mm [1]. Although this method can accurately measure large-sized objects, it is one of the point-by-point measurement methods, and it is necessary to first obtain a large number of discrete points on the surface of the object to be tested, and the measurement efficiency is low. A digital measuring system is applied to the measurement of industrial large-size slabs, and the experimental results show that the accuracy of the measurement system can reach 0.01mm [2]. The system can accurately measure a wide range of areas, but its operation is complicated, and the measurement data is computationally intensive. It is often difficult to meet the requirements of rapid measurement of large-scale sheet metal measurement; Sun [3] compensated the measurement results of the cylindrical gear profile by establishing a nonlinear model of perspective projection error. The experimental results show that the accuracy of this method meets the measurement requirements of gear profiles with different thicknesses. However, with respect to small-sized objects, as the size of the measuring object increases, the degree of lens distortion becomes larger and larger, and the compensation for one side in the measurement process alone cannot satisfy the accuracy requirement. Some measurement systems have the disadvantages of low measurement efficiency, high manual skill and high cost when measuring large-size plates. Therefore, an error compensation model of the measurement system based on the plane control field is proposed. The system not only can measure large-sized plates quickly and efficiently, but also has accurate measurement results, convenient operation, small calculation amount and low cost, and is very suitable for industrial field measurement of large-sized plates.

2. Error analysis

The measurement system of sheet consists of four processes in the measurement process which contains plate image acquisition, camera calibration, sub-pixel edges extraction and edges fitting. First of all, the system's image acquisition relies on a line scan camera. The camera mounted on the robot arm moves at a non-uniform speed, which causes the captured image to stretch, causing the image to have an acquisition error of μ_a. Secondly, the system uses nonlinear calibration model calibrates camera [4], and the back projection error of the calibration result is 0.2901 pixels. Since the actual distance represented by one pixel in the image is 0.71 mm, the calibration error of the measurement system is μ_c=0.206 mm; Then, the system uses sub-pixel extraction algorithm based on the picture element gradation moment characteristic for edge localization [5]. When the input pixel set is not ideal, the positioning error can reach 0.3 pixel, so the positioning error μ_s=0.21mm. Finally, the edge fitting uses the least-square method based on weight. Because the distance threshold τ [6] is introduced when defining the weight, the selection of different thresholds results in a poor fit in the image, forming a fitting error named μ_f [7].

In summary, the total error of the system consists of four parts. If only one of the errors is corrected by error compensation, complicated algorithms need to be introduced. In addition, the error of image acquisition and calibration cannot be eliminated. Therefore, compensates for the sum of four errors in the measurement system is introduced. In the following formula, μ_T represents the sum of the total errors.

$$\mu_T = \mu_a + \mu_c + \mu_s + \mu_f \tag{1}$$

3. Constructing plane control field of measurement area

The randomness and uncertainty of the error distribution result in compensation of plate measurement results inaccurate. Therefore, if the total error of the measurement system is directly correct, a detailed error distribution in the measurement area of the system is obtained.

3.1. Pixel interval error of grid standard plate

In this paper, a grid standard plate is designed for the total error of the measurement system, and it is pasted on the measured plane. The plate is composed of a plurality of horizontal and vertical lines which are perpendicular to each other and have a fixed pitch. In order to avoid the secondary error caused by image stitching, it is necessary to obtain the error distribution in the whole measurement area one time, to ensure that the same conditions are met when collect the grid standard image. The error of network standard plate measured by the image measuring instrument is less than 0.08 mm.

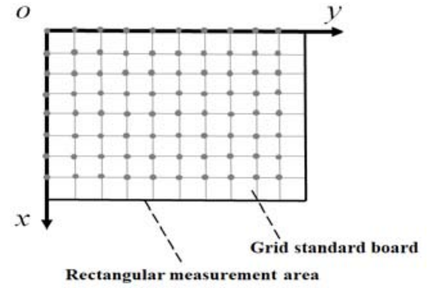

Figure 1. Coordinate system of grid standard board.

