Measuring method for micro-diameter based on structured-light vision technology

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Based on structured-light vision measurement technology, we study a measuring method for micro-diameter. The measurement principle and mathematical model are described. A novel grayscale barycenter extraction algorithm along the radial direction is proposed, which can precisely gather the image coordinates of the ellipse-shaped light-stripe centers. The accuracy of the measurement result shows marked improvement by using the algorithm. The method executes circle fitting to the measured three-dimensional (3D) data using linear least square method, which can acquire the diameter, surface profile, and other information of the object effectively. On the scene, a line-structured light vision system using the presented method is applied to measure the curvature radius of metal blades. Experimental results show that the measurement precision of the system is higher than 2 μm.

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Three-dimensional (3D) vision measurement technique has recently become the focus of geometric measurement theories for its excellent fit with digitized object shapes expressed as 3D coordinates (x, y, z) in a series of surface points. With the development of photoelectric sensor and computer technology, 3D vision measurement techniques are continuously enriched and developed. Characterized by non-contact measurement, fast speed, and good flexibility, structured-light vision measurement technology has become the most effective to implement 3D vision measurements[1], such as in measuring the 3D geometry size of industrial work-pieces[2], soldering pastes printed on printed circuit boards (PCBs)[3], tooth modeling[4], and even on the application of profile in coin surfaces[5].

Based on structured-light vision measurement technology, this letter offers a high-precision measuring method for micro-diameter to measure the diameter of cylindrical parts and curvature radius of metal blades. We describe the measurement principle and mathematical model of the method, and then propose the image and data processing method. Experimental results of the system using this method prove that the system has high precision and good repeatability.

In the light-plane coordinates system $O_l - x_l y_l z_l$, $P_l(x_l, y_l, 0)$ is one of the crossing points of the light-plane and the measured cylindrical object (Fig. 1). In the camera coordinate system $O_c - x_c y_c z_c$, the coordinate is $P_c(x_c, y_c, z_c)$.

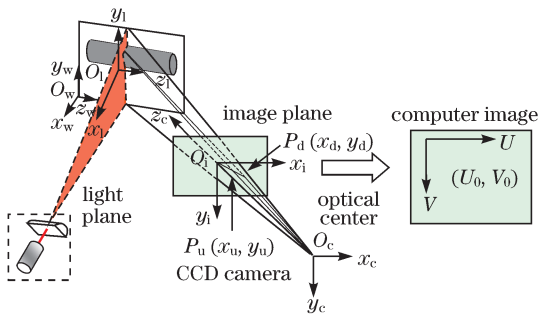

Fig. 1. Mathematical model of the system.

Lens radial distortion may occur in an image-plane. The corresponding image distorted coordinates of $P_l(x_l, y_l, 0)$ is in fact $P_d(x_d, y_d)$, with an offset from the undistorted coordinates point $P_u(x_u, y_u)$. We use (U, V) as the pixel coordinates of the point in the computer image coordinate system. The relation between light-plane coordinates $P_l(x_l, y_l, 0)$ and the pixel coordinates (U, V) is described as[6]

$$\begin{cases} x_d = (U - U_0) \cdot d_x \cdot s_x^{-1} \\ y_d = (V - V_0) \cdot d_y \\ r^2 = x_d^2 + y_d^2 \\ f \frac{r_1 x_l + r_2 y_l + t_x}{r_7 x_l + r_8 y_l + t_z} = x_u = x_d \left(1 + k_p \cdot r^2\right) \\ f \frac{r_4 x_l + r_5 y_l + t_y}{r_7 x_l + r_8 y_l + t_z} = y_u = y_d \left(1 + k_p \cdot r^2\right) \end{cases}, \quad (1)$$

where d_x and d_y are the center-to-center distances between pixels in the row and column directions, respectively. The specifications of charge-coupled device (CCD) are followed according to manufacturer instructions. Then, s_x is the uncertainty image factor, (U_0, V_0) is the center pixel of the computer image, f is the focus of the lens, and k_p is the distortion coefficient. The parameters of the system that need calibration are divided into two categories. The camera inner parameters of U_0, V_0, s_x, f, k_p, d_x, and d_y are denoted by the characteristics of the lens and CCD. The light-plane parameters of r_1, r_4, r_7, r_2, r_5, r_8, r_3, r_6, r_9, t_x, t_y, and t_z are the elements of the transformation matrix from the camera coordinate to the world coordinate system. The calibration of these parameters is implemented using the method proposed in Ref. [3].

