Module Calibration and Image Processing Based on Measurement System for 3-D Foot Shapes

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Abstract. A method of module calibration and image processing based on a measurement system for 3-D foot shapes is described, which contains a module calibration system for the compensation of different position errors. A double scanning process with a calibration frame structure is performed, realizing thus a mapping conversion between the two coordinate systems. With the feature points formed by the intersection of the edges of the calibration frame and the light sectioning planes, different position errors can be automatically compensated. The disadvantages caused by the gradient prediction method can be reduced. Calibration and measurement experiments were conducted with satisfactory results.

1. Introduction
Optical 3-D profilometry is widely used in industry measurement, machine vision, reverse engineering, profile modeling, etc. One of its typical applications is to measure the 3D foot shapes in shoemaking industry. There are two important factors in the 3-D foot shapes measurement systems, one is calibration, and the other is image processing.

The calibration methods at present can be divided into two types: configuration parameter calibration and module calibration. Configuration parameter calibration requires non-linearity iteration and onerous calculation, which is not suitable in foot’s measurement. On the other hand, module calibration method can be employed, which is composed of two usual methods: (1) the calibration based on the feature points, which employs a calibration board with amounts of feature points as the reference in calibration, (2) the calibration based on the feature module, mainly based on the incline model or the tooth-like model. The calibration method used in the 3-D foot shapes measurement systems combines above two methods, and will have more advantages.

In this paper, a calibration method based on the table-lookup method is proposed. The measuring accuracy can be further improved by a compensation for the errors caused by moving parts. With this method, 8 CCD sensors can be calibrated at the same time. The calibration module is composed of three different parts, calibration frame Feature points can be obtained by double scanning, which can be used to calibrate the X an Y coordinates. This method can be widely used in the calibration of multi-sensor vision system, and is suitable for complex measurement conditions.

2. Overview of the measurement system
The 3-D vision system shown in figure 1, is based on the laser line-scanning triangulation method. As is shown in figure 1, with four groups of vision sensors for image acquisition, the system can obtain a full range of 360 degree profile covering the heel.
3. Calibration system

3.1. The calibration module
As is shown in Figure 2, the calibration board can be placed in two different orientations, which has an included angle of 45° with the axis Z. Two edges in the calibration block can be used to determine the orientation of the axis Z accordance with the direct-axis of the calibration frame. It also can be used to reduce the errors which are caused by the small angle errors between the axis Z and the forward axis of the magnetic stepping motor.

3.2. Method of calibration
Non-linearity distortion of the CCD is resulted from many factors, such as the manufacture errors, bend surface error of the lens in the CCD, the space between different lens, etc. Radial aberrance is the most important factor. Non-linearity distortion can be expressed as

$$\delta_x = k_1(x^2 + y^2), \delta_y = k_2(x^2 + y^2)$$

(1)

Where \(x, y\) are the coordinates of the image element in image coordinate system (ICS), \(\delta_x\) and \(\delta_y\) are the distortions of X and Y in ICS, \(k_1, k_2\) are the coefficients of the radial aberrance.

With The module calibration method based on feature points, the non-linearity equation can be transformed to linearity, which simplify the calculation, and the result of the calculation is satisfactory, we can further control the measuring error by reducing the grid spaces or increasing the number of the nodal point. Figure 3 and Figure 4 show two orientations of the calibration board:

In theory, the magnetic stepping motor advances \(\Delta z\) along the axis Z each time. Suppose light-sectioning plane which the motor stops first is the start position \((x, y)\). In Figure 4 and Figure 5, the light-section plane moves from position 1 to position 2, then it advances \(\Delta x\) and \(\Delta y\) along the axis X and Y respectively. For the incline angel between the board and the axis Z is 45°, then \(\Delta x = \Delta y = \Delta z\).

The light band is received by CCD sensors when light sectioning plane moves along the calibration board. After image processing and refining, the coordinates in the image coordinate system corresponding to the pixel points can be calculated. Then the coordinates in the world coordinate
system can be obtained based on the pixel points’ coordinates in the image coordinate system. Since
the curves are not distributed at the same interval, the actual coordinates should be determined
according to the gradient of the curve’s distribution.

3.3. Compensation of the deflection angle
Due to the angle between the motor’s motion direction and z axis in WCS, the distances moving along
z axis is not the same as those along x and y axis. So it is necessary to calibrate the motion direction of
the motor. To calibrate the motion direction, a standard block, whose length, width, and height have
been known, is selected.