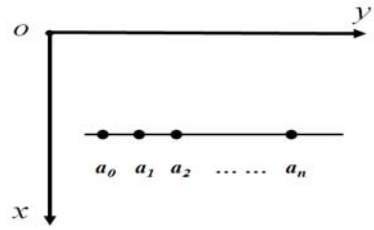

Figure 2. Cross point on the horizontal line.

To descript obviously, the placement of the grid standard plate in the measurement area is simplified shown in Figure 1.

Assume that the fixed distance between parallel horizontal lines and parallel vertical lines in the standard plate is $\bar{D}$ mm, and it is known that σ mm is represented 1 pixel in the image, so the pixel distance between parallel lines is $D = \bar{D}/\sigma$ pixel. In order to obtain the error distribution of the measurement area, Firstly, an image of the grid calibration plate is acquired by a line scan camera, and then a sub-pixel edge operator is used to locate the sub-pixel edge of each horizontal line and vertical line in the grid line. The extracted edges are fitted to the straight line by based on the weight of least-square method, and then the intersections of all the straight lines are obtained according to the fitting result. Finally, the spacing of pixel between adjacent points is calculated by obtaining the coordinates of the intersection points.

Assume that there are m horizontal parallel lines and n longitudinal parallel lines in the image, the fitting line equations of all horizontal lines and vertical lines in the image can be expressed by formula (2):

$$y = a_i x + b_i \qquad i = 1, 2, \ldots m \tag{2}$$

$$y = a_j x + b_j \qquad j = 1, 2, \ldots n \tag{3}$$

Suppose the fitting line equation for a horizontal line in the image is:

$$y = ax + b \tag{4}$$

Then the intersection coordinates of the horizontal line in the grid board are $\left(\frac{b_j - b}{a - a_j}, \frac{ab_j - a_j b}{a - a_j}\right)$.

Therefore, the spacing of pixel between the intersections on the horizontal line in the grid plate is:

$$D_j = \sqrt{(x_j - x_{j-1})^2 + (y_j - y_{j-1})^2} \qquad j = 2, 3, \ldots n \tag{5}$$

It is known that the spacing error between the intersections on the horizontal line is ε_h , and the pixel distance between the parallel vertical lines on the grid plate is D pixel, it is obtained:

$$\varepsilon_h = D - D_j \qquad j = 2, 3, \ldots n \tag{6}$$

The spacing error of the intersection point on the vertical line in the grid plate is similar. The spacing error between the intersections on the vertical line is ε_v , so the spacing error of the intersection of a certain vertical line in the image can be expressed as:

$$D_i = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} \qquad i = 2, 3, \ldots m \tag{7}$$

$$\varepsilon_v = D - D_i \qquad i = 2, 3, \ldots m \tag{8}$$

3.2. Error curve acquisition based on spacing error

The spacing error between the intersection of the horizontal and vertical lines in the grid standard plate obtained according to the formulas (6) and (8) can only describe the error of distance between the current intersection and the previous intersection. When we need the error of a certain point on the horizontal line, it is necessary to first measure the spacing error between all the previous intersections, which is not conducive to the establishment of the plane control field. Therefore, the error curve on the line is based on spacing error on the horizontal and vertical fitting lines in the grid standard board which is obtained firstly.

The grid standard plate coordinate system is established to describe the process of establishing the error curve. The vertical line direction of the standard plate is the x-axis, the horizontal line direction is the y-axis, and the origin is the top left corner intersection, as shown in Figure 1. It is assumed that there are n intersections on a horizontal line in the grid standard plate, which are $a_0, a_1, \ldots\ldots a_n$ from left to right, as shown in Figure 2.

The equation of the line is still expressed by the formula (2), and the distance between the pixel at any intersection of the horizontal line and the pixel of previous intersection is obtained by the formula (5):

$$D_{a_n a_{n-1}} = \sqrt{(x_n - x_{n-1})^2 + (y_n - y_{n-1})^2} \qquad n = 2,3,\ldots \tag{9}$$

