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Hard-Disk Stereo Vision Measurement System Calibration Using Light Plane Constraint

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Abstract

This paper proposed a calibration method of sheet-of-light vision measurement sensor based on light plane constraint. Through capturing 12 images of different direction from homemade circular calibration target, the center of the circle and the light stripe is extracted based on Halcon platform of Germany. The experimental results obtained the intrinsic parameters, extrinsic parameters and radial distortion coefficient of the nonlinear model. At the same time the light plane constraint equation is got based on PCA plane fitting method. The results show that the calibration method is simple and reliable, and the method does not need any auxiliary adjustment. The work laid the better foundation for hard disk planeness vision measurement.

Keywords: *light plane constraint, line sheet-of-light sensor, calibration*

1. Introduction

In planeness measurement with particular application for computer hard-disk surface at a foreign-founded enterprise in Singapore, the requests on the planeness measurement of the hard-disk surface is very high to realize zero waste production. On the basis of our previous study, in order to improve the accuracy of measurement system, on the conditions of laboratory, we determine to use line sheet-of-light vision measurement system to detect the planeness of the hard disk. The measured object is hard-disk surface of computer; see Figure 1. On the analysis of the mathematical model of the line sheet-of-light vision measurement, it is key to determine suitable calibration method and calibration parameters. The paper is mainly studied the calibration method of the line sheet-of-light vision sensors on base of light plane constraint. Halcon, powerful platform for image processing algorithm, is used to determine the camera parameters (both interior and exterior parameters) and light plane parameters, to lay the foundation for the application of the hard disk planeness vision measuring system.

Figure 1. Measured Object: Hard-disk of Computer

2. Sheet-of-light Vision Measurement Principle

The measurement principle of structured light is to generate a thin luminous straight line by a laser line projector and project onto the surface of the object that is to be measured. Then,

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the stripe image modulated by the object height is formed in camera. As shown in Figure 2, $o_c - x_c y_c z_c$ is camera coordinate system, and define it is the world coordinate($o_w - x_w y_w z_w$) system of the hard-disk measured system. Point O_c is center of perspective projection, $o_c z_c$ optical axis of camera, $o_i - x_i y_i$ is image coordinate system, where o_i is intersection point between optical axis $o_c z_c$ and image plane. Distance between point o_i and o_c is focal length. Linear structured light laser projects light plane, the 3D coordinate of P on the light plane is $P_C(x_c, y_c, z_c)$, of cause, it is on the surface of object. The point P is projected through the projection center of the lens to the point P' in the image plane. The points, such as P, depend on the height of the object, thus, if the object onto which the laser line is projected differs in height, the line is not imaged as a straight line but represents a profile of the object. Using this profile, we can obtain the height differences of the object. In order to get many the object height profiles, the object should be moved by a scanning system.

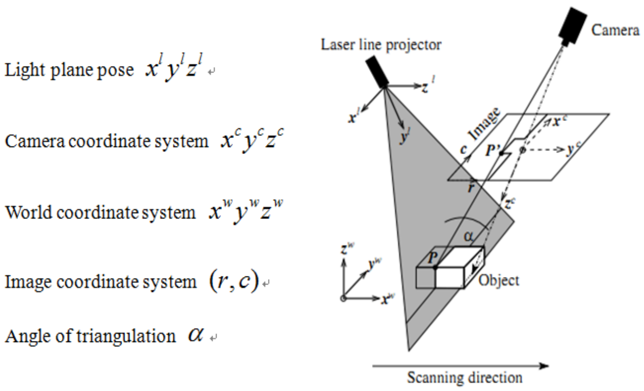

Figure 2. Sheet-of-light Vision Measurement Principle

2.1. Nonlinear Camera Models

The transformations from the pixel coordinates to the world coordinate system can be expressed mathematically as:

$$Z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{1}{dx} & 0 & u_0 \\ 0 & \frac{1}{dy} & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix}$$

$$= \begin{bmatrix} a_x & 0 & u_0 & 0 \\ 0 & a_y & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \tag{1}$$

Here, $a_x = f / dx, a_y = f / dy$.

After the projection to the image plane, lens distortions cause the coordinates $(u,v)^T$ to be modified. This is a transformation that can be modeled in the image plane alone, i.e. ,3D information is unnecessary. For most lenses, the distortion can be approximated sufficiently well by a radial distortion, given by:

$$\begin{pmatrix} \tilde{u} \\ \tilde{v} \end{pmatrix} = \frac{2}{1+\sqrt{1-4k(u^2+v^2)}} \begin{pmatrix} u \\ v \end{pmatrix} \tag{2}$$

Therefore, camera imaging model includes 6 extrinsic parameters ($\alpha, \beta, \gamma, t_x, t_y, t_z$) and 6 intrinsic parameters (f, k, d_x, d_y, u_0, v_0). Together represented by vector $c = (f, k, d_x, d_y, u_0, v_0, \alpha, \beta, \gamma, t_x, t_y, t_z)$. Coordinates of calibrating points in 3D space are M_i. Projection coordinates obtained through the camera model are $\pi(M_i, c)$, coordinates of calibration points extracted from 2D images are m_i. Then, the camera parameters can be determined by minimizing the distance of the extracted mark centers m_i and their projections $\pi(M_i, c)$:

$$d(c) = \sum_{i=1}^{k} \left\| m_i - \pi(M_i, c) \right\|^2 \rightarrow \min \tag{3}$$

Here, $k = mn$ is the number of calibration marks.