Based on the mathematical model, and upon confirmation of the parameters of the system, the light-

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plane coordinates $P_1(x_1, y_1, 0)$ of one surface point was derived using the image coordinates (U, V) of the corresponding light-stripe point. The point was acquired using related image processing. Thus, we obtained an amount for the 3D surface points of the cylindrical object. The diameter of the cylindrical object was calculated by processing the light-plane coordinates data of these 3D surface points using the appropriate fitting method.

According to the measuring principle, the image coordinates of light-stripe points are fundamental in calculating the real space coordinates of corresponding surface points. Thus, developing a precise and effective image processing algorithm is important in guaranteeing the accuracy of measurement results. Common extrication methods for sub-pixel center of structured-light strip include the gray threshold method, extremum method, and gradient threshold method[7]. However, although easy to implement, it is difficult to achieve high precision results for these methods. The Steger algorithm[8] can obtain high precision and good robustness, but it offers complex computations for the algorithm. Thus, an appropriate image processing method is developed according to the practical needs of the system, such as in the measurement of the diameter of cylindrical pins.

Figure 2 shows the actual light-stripe image captured while measuring the diameter of cylindrical pins. The light-stripe presents an ellipse shape because of the presence of an angle between the optical axis of the camera and the light plane. The grayscale barycenter extraction algorithm[9] is then used to gather the image coordinates of the light-stripes center. The algorithm is described as

$$\begin{cases} u_j = j \\ v_j = \dfrac{\sum_i iG(i,j)}{\sum_i G(i,j)} \end{cases}, \quad (2)$$

where $G(i, j)$ is the gray value in the ith row and jth column, and (u_j, v_j) is the image coordinates of the extracted light-stripe center in the jth column.

The extraction result using the above-mentioned algorithm is shown in Fig. 3. The red points (colorful online) represent extracted light-stripe centers. The method produced serious distortions between the extracted and actual centers at some areas in the image. For example, there are serious distortions at area A, which can affect the precision of the follow-up diameter calculation. The

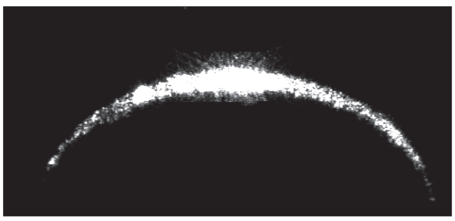

Fig. 2. Actual light-stripe image.

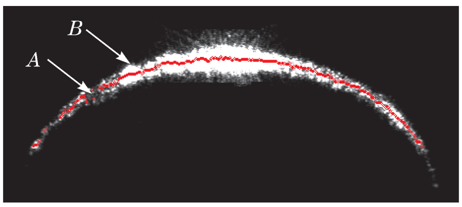

Fig. 3. Result using grayscale barycenter extraction algorithm.

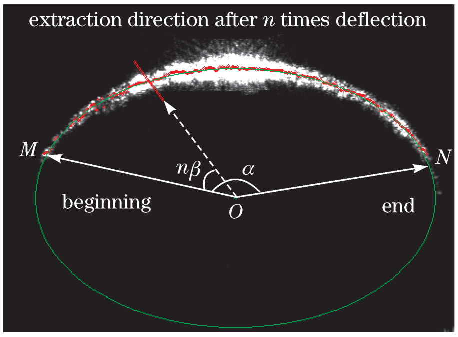

Fig. 4. Grayscale barycenter extraction algorithm along radial directions.

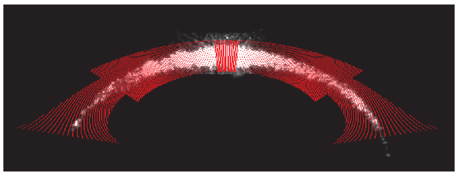

Fig. 5. Confirmed extraction directions and ranges.