Bring the above formula into the formula (6) to get the error between the measured distance and the standard distance value between any intersection and its previous intersection:

$$\varepsilon_{a_n a_{n-1}} = D - D_{a_n a_{n-1}} \tag{10}$$

Therefore, the error accumulated in the direction of the horizontal line can be expressed as follows:

$$\begin{gathered} \varepsilon_{a_2 a_0} = \varepsilon_{a_1 a_0} + \varepsilon_{a_2 a_1} \\ \varepsilon_{a_3 a_0} = \varepsilon_{a_1 a_0} + \varepsilon_{a_2 a_1} + \varepsilon_{a_3 a_2} \\ \varepsilon_{a_n a_0} = \varepsilon_{a_1 a_0} + \varepsilon_{a_2 a_1} + \cdots + \varepsilon_{a_n a_{n-1}} \end{gathered} \tag{11}$$

Formula (11) describes the error distribution of any intersection in the horizontal line in the horizontal direction, which is expressed as an error curve, as shown in Figure 3.

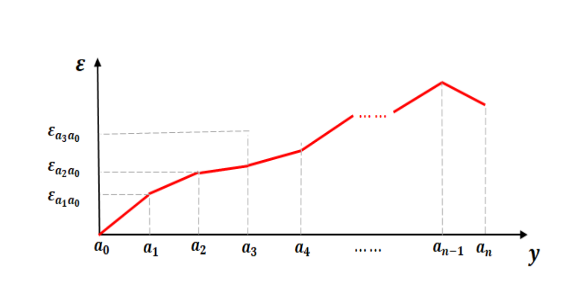

Figure 3. Error curve of a horizontal line along the y-axis in the grid plate.

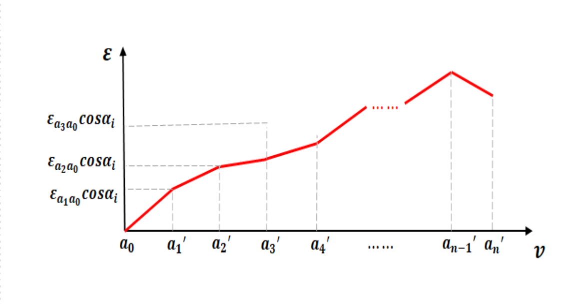

Figure 4. Error curve on projection line.

The horizontal axis of the above figure represents the y-axis in the grid standard plate, and the vertical axis is the error of distance between any point of the fitted line and the first intersection a_0. Similarly, an error curve for a vertical line on a standard plate is the same as an error curve for a horizontal line. Therefore, by establishing an error curve for all the horizontal and vertical axis of the grid standard plate, the error of any point in the y and x directions can be quickly obtained.

3.3. Establish control field of measurement area

The position of the coordinate system of grid is not known when process other non-grid images, it is even impossible to compensate the image of sheet using the error curve. The error curves in the grid plate coordinate system are converted to the error curves in the image pixel coordinate system what is necessary to establish the control field of the measurement area.

It is supposed that there are m horizontal lines on the grid plate. The fitted lines are $t_0, t_1, t_2, \ldots, t_{m-1}$. The intersection coordinates of pixel on the left line in the image are $\left(u_{t_0}, v_{t_0}\right)$, $\left(u_{t_1}, v_{t_1}\right)$, …, $\left(u_{t_{m-1}}, v_{t_{m-1}}\right)$. Figure 5 shows the coordinate system of image and grid plate.

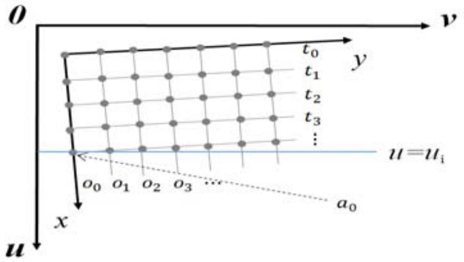

Figure 5. Relationship between image coordinate system and grid plate coordinate system.

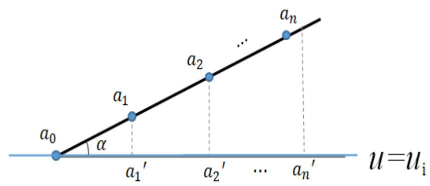

Figure 6. The horizontal line of the grid plate is projected to the image coordinate system.