2.2. Light Plane Equation

By above mathematical model of structured light vision measuring system, light plane projected by optical projector and the measured object surface intersect and form characteristic light stripe. An arbitrary point in characteristic stripe can be expressed by a ray and optical plane. The image coordinates in camera image plane of the feature points on the light stripe can be obtained by image processing. According to the camera model, a feature point's image coordinates corresponds only the ray through the camera optical center, that is it can be obtained the 3D camera coordinates equation of the ray. If we can obtain the equation of the light plane in the camera coordinate system, the ray equation and the light plane equation can only determine the 3D coordinates in the camera coordinate of the feature point on the light stripe.

The light plane equation in the $O_W - x_w y_w z_w$ coordinates can expressed:

$$a_w x_w + b_w y_w + c_w z_w + d_w = 0 \tag{4}$$

3. Calibration Process Design

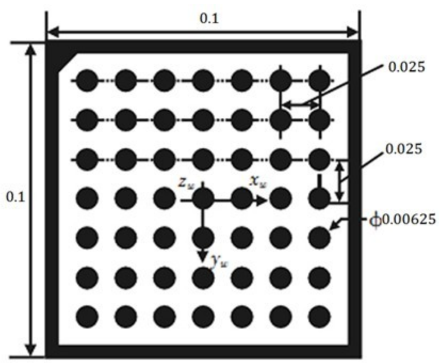

Figure 3. Calibration Board and Specific Dimensions

Calibration method this paper researched chooses one plane circular target. Respect to the angular point extracting of the chessboard, center extracting algorithm has strong anti-noise ability, the algorithm is simple and fast. The calibration board and specific dimensions is shown in Figure 3. Definiting the world coordinate system origin is at the center of the central of the board, z axial is vertical to the calibration board upward, coordinate direction can be uniquely determined by the black box in the triangle at the upper left corner.

The specific algorithm and the steps are as follows:

(1) Collect a set of images of the target at various positions, see Figure 4. Of course, the target feature points should be located in the camera view field.

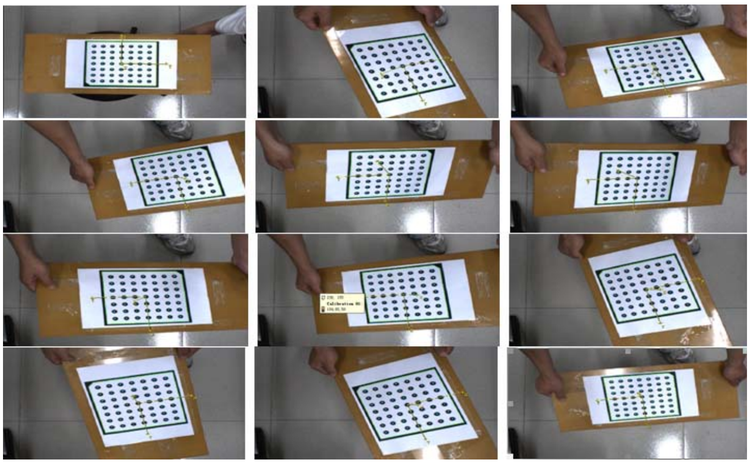

Figure 4. Collect a Set Various Position's Images of the Target

(2) Extract the edge of circular of the target using Canny operator, get the edge of sub-pixel precision, and then extract circular target contour and fit ellipse using the algebraic distance least square ellipse fitting algorithm;

(3) Based on elliptic minimum circumscribed quadrilateral center coordinates, determine the corresponding relation between calibrating point and projection image; see Figure 5.

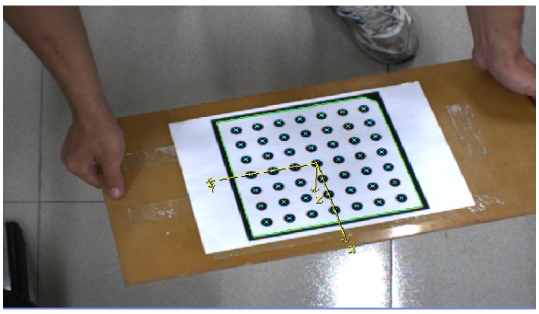

Figure 5. Extract Edge and Center Coordinates

(4) Determine the internal and external parameters $(f,k,d_x,d_y,u_0,v_0,\alpha,\beta,\gamma,t_x,t_y,t_z)$. The camera calibration corresponds to an optimization of the internal parameters and the poses of the cameras and of the calibration objects' poses such that the back projection of calibration object feature points into the modeled cameras fits the actual observed projections as well as possible. Note that the optimization needs an initial estimate for the internal camera parameters.