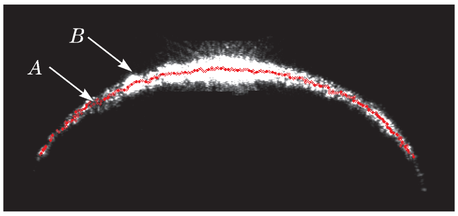

Fig. 6. Result using two-step extraction algorithm.

Table 1. Calibration Result of the System

Inner Parameters	f = 79.144103 mm
	k_p = 0.000372 mm^{-2}
	s_x=1.012039
	d_x = 0.00465 mm
	d_y = 0.00465 mm
	U_0 = 670.824570 pixels
	V_0= 510.347820 pixels
Light-Plane Parameters	r_1 = 0.616721
	r_2 = −0.001887
	t_x = −1.523741
	r_4 = 0.004469
	r_5 = −0.999638
	t_y = 18.048379
	r_7 = −0.786619
	r_8 = 0.009534
	t_z = 248.718079

image processing result cannot reflect the exact object surface topography at area B.

The main reason for the distortions and inaccuracy is the inappropriate processing direction of the grayscale barycenter extraction algorithm. In the algorithm, the processing direction was along the height direction of the image. As mentioned earlier, the light-stripe presented an ellipse shape in the image. Thus, a novel grayscale barycenter extraction algorithm along radial directions (hereinafter referred to as two-step image processing algorithm) was developed. Radial directions of the ellipse formed by the light-stripe points were used as the extraction direction. The algorithm was employed as follows:

1) The image was processed using the grayscale barycenter extraction algorithm along the height direction. The image coordinates and the total number (denoted by n_{T}) of all extracted light-stripe centers were recorded. Then the ellipse fitting to the extracted light-stripe centers was executed. Center coordinates, and the major and minor axes of the ellipse, were calculated[10,11].
2) Beginning and end positions of the extraction directions were confirmed. M was used as the first point in the set of the extracted light-stripe centers and N was the last (Fig. 4). O was the center of the ellipse; vector OM was defined as the beginning position of the extraction directions while vector ON was the end position; angle α between these two vectors was then calculated. Then the extraction directions were confirmed: center O was selected as the axis of the extraction directions. Several angles were deflected at the beginning position to generate extraction directions along radial directions. Angle β in each deflection was defined as $\beta = \alpha/n_{\mathrm{T}}$. In Fig. 4, the red line (colorful online) represents the extraction direction and range after n time deflection.

Figure 5 shows the entire extraction directions and ranges confirmed by the image processing algorithm. The processing result is shown in Fig. 6. Compared with the previous algorithm at areas A and B, the developed two-step algorithm improved the processing result effectively.

Based on the measuring principle of the system, real space coordinates of the object surface points were gathered by the image coordinates of the corresponding light-stripe centers that have been precisely extracted by image processing. These space coordinates were used to calculate the diameter of the cylindrical object. While the required measuring range of the diameter was less than 2 mm, the system was designed such that the light-stripe could cover nearly the semi-circle of the object surface. Hence, the effectiveness of the system in executing circle fitting to the data using least square method could be shown. The diameter of the circle was equal to that of the object.

Based on the circle formula $(x-x_0)^2 + (y-y_0)^2 = R^2$, three parameters obtained are the coordinates of the circle center (x_0, y_0) and radius R. The formula suggests that a nonlinear fitting method is appropriate when gathering parameters[12,13]. After deforming the formula

$$2xx_0 + 2yy_0 + x^2 + y^2 = C, \quad (3)$$

where $C = R^2 - x_0^2 - y_0^2$, the parameters are calculated using the linear least square fitting method[14]. In Eq. (3), the parameters are reconstituted as x_0, y_0, and C. After calculation using least square method, the radius can be obtained using the three parameters.

The system is shown in Fig. 7, and its calibration results are shown in Table 1. Figure 8 shows the diagram of the self-developed software interface. The software can display all measured data and an AutoCAD graphic of the measured surface profile. In this letter, the precision machined cylindrical pin (Fig. 9) was used to test the repeatability of the system. The nominal diameter of the pin was 2.000±0.001 mm. The system was applied to measure the curvature radius of metal blades on the scene (Fig. 10).

The cylindrical pin was placed at eight different positions in the field of view of the CCD camera. The measured data are shown in Table 2. The average value of the measured diameter is 2.0025 mm using the one-step image processing and standard deviation is 0.0014 mm. Thus, the system allowed high-precision measurement.