It is assumed that the fitting line of a horizontal line in the grid plate coordinate system is t_i $(0 \le i < m)$. There are N intersection points on the line, which are $a_0, a_1, a_2, \ldots, a_N$. The coordinates of a0 in the pixel coordinate system are $\left(u_{t_i}, v_{t_i}\right)$. The error curve of the line along the y-axis in the grid plate coordinate system is shown in Figure 3. The error data in the line is projected into the line of $u = u_{t_i}$ in the image coordinate system. Process is shown in Figure 6.

It is supposed that the intersections which are on the horizontal line are overshadowed the straight line $u = u_{t_i}$, the projected points are $a_0, a_1', a_2', \ldots a_N'$. As can be seen from Figure 6, a right triangle can be formed between any intersection a_i, a_0, and a_i'. The error $\varepsilon_{a_i a_0}$ between the intersections a_i' and a_0 can be obtained according to the error curve, so according to the Pythagorean theorem can get the error between a_i' and a_0:

$$\varepsilon_{a_i' a_0} = \varepsilon_{a_i a_0} cos\alpha_i \tag{12}$$

α_i is the angle between the horizontal line and the image coordinate system, and K is the slope of the fitted straight line. α_i can be got according to formula (1),

$$\alpha_i = arctan(k) \tag{13}$$

Therefore, the error curves of all points on the line $u = u_{t_i}$ in the image coordinate system can be obtained according to formulas (12) and (13), as shown in Figure 4:

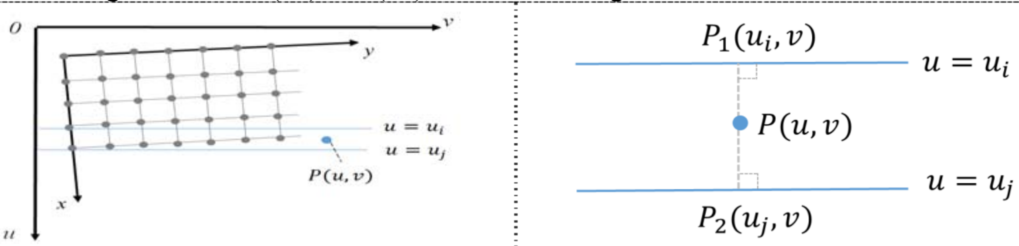

Figure 7. Interpolating the projected line.

Therefore, m error curves can be obtained after all the horizontal lines in the grid standard plate are projected into the image coordinate system, as shown in Figure 4. According to these curves, the error of all points on the projection line in the v-axis direction can be obtained, and linear interpolation can be performed in the image to obtain the v-direction error of any point in the whole image to form the v-direction control field of the image, and the v-direction control field of the image is generated, finally, the control field of the entire measurement area is obtained. Any position in the image can be directly obtained in the control field. The error value is used to compensate for the measured value at these points.

4. The compensation experiment of measurement system error

4.1. Plane control field of large size sheet

This paper designed a grid plate with a length of 2600mm and a width of 1200mm for the measuring range of the measuring system. The grid area consists of 240 horizontal parallel lines with a spacing of 10mm and 108 longitudinal parallel lines with a spacing of 10mm.

Before establishing the control field of the plate measurement area, it is necessary to obtain the pitch error of the grid plate. The specific process is to firstly locate the horizontal and vertical edges of the grid lines through the sub-pixels of the grid image, secondly, use a weight-based straight line fitting algorithm to fit the straight line and bring the straight line into the formula (4). Finally, Get all intersection coordinates and calculate the spacing of pixel between intersection and adjacent points.

Because the pitch of the grid plate is 10 mm, and one pixel in the image is 0.71 mm, the spacing of grid should be 14.0845 pixels. The pitch error of the grid plate can be obtained according to the formula (5). Take 15 sets of adjacent points on a horizontal line in the grid board as an example. The pixel pitch error is shown in Table 1:

Table 1. Fifteen sets of pixel pitch error on a horizontal line. (unit: pixel)

Point	a_1	a_2	a_3	a_4	a_5
Error of Spacing	-0.3584	-0.2623	-0.4186	-0.3684	-0.4247
Point	a_6	a_7	a_8	a_9	a_{10}
Error of Spacing	-0.3764	-0.3681	-0.2470	-0.1355	-0.2732
Point	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}
Error of Spacing	-0.0220	-0.1404	-0.1152	-0.1147	-0.0676