(5) Extract each article optical feature points on the reference target images, using the camera internal parameters and the target plane equation in camera coordinate; calculate the coordinates of each point of the light stripe in the camera coordinate system. Fit the light plane using PCA algorithm of so many points. At last, we can obtain the light plane equation under the condition of the camera coordinate system. PCA algorithm uses simple statistics and matrix operations, don't have to solve the partial derivatives of the equation. So , it is more simple, stable and reliable than the least square method .Assuming that the N light points coordinates in camera coordinate system are (x_{ci} , y_{ci} , z_{ci}), the center coordinates are $\left(\overline{x}_{ci}, \overline{y}_{ci}, \overline{z}_{ci}\right)$, by the covariance formula:

$$\operatorname{cov}(x, y)=\frac{1}{N-1} \sum_{i=1}^{N}\left(x_{ci}-\overline{x}_{ci}\right)\left(y_{ci}-\overline{y}_{ci}\right) \tag{5}$$

Covariance matrix can be constructed:

$$\mathbf{C}=\begin{pmatrix} \operatorname{cov}(x, x) & \operatorname{cov}(x, y) & \operatorname{cov}(x, z) \\ \operatorname{cov}(y, x) & \operatorname{cov}(y, y) & \operatorname{cov}(y, z) \\ \operatorname{cov}(z, x) & \operatorname{cov}(z, y) & \operatorname{cov}(z, z) \end{pmatrix} \tag{6}$$

(6) Solve the eigenvalue and eigenvector of C, and find the smallest eigenvalue corresponding to the eigenvector, namely to fit plane normal vector (a, b, c), and take center coordinates into the light plane equation axc + byc + czc + d = 0, the fourth component d in the plane equation can be determined.

4. Calibration Experiments and Results

According to the measure principle of line structured light vision sensor, we designed a line structured light vision sensor, the real object is shown in Figure 6. Image pixels of camera are 640(h)x480(vXCCIR), pixel size is 7.8$\times$7.9μm.Laser line projector is semiconductor red light laser, its wavelength is 650nm , line width is less than 1mm. The position and orientation of the projector with respect to the camera are fixed. Figure 6 is for the designed calibration target objects. Using the fixed point provided by the target, we calibrate the line structured light vision sensor by above method, the results are shown in Table 1 to Table 3. The average error is 0.023mm.

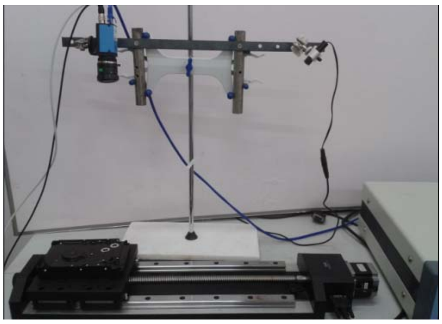

Figure 6. Real Object of Line Structured Light Vision Sensor

Table 1. Intrinsic Parameters of Camera

f	k	d_x	d_y	u_0	v_0
8.66973	-1467.08	7.88398	7.9	307.073	222.719

Table 2. Extrinsic Parameters of Camera

X	Y	Z	α	β	γ
40.6145	10.6715	922.203	14.5302	354.384	348.57

Table 3. Light Plane Parameters

a	b	c	d
0.48502	0.09012	0.83951	81.251

5. Measurement Accuracy Evaluation Test

Measuring accuracy of the line structured light vision measurement system is evaluated based on standard height value of hard disk surface provided by manufacturer. Table 4 shows the comparison between standard height value and measure height value. It can be seen from Table 4, the measure accuracy of the calibrated structured light measurement system is less than 0.023mm, and root-mean-square error (RMSE) is about 0.01795mm, which meets fully the requirements of computer hard disk planeness measurement.

Table 4. Measurement Accuracy Evaluation Test Data

Measure point	Measure height value (mm)	Standard height value (mm)	Error (mm)
P1	23.398	23.442	-0.044
P2	4.225	4.201	0.024
P3	23.396	23.420	-0.024
P4	21.701	21.611	0.09
P5	9.403	9.418	-0.015
P6	16.518	16.551	-0.033
P7	8.497	8.507	-0.01
P8	6.334	6.313	0.021
P9	6.345	6.317	0.028
P10	23.428	23.446	-0.018
RMSE		0.037618	

6. Conclusion

Based on the accuracy requirement of the hard disk planeness visual measurement system, this paper proposed a calibration method of line structured light vision measurement sensor based on light plane constraint. Combining with Halcon software we can complete quickly the camera calibration of internal parameters and external parameters, and parameters of the light plane. And do not need any auxiliary adjustment, calibration process is simple, reliable and suitable for field calibration, and the work laid the better foundation for hard disk planeness visual measurement.

Acknowledgements

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