As shown in Figure 5, Light strap intersect edge 1 at point A, and edge 2 at point B. The length of
AB along x axis is 80mm. According to the coordinates corresponding to A and B in image plane, the
coordinate along x axis in WCS can be obtained. The length of l’ is the difference between the two
coordinates above mentioned. The angle between the motion direction and the z axis in WCS
projected in x axis is \( \alpha \), then \( \tan \alpha = l' / 80 \). Substitute the correction result in former formulae, and the
distance along x axis in WCS can be expressed as \( \Delta x = \Delta z \cdot \tan(45 + \alpha) \). To reduce the error caused by
the deflection angle, let motor move along the calibrating block, many intersection points formed by
light straps and edges and the data of deflection angles calibration can be obtained. When the motor
moves along z axis, the values of \( \alpha \) are different. We can get a determined value of \( \alpha \) from the
corresponding curve in gridding map. Then the calibration with high accuracy can be realized.

The calibrating method in y axis is the same as that above mentioned, and description thereof is
omitted.

4. The image processing system
The images obtained by CCD sensors require a preprocessing, such as the image filtering and
centralization, etc. First, the effective range of the image for 8 CCD devices is obtained. Secondly, the
threshold is determined by computing the variance between classes to implement image partition in
complex environment according to different features of lasers and foot surfaces. Then improved
method for center axis tracking is proposed, which is applied to obtain and process the information
from the center of the light-sectioning, and the centers for the Gaussian distribution of the light bands
can be accurately obtained. Finally, with a method of pruning for complex thinned curves the
preprocessing is completed. After the preprocessing, it is necessary to reconstructed the measured
points:

Suppose an array composed of \((m+1) \times (n+1)\) controling points \( \mathbf{d}_{ij} \) \((i=0,1,\ldots,m; j=0,1,\ldots,n)\),which
constitute a control grid, and the degree \( k \) and \( l \) of the parameter \( u \) and \( v \), two vectors of the nodes
\( \mathbf{U} = [u_0,u_1,\ldots,u_{m+k+1}] \) and \( \mathbf{V} = [v_0,v_1,\ldots,v_{n+l+1}] \) are also presented. Then we can acquire a B-spline surface
with the degree of \( k \times l \):

\[
p(u,v) = \sum_{i=0}^{m} \sum_{j=0}^{n} d_{ij} N_{i,k}(u) N_{j,l}(v) \tag{2}
\]

\( u_k \leq u \leq u_{m+1}, v_l \leq v \leq v_{n+1} \).

\( N_{i,k}(u) \) \((i=0,1,\ldots,m)\) and \( N_{j,l}(v) \) \((j=0,1,\ldots,n)\) are the spline bases of order \( k \) in \( u \) aspect and order \( l \) in \( v \) aspect,
respectively. They are determined according to the vectors \( \mathbf{U} \) and \( \mathbf{V} \) based on the Debor recurrence equation:
The reconstruction of the foot shape can be divided into two parts:

1. Creating section curves: fit the measured points into the B-spline curves with the least squares fitting, then make sure every curve has the same degree and vectors of nodes. Thus we will acquire $s+1$ section curves:

$$s_j(u) = \sum_{i=1}^{m} \tilde{d}_{ij} N_{i,k}(u), \quad j = 0, 1, \cdots, s$$

2. Creating surfaces: a group of section curves can be employed to create the surfaces, with the control points of the curves we can get the control points of the surfaces, the final B-spline surfaces can be acquired.

5. Experiments

Figure 6 and Figure 7 show the curves in calibration experiments from two different directions. We can acquire the grids after the nestification of the two pictures.

| Table 1. Measurement results of a block (mm) |
|---------------------------------------------|
| Real value | Measured value | Deviation | Mean square dev. |
| 80          | 79.874         | 0.126     | 0.0102          |
| 80          | 79.922         | 0.078     |               |
| 80          | 79.827         | 0.173     |               |
| 80          | 79.965         | 0.035     |               |
| 80          | 80.001         | 0.001     |               |

Table 1. Shows the measured length of the calibration block. The length of the block is 80mm, and the mean square deviation is 0.0102mm. In summary, with this method, high accuracy is achieved, and the method is suitable for the foot shape measurement.

6. Conclusion

A method of module calibration based on a measurement system for 3-D foot shapes is described in this paper. A double scanning process with a calibration frame structure is performed, realizing thus a mapping conversion between the two coordinate systems. With the feature points formed by the intersection of the edges of the calibration frame and the light sectioning planes, different position errors can be automatically compensated. The image processing module in the system is also introduced. With this module, 3D solid foot model can be reconstructed accurately using the data point obtained by light sectioning device.
Future development will be aimed at employing this automated inspection system in modern shoe-making industry production to increase the efficiency and accuracy of manufacture. The technology discussed in this paper possesses widely application prospection.

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