Research on the System Error Analysis and Compensation Method for the 3-D Profile Measurement with CCD Based on Linear Structure Lighting

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Abstract. For the 3-D profile measurement with CCD, the calibration of CCD measurement system is still the focus of the researchers’ attention. Firstly taking no account of some factors, such as the CCD lens aberration, image process error, etc., the principle error of the CCD calibration method constructing the coordinates mapping relation from image coordinates to space coordinates based on the polynomial fitting solution is analyzed through the experimental data in the paper. Then the paper analyzes the device error and operation error that is mainly from CCD lens aberration and image process. By measuring the standard geometry element, the error value can be picked up on the different depth position of field. After filtering the noise, the system error can be got, and can be used to compensate and amend the measurement result. The experimental result shows that with the system error compensation method, the measurable depth of field can be increased efficiently and the precision of the measurement result can be control within ±50um with common table of which the simple axis machine precision is 15um and open-loop control driven by the stepper motor, which can meet the profile measuring requirements well.

1. Introduction

With a simple system structure, higher measurement speed, better resolving power and computer control performance, the 3-D profile measurement with linear structure lighting has attracted the attention of many researchers, and some documents has given out the correlative research and analysis for the application prototype and technology. Franke Ernest A. introduces a method of 3-D precision surface measurement with dynamic structured light [1]. In the document [2], a 3-D profile measurement mode with multi structure linear lighting is given out. Zhang Aiwu, etc. also research the computer vision principle for the profile measurement [3]. General speaking, it is difficult for the 3-D vision measurement method to find the corresponding points in the different images, so it is also difficult to achieve a better measurement precision, and the bad operability has become the biggest obstacle to the practical application. For the trigonometric measuring principle, the relation of the practical height change and imaging length change is nonlinear in the height direction of the measured object, and can be considered approximately to be linear only in a short measuring range in which the measurement precision changes with the depth of field. So in order to achieve a better measurable performance in a long measuring range, the system hardware device must be fixed strictly. Self-
adaptation adjustment of the probe position method has been given out in some document to solve the 
adjustment of the measurement depth of field [4], which still cannot eliminate the nonlinear error of 
the measurement result.

The basic principle of the 3-D profile measurement with CCD based on linear structure lighting 
described in the paper is trigonometric measuring principle, and with the polynomial interpolation 
solution based on the grid lattice, the system can calculate the profile data rapidly. In order to reduce 
the influence of nonlinear mentioned above on the measurable depth of field, and improve the 
measurement precision further, the paper begins with the analysis of system error existing in the CCD 
profile measurement system, and puts forward the system error compensation and amendment model 
method for the 3-D profile measurement system with CCD based on linear structure lighting.

2. Basic principle analysis of the CCD profile measurement based on linear structure lighting 

The basic principle of profile measurement based on the linear structure lighting is shown in figure 1. 
The laser plan produced by semiconductor laser intersects the measured surface at a curve, the shape 
and position information of which in the CCD imaging plan implies the height information of the 
measured surface. With the calibration result, all the points in the curve can be figured out at a time. 
According to figure 1, the figure 2 analyzes the ideal geometry imaging principle of CCD in plan 
XOY and plan YOZ respectively. It is evident that in plan YOZ, the space displacement of the 
measured point is proportional to the corresponding imaging point displacement. In plan XOY, the 
relation of the correlative parameters can be described by the following formula,

\[ \frac{\Delta}{\sin \theta} = \frac{L}{\sin(\alpha - \theta)}, \quad \frac{\delta}{\sin \theta} = \frac{l}{\sin(\beta - \theta)}. \]  

(1)

We can deduce that the space displacement \( \Delta \) of the measured point and the image displacement \( \delta \) 
of the corresponding imaging point have the following relationship described in formula (2).

\[ \frac{1}{\delta} = \frac{1}{\Delta} \frac{L \sin \beta}{l \sin \alpha} + \left( \frac{\tan \alpha \tan \beta}{\tan \beta \tan \alpha} \right) \frac{\sin \beta}{l}. \]  

(2)

That is to say that there is linearity relationship between the reciprocals of \( \Delta \) and \( \delta \) in plan XOY.

3. The system error analysis of CCD profile measurement based on the linear structure lighting

3.1. The system error analysis from the calibration principle

The polynomial fitting solution is adopted to construct the mapping function approximately in the 
paper, which will also reduce the influence of some factors such as imaging aberration on the 
measurement result. Table 1 is the corresponding grid lattice of the image coordinates and space 
coordinates gotten according to the above relationship in which the unit of space displacement is millimeter.
Table 1. The corresponding lattice constructed according to the ideal geometry imaging relationship.

