Laser scanning probe with multiple detectors used for sculptured surface digitization in reverse engineering

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Abstract. This paper presents a single-point laser probe with multiple detectors for scanning of a sculptured surface for digitization by reverse engineering. The probe consists of a point laser source and four linear high-resolution PSDs (Position Sensitive Devices). Its target scanning distance is 180 mm from the probe to the measured surface, with a measurable range of 90 mm. Assuming a diffusive surface, the displacement from the light spot on the measured surface to the probe along the light-axis can be derived by the Lambert model. In addition, the inclination angle of the measured point from the vertical axis of the light beam is also calculated. In this study, the probe is mounted on the NC machine integrating the three-axis controller, personal computer and A/D card to conduct the digitization process. Functions of the probe are verified by a standard half-sphere model. The test results show that the displacement resolution is reaching 50 μm and the measurable range of the inclination angle is 80 degrees. A mask model is digitized to demonstrate the scanning results.

1. Introduction
Rapid object digitizing process is a critical technology in product design using reverse engineering. Although the contact methods obtain a higher accuracy and reliability than the non-contact method, it also comes with several shortcomings, such as the contact pressure on the measured surface, the compensation computation of the probe tip and the measurement of small corners, which greatly limit their applications [1-5].

In recent years, photoelectric non-contact probes have developed rapidly. Several laser probes have successfully been applied in 3D object scanning projects, such as the point laser probe with a single detector [2,6-7], the laser stripe scanner couple with CCD device [3-4,8] and the circular triangulation laser probe [5]. However, the triangulation principle is usually adopted as the measurement principle to derive point cloud data in laser scanning.

Basic elements of a system using triangulation for surface scanning consist of a light source that is usually a laser, a scanning mechanism to project the light spot onto the object surface, and a position sensor with a collecting lens located off-axis for the light spot [6]. Based on the photocurrent detected from the PSDs, the displacement between the light spot and the sensor can be computed. Nevertheless, the coordinates are merely derived by single spot data. They resulted in several measurement errors, such as the centroid of the light spot varying, the non-linear relationship between the displacement and the spot position, the measurement ‘dead space’ resulting from the shadow effect and a lack of angular...
data of the measured point [9]. To overcome these shortcomings in laser triangulation measurement, this paper presents a new single-point laser probe with four detectors, and develops a measurement method to derive a more accurate measuring results.

2. Single-point laser probe with multiple detectors

Figure 1 shows the structure of the proposed probe. It includes a visible laser diode, four position detectors and a signal processing circuit.

![Figure 1. Schematic diagram of the probe structure.](image)

2.1. Displacement measurement

The principle of displacement measurement is expressed in Figure 2. The relationship between displacement, \( z \), and the corresponding displacement, \( x \), on the PSD is derived according to the relationship shown in figure 2. The geometrical formula is given as:

\[
\frac{1}{z + f_1} + \frac{1}{d} = \frac{1}{f_1}
\]  

(1)

Based on the similar relations between \( \Delta AB''C'' \) and \( \Delta AB_MC_M \), we obtain

\[
\frac{f_2}{x} = \frac{d - b}{h}
\]

(2)

Then from equation (1) and equation (2), the displacement of the measured point, \( z \), is given as:

\[
z = \frac{f_1^2 \cdot x}{f_2 \cdot h - (d - b) \cdot x}
\]

(3)

When the output currents from the two electrodes of PSD are defined as \( I_1 \) and \( I_2 \), respectively, the following equation could be used to calculate the displacement of \( x \) on PSD.

\[
x = L \cdot \frac{I_1 - I_2}{I_1 + I_2}
\]

(4)

where, \( L \) is the sensitive length of PSD.

The feature of PSD is expressed by the sum of output photocurrent, denoted as \( I_s \). It is proportional to the incident light power, \( P_s \), on the PSD, collected by the focal lens, and is given as:

\[
I_s = I_1 + I_2 = K_P \cdot P_s
\]

(5)

where, \( K_P \) is the sensitivity factor of PSD, which is the conversion coefficient calculated by the light power and the current.

2.2. The derivation of angle of inclination

The derivation of the inclination angle is based on the light power of the measured point detected by the PSD. Figure 3 shows the derivation principle of the X-Z inclination angle with two PSDs. From the Lambert model, the light powers detected by PSDa and PSDc are given as
\[
P_{sa} = I_{sa} \cdot \Omega \cdot \cos(\theta + \alpha_x) \tag{6}
\]
\[
P_{sc} = I_{sc} \cdot \Omega \cdot \cos(\theta - \alpha_x) \tag{7}
\]

where, \( \Omega \) is the solid angle subtended by the receiving lens aperture, \( \theta \) is the incident angle between the incident beam and the light receiving direction. Thus, the inclination angle, \( \alpha_x \), can be qualitatively calculated by
\[
\frac{P_{sa} - P_{sc}}{P_{sa} + P_{sc}} = \frac{I_{sa} - I_{sc}}{I_{sa} + I_{sc}} = K_s = \tan \alpha_x \cdot \tan \theta \tag{8}
\]

\[
\alpha_x = \tan^{-1} \left( \frac{K_s}{\tan \theta} \right) \tag{9}
\]

By the same principle, the inclination angle, \( \beta_y \), of the Y-Z plane can be calculated.