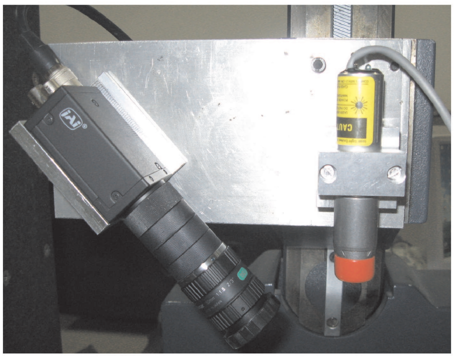

Fig. 7. Actual picture of the system.

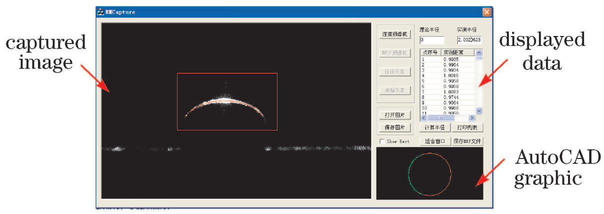

Fig. 8. Self-developed software interface.

Table 2. Result of the Repetitive Experiment

No.	One-Step Image Processing (mm)	Two-Step Image Processing (mm)
1	2.0031	2.0021
2	2.0035	2.0025
3	2.0021	1.9997
4	2.0005	1.9992
5	2.0001	1.9988
6	2.0039	2.0013
7	2.0031	2.0020
8	2.0034	2.0014
Average	2.0025	2.0009
Standard Deviation	0.0014	0.0014

Fig. 9. Precision machined cylindrical pin.

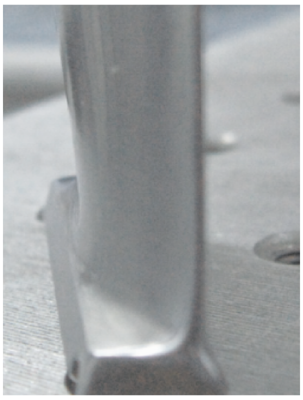

Fig. 10. Measured metal blade.

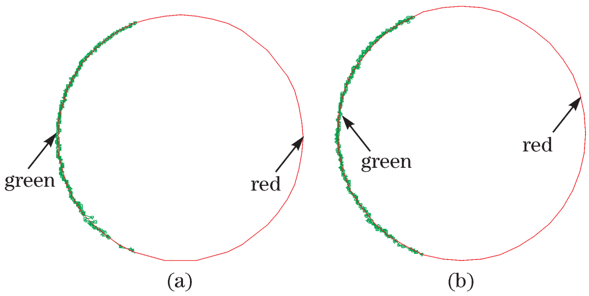

Fig. 11. AutoCAD graphics of the measured surface profile. (a) Using one-step algorithm and (b) using two-step algorithm.

Table 3. Measured Result of the Curvature Radius of Metal Blades

Position	Measured Curvature Radius (mm)
1	0.2630
2	0.2725
3	0.4985
4	0.5489
5	1.1678

The average value of the measured diameter is 2.0009 mm using the developed two-step image processing and standard deviation is 0.0014 mm. The result proves that the novel image processing algorithm effectively improves the accuracy of the system.

AutoCAD graphics of the 8th experiment are shown in Fig. 11. The red line (colorful online) represents the standard circle. The green line (colorful online) is constituted by measured space coordinates (x_i, y_i, 0) of the surface points. The measured surface profile is more relevant to the standard circle when the two-step algorithm, rather than the one-step algorithm, is used.

The system is applied to measure the curvature radius of metal blades on the scene. The real curvature radius increases from head to tail along the edge of the metal blades. The curvature radius is measured at five different positions from head to tail on the edge of the metal blade. The result is shown in Table 3.

In conclusion, based on structured-light vision measurement technology, a high-precision micro-diameter measurement system has been developed. The measurement principle and mathematical model of the system are described. A novel two-step image processing algorithm is proposed; findings prove that it effectively improves the accuracy of the measured result. A precision machined cylindrical pin has been used to test the repeatability of the system. The system is applied to measure the curvature radius of metal blades on the scene. Experimental results prove the high precision and good repeatability of the system.

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