| No. | Image point | Space point | No. | Image point | Space point | No. | Image point | Space point |
|-----|-------------|-------------|-----|-------------|-------------|-----|-------------|-------------|
| 1   | 0,1         | 0,0         | 13  | 75/11, 107/66 | 10,2         | 25  | 45/13,109/26 | 6,6         |
| 2   | 1,8/9       | 2,0         | 14  | 9,3/2        | 12,2         | 26  | 5,77/18     | 8,6         |
| 3   | 15/7,16/21  | 4,0         | 15  | 0,3         | 0,4         | 27  | 75/11,289/66 | 10,6        |
| 4   | 45/13, 8/13 | 6,0         | 16  | 1,3         | 2,4         | 28  | 9,9/2       | 12,6        |
| 5   | 5,4/9       | 8,0         | 17  | 15/7,3      | 4,4         | 29  | 0,5         | 0,8         |
| 6   | 75/11,8/33  | 10,0        | 18  | 45/13,3     | 6,4         | 30  | 1,46/9      | 2,8         |
| 7   | 9,0         | 12,0        | 19  | 5,3         | 8,4         | 31  | 15/7,110/21 | 4,8         |
| 8   | 0,2         | 0,2         | 20  | 20         | 75/11,3     | 10,4 | 32           | 45/13,70/13 | 6,8         |
| 9   | 1,35/18     | 2,2         | 21  | 9,3         | 12,4        | 33  | 5,50/9      | 8,8         |
| 10  | 15/7, 79/42 | 4,2         | 22  | 0,4         | 0,6         | 34  | 75/11,190/33 | 10,8        |
| 11  | 45/13, 47/26 | 6,2        | 23  | 1,73/18     | 2,6         | 35  | 9,6         | 12,8        |
| 12  | 5,31/18     | 8,2         | 24  | 15/7,173/42 | 4,6         |      |             |             |

Based on these ideal data, we can construct the polynomial mapping function and calculate the polynomial coefficient, which is shown in table 2, according to formula (3).

\[
X(u, v) = \sum_{j=0}^{n} \sum_{i=0}^{n} C_{ij} u^i v^j, \quad Z(u, v) = \sum_{j=0}^{n} \sum_{i=0}^{n} D_{ij} u^i v^j
\]  

(3)

With the mapping function, we can calculate the space grid lattice, which is shown in table 3. Compared table 1 with table 3, the system error exists in the calibration method can be got. After the contrast, we find that the sum of the distance error between the corresponding points is 0.289386 mm, and the average distance error is 0.008268 mm.

Table 2. The coefficient of mapping function calculated based on the corresponding lattice.

| i, j | C_{ij} | D_{ij} | i, j | C_{ij} | D_{ij} |
|------|--------|--------|------|--------|--------|
| 0,0  | 0.006692410864696 | -1.986792171838005 | 1,1  | -0.0000000000000072 | -0.102479809382781 |
| 0,1  | 0.0000000000000067 | 1.995597390612979  | 1,2  | 0.0000000000000006 | 0.0000000000000004 |
| 0,2  | -0.0000000000000163 | -0.0000000000000134 | 2,0  | -0.117451540989080 | -0.009692534149175 |
| 0,3  | 0.0000000000000014 | -0.0000000000000012 | 2,1  | 0.0000000000000003 | 0.03230844716391 |
| 1,0  | 2.0968128268793931 | 0.307439428148319  | 3,0  | 0.003618966255924 | 0.0000000000000000 |

Table 3. The space lattice calculated with mapping function, the average error is 0.008268 mm.

| No. | Calculated space point | No. | Calculated space point | No. | Calculated space point |
|-----|------------------------|-----|------------------------|-----|------------------------|
| 1   | 0.006692, 0.008805     | 13  | 9.990211, 2.004803     | 25  | 6.007680, 6.002567     |
| 2   | 1.989678, -0.003402    | 14  | 12.002708, 1.997534    | 26  | 8.006866, 5.998405     |
| 3   | 3.996165, 0.008056     | 15  | 0.006692, 4            | 27  | 9.990211, 5.995197     |
| 4   | 6.007680, -0.005134    | 16  | 1.989678, 4            | 28  | 12.002708, 6.002466    |
| 5   | 8.006866, 0.003189     | 17  | 3.996165, 4            | 29  | 0.006692, 7.991195     |
| 6   | 9.990211, 0.009607     | 18  | 6.007680, 4            | 30  | 1.989678, 8.003402     |
| 7   | 12.002708, -0.004933   | 19  | 8.006866, 4            | 31  | 3.996165, 8.008056     |
| 8   | 0.006692, 2.004403     | 20  | 9.990211, 4            | 32  | 6.007680, 8.005134     |
| 9   | 1.989678, 1.982999     | 21  | 12.002708, 4           | 33  | 8.006866, 7.996811     |
| 10  | 3.996165, 1.995972     | 22  | 0.006692, 5.995597     | 34  | 9.990211, 7.990393     |
| 11  | 6.007680, 1.997433     | 23  | 1.989678, 6.001701     | 35  | 12.002708, 8.004933    |
| 12  | 8.006866, 2.001595     | 24  | 3.996165, 6.004012     |      |                       |
3.2. The system error analysis from hardware device

The main hardware devices bringing the measurement error are CCD and correlative optics elements. The geometry imaging relation analyzed above is built on the ideal imaging condition. Because of the limit of the imaging principle and the manufacturing process of the optical elements in practice, the actual imaging position of the space point will be not consistent with the ideal position. That is to say, there is aberration in the whole optics imaging system. We can determine the aberration degree with the help of standard plan. Figure 3 is the image process result of linear structure lighting projection image on the standard plan on different measurement depth position of field and the line on every position is the fitting result with pixel coordinates of the laser projection image, which reflects the aberration degree on different measurement depth position of field. When we get the image calibration grid lattice, the laser projection image is treated as line, just like the fitting line in the figure. Thus the error caused by the hardware factors will bring the new system error for the system.

