Multi-beam laser probe for measuring position and orientation of freeform surface

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\textbf{Abstract}

This study develops a novel optical non-contact probe that measures the position and orientation (normal vector) of a freeform surface. The probe system comprises a five-laser-beam projector and a charge-coupled device (CCD) camera. The probe is integrated on a three-axis platform. Five designed laser beams project onto a measuring surface, where five light spots are observed. The CCD captures the image of this surface and processes it. The 3D coordinates of the five light spots can be then computed. The normal direction at the central spot on the measuring surface is determined from two crossed curves through the coordinates of these five light spots. Two crossed curves are constructed using the Bezier method. The normal vector is the cross-product of two tangent vectors to the two crossed curves at central spot. A scheme for calibrating and making measurements using this five-laser-beam probe is proposed and verified experimentally. Experimental results demonstrate that this five-laser-beam probe system can measure the position and orientation of a freeform surface. The range of depths that can be measured using this probe is 2.4 mm and the range of angles is $40^\circ$. The positional measuring accuracy of the complete system is approximately 30 $\mu$m while the orientational accuracy is 1.8$^\circ$.

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1. Introduction

Information technologies, including CAD/CAM/CAE, reverse engineering, concurrent engineering, collaborative operation, PDM and others, are extensively adopted in engineering. Successful product development and manufacture depend on the digitization of information, especially for reverse engineering and quality inspection. Digitization of three-dimensional geometric data for a freeform surface and the subsequent reconstruction of a geometric model are very difficult and complicated tasks. Approaches for digitizing the geometric data of a physical model can be broadly classified into two categories – contact probe and non-contact probe methods [1–16].

Contact probe methods can also be divided into touch trigger probe and analog scanning probe methods [17]. A ball-end stylus is mounted on a mechanical touch probe system and moves into contact with a measuring surface, emitting a signal, from which a computer can extract the spatial coordinates of the center of the ball end of the stylus. The advantages of using a contact probe are its reliability and accuracy. The disadvantages include the long operating time and slowness of the measurement, the need to compensate for the radius of the stylus and deformation at the contact point by the measuring force.

Various non-contact probe approaches are available. They include optical, microwave, ultrasonic, capacitive and inductive methods. Almost all non-contact probe systems for 3D profilometry are optical because they are easier to use in engineering applications. The optical non-contact probe has a depth range, $Z$, from $10^{-4}$ m to $10^{4}$ m...
and a good depth resolution, \( dz \), such that the relative resolution, \( dz/Z \), is between \( 10^{-2} \) and \( 10^{-7} \) [11]. This optical non-contact probe, used in 3D measurement, consists of a variety of illumination and vision devices. Typical illumination techniques are the projection of a light pattern on a measuring surface (point, line, grid, cross hair ... ) by laser systems. The most common vision device for obtaining a stereovision of a measured scene is the charge-coupled device (CCD). Three-dimensional information is extracted from this scene chiefly by triangulation, phase shifting, interferometry, deflectometry, Moiré, speckle detection, the time of flight method and stereo-vision methods. The advantages of optical non-contact probe are high measurement speed, remote and non-destructive evaluation. The shortcoming is that the light intensity, reflection and color on measuring surface affect accuracy.

3D optical non-contact probe can be broadly classified into three categories: point-type, point laser triangulation [8]; line-type, a line laser diode with two CCD cameras [7]; area-type, a structured light projector with CCD camera [12]. Point laser triangulation is more appropriate for digitizing the 3D surface of small complex objects due to its small light spot but long measuring time is its drawback. Structured light method is benefit for digitizing a large surface like car body because of its efficient measurement [15].

At present, the geometric information that can be obtained by digitizing a freeform surface using a commercial contact or non-contact probe includes only 3D spatial coordinates, but not the orientation (normal direction) of the surface. This study develops a novel optical non-contact probe, that can be used to extract 3D coordinate (position) and the normal direction (orientation) of a measured surface simultaneously. Measurement of the position and orientation of a freeform surface is important to some manufacturing processes. For instance, in the laser cutting of a 3D freeform sheet metal for the body of a car, the position and orientation of the formed sheet metal panel must be measured to ensure that laser cutting tool can be accurately controlled [18]. Other applications exist in which surface orientation and the continuity of the tangent of the profile are important, such as for aerofoil, car body, mold and die.

The new measuring probe system proposed herein employs a triangulation algorithm. Five light spots on a measuring surface are illuminated by a five-laser-beam projector and are retrieved by a CCD sensor. The image from the CCD sensor is processed to yield the 3D coordinates of