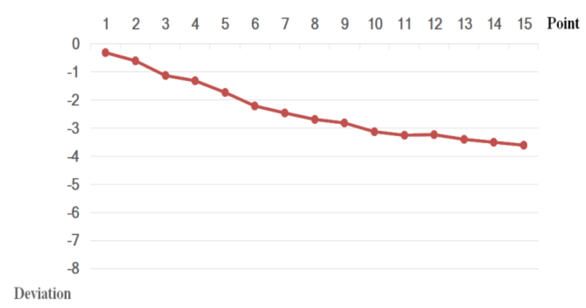

Figure 8. Error curve of a horizontal line in its direction.

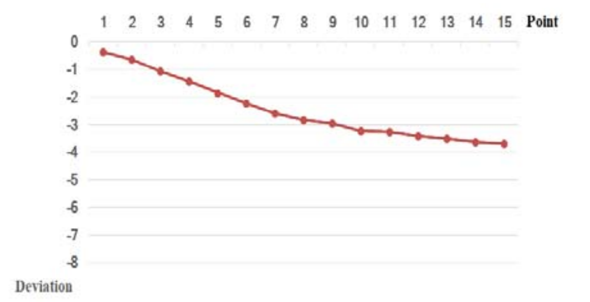

Figure 9. Error distribution curve of a horizontal line in its projected line.

According to the data in Table 1, the pitch error of 15 sets of intersections can be obtained, and then the error curve along the horizontal line between these points can be obtained by bring the pitch error into the formula (11), as shown in Figure 8. The oblique line equation in the horizontal line fitting line is:

$$v = -46.9586\,u + 2554.3532 \tag{14}$$

The pixel coordinate of a_1 is $(54.2839, 5.2573)$, so the error curve of the horizontal line $u = 54.2839$ in the image coordinate system can be obtained by taking the formula (12) and (13).

The other horizontal and vertical lines of the grid standard board are treated similarly. Finally, 235 error curves of $u = u_i$ and 100 error curves of $v = v_j$ are obtained by calculation. These error curves form the skeleton of the control field in the whole measurement area, and then the control field of the whole image is obtained by linear interpolation.

4.2. Analysis of experiment results

After the control field is obtained, the coordinates of pixel after the edge fitting are substituted into the control field, and then the compensated pixel point of row and column coordinates are obtained. Finally, the conversion relationship between pixels with millimetre and the Euclidean distance formula can be used to obtain the compensated distance of the central of a circle. In order to verify the accuracy and robustness of the algorithm, the error compensation algorithm is used to measure different central distances.

Table 2. Result of error compensation of round hole. (unit: mm)

Central Distances	Result with image measuring instrument	Result with sheet measuring system	Result with error compensation	The error of measurement
D1	999.962	1003.02	999.0814	-0.8806
D2	919.986	922.127	919.1685	-0.8175
D3	759.958	761.206	759.2446	-0.7134
D4	599.973	600.352	599.4169	-0.5561
D5	439.927	440.278	439.294	-0.633
D6	279.984	280.129	279.6897	-0.2943
D7	120.001	120.037	119.764	-0.237
D8	40.003	40.051	39.9483	-0.0547

It can be seen from Table 2 that in the measurement area of 1.2m$\times$2.6m, the error of the measuring result can be controlled within 1mm per meter. Compared with previous accuracy of 3mm per meter, the error of the measuring result is increased by 71%. Therefore, the measurement accuracy of the large-scale sheet metal measuring system can be effectively improved by establishing the plane control field of the measurement area.

5. Conclusion

In this paper, in order to solve the problem that the error in the measurement system is large and exceeds the tolerance range of the system setting, the correction method of the total error compensation of the system is adopted by analysing the cause of the error. The error distribution on the grid line is obtained by the measurement result of the grid standard plate. The plane control field of the measurement area is established by the linear interpolation. Finally, the measurement precision is improved by the measurement result of the sheet is compensated.

Acknowledgments

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