![Figure 3. Error analysis from hardware device.](image1)

![Figure 4. CCD measurement error calibration.](image2)

4. System error compensation and amendment principle and method

4.1. Measurement error calibration

Figure 4 is the system error calibration setting for the profile measurement system based on linear structure lighting. The laser produced by semiconductor laser vertically shoots the measured surface, and two CCD fixed beside get the image. The laser plan intersects the standard calibration plan, thus the laser project image of the laser should be a line. Fitting the measurement result according to the line, and comparing the measurement result with the fitting line, we can get the measurement error on the current measurement depth position of field. Moving the measurement setting at a lesser step, the measurement error on the different depth position of field can be calibrated. Figure 5 gives out the error calibration result on the different depth position of field and different height position. In the figure the measurement depth of field is 60 mm. There are a curve and a line on every error calibration position. The curve is the actual measurement result, and the line is the fitting result by measurement data. The variance between the curve and the line is measurement error of corresponding point.

![Figure 5. CCD measurement error calibration result on the different depth position of field.](image3)
4.2. System error compensation and amendment method

4.2.1. Smooth filter process for the error calibration result. Because of the machine error and the image process error, there will be some random error in the measurement result. So the error calibration result must be filtered, and only the error curvilinear trend information will be reserved, which will be used to compensate and amend the measurement result. Here the weighted average method with a moving window is adopted to realize the smooth filter process [5] for the measurement error calibration result in the paper.

Suppose that there is an aggregate composed of measurement error points which is defined as 
\[ \{ p_i = (x_i, y_i, z_i) \mid i = 0, \cdots, n-1 \} \]. Here \( w(j) \) is the eudipleural weight function defined by \( 2N+1 \) points. Define \( j = -N, \cdots, N \), and \( N \) is the moving window half width, then we can get the smooth function of any point just like formula (4).

\[
\bar{p}_i = \sum_{j=-N}^{N} p_{i+j} w(j) / \sum_{j=-N}^{N} w(j), \quad i = N, \cdots, n - N.
\]  

In order to ensure that the above method can be applied to any point in the aggregate, here the \( N(i) \) is defined as the following form:

\[
N(i) = \begin{cases} 
  i, & 0 \leq i < N \\
  N, & N \leq i \leq n - N \\
  n - i, & n - N < i \leq n - 1 
\end{cases}
\]  

4.2.2. The realization of system error compensation and amendment with interpolation method. After calibrating the measurement error and processing with smooth filter, we can get the system error compensation value \( f(x, z) \) on any error calibration position in the height direction. With the bivariate interpolation method, the system error compensation value at the given point can be worked out. The realization of bivariate interpolation algorithm is complicated. In order to reduce the calculation complexity and improve the data process efficiency, the unitary interpolation is adopted in the paper. The detail realization approach is described as the following content.

Firstly, construct the data aggregate \((z, f(z))\) based on the system error compensation value on every measurement error calibration position and do the curve interpolation \( z = z_0 \) based on the aggregate. Thus we will get the system error compensation value \( f(z_0) \) on every error calibration position.

Then construct another data aggregate \((x, f(x, z_0))\) based on the result of the first step, and do the curve interpolation \( x = x_0 \). Thus we will get the system error compensation value \( f(x_0, z_0) \) of point \((x_0, z_0)\).

At last, add the system error compensation value of current measurement position to the actual measurement result, we can get the last profile measurement result.

5. Application analysis

The basic hardware of the CCD profile measurement system described in the paper is made up of table with common machine precision (simple axis machine precision is 15um) and open-loop control cell driven by stepping motor without position feedback. With the method given out in the paper, we has measured a standard plan with the flatness less than 5um. Through the contrast between the measurement results shown in figure 6, it is indicated that after compensation, measurement result precision can be improved (arrived at ±50um) and can meet the profile measuring requirements well.
6. Conclusion
The CCD profile measurement system based on the linear structure lighting can measure the 3-D profile quickly and efficiently. Because of the limit of the optics trigonometric measuring principle and the hardware device condition, there is a big measurement error in the measurement result. Calibrate the measurement error in the height direction according to the trigonometric measuring principle and filter out the random error smoothly, then we can pick up the system error on different position with interpolation algorithm. Compensating the actual result with the system error compensation value, we will get a better measurement result. The method will also reduce the limit of trigonometric measuring principle to the measurement depth of field and can ensure a better measurement precision in a bigger measurement depth of field. All these will make the device setting and debug easy.

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