3. Single-point laser digitization system

In this study, the integrated scanning system consisted of a NC machine (FANUC-OM), laser probe, personal computer, three-axis controller and an A/D card. In terms of displacement resolution, the measured plane was set at the target position of 180 mm from the probe. The displacement resolution has reached 50 \( \mu \)m. The measurement range was from 0° to the maximum measurable angle. The relationship between the angular measurement error and the angle of inclination of the measured point presented a Gauss distribution. The measurable angle of inclination is approximately to 80 degrees with a displacement error of less than 0.9 mm.

After the static scanning function tests, non-tracing scanning test were conducted to verify the function of 3D object digitization. The measurable height of the developed probe was set within 90 mm. A standard half-sphere model with a radius of 50 mm was used to conduct the function test. The measurement results showed that the maximum displacement error was 0.9 mm at the position of 80° near the model base and the angular measurement error at the five evenly spaced positions was less than 7°.

4. Solid models digitization

The model of a mask with complex contour was digitized to examine the scanning function for freeform surface measurement by the proposed probe system. The digitizing range was 200 × 125 × 80 mm\(^3\). The model and the scanning results are shown as figure 4(a) and figure 4(b)~(d), respectively. The models were derived in a scanning interval of 2 mm, and expressed by the AutoCAD software based on the cloud points data, no filtering or compensating process was used. A mask models were successfully reconstructed.
5. Conclusions
This paper developed a single-point laser probe with multiple detectors used to establish a freeform surface scanning system. Based on the Lambert model, the mathematical models of both the displacement and the angle of inclination from the probe to the light spot on the measured surface were derived, using the photocurrent of the four PSDs. If a database of the angle of inclination of the measured surface and its displacement error could be built, it would be useful to compensate the measurement error due to the inclination of the surface, resulting in great improvement of the measurement precision. The verification experiments showed that the four detectors design could digitize the surface with a larger inclination angle and reduce the dead zone problem in the laser measurement. This improved the defects encountered with the laser triangulation probe with a single-detector. The laser probe is modular. It is easy to place on a NC machine or X-Y platform to carry out the freeform scanning.

![Figure 4](image)

Figure 4. (a) mask model (b)~(d) results of the digitization

References
[1] Jones C, Bradley C and Vickers G W, 1994, *Computers industry Engineering*, “Laser scanning and Quasi-Helical tool path definition of arbitrary curved surface models,” 26(2), 349-357.
[2] Wang G J, Wang C C and Chuang S H F, 1999, *International Journal of Advanced Manufacturing Technology*, “Reverse engineering of sculptured surfaces by four-axis non-contacting scanning,” 15, 800-809.
[3] Lee K H, Park H and Son S., 2001, *International Journal of Advanced Manufacturing Technology*, “A framework for laser scan planning of freeform surfaces,” 17, 171-180.
[4] Bradley C and Chan V, 2001, *Transactions of ASME, Journal of Manufacturing Science and Engineering*, “A complementary sensor approach to reverse engineering,” 123, 74-82.
[5] Shiou F J and Gao J S, 2004, *International Journal of Advanced Manufacturing Technology*, “Effect of slice thickness on the profile accuracy of model marker rapid prototyping measured by a circular triangulation laser probe,” 22, 796-804.
[6] Hosni Y and Ferreira L, 1994, *Computer Industry Engineering*, “Laser based system for reverse engineering,” 26(2), 387-394.
[7] Smith K B and Zheng Y F, 2000, *Transactions of ASME, Journal of Manufacturing Science and Engineering*, “Point laser triangulation probe calibration for coordinate metrology,” 122, 582-586.
[8] Weir D J, Milroy M J, Bradley C and Vickers G W, 2000, *Transactions of ASME, Journal of Manufacturing Science and Engineering*, “Wrap-around B-spline surface fitting to digitized data with application to reverse engineering,” 122, 323-330.
[9] Saito K and Miyoshi T, 1991, Annals of the CIRP, “Noncontact 3-D Digitizing System for Free-Form Surface,” 483-486.
[10] M. Beckmann et al., 1980, *Principle of Optics*, Pergamon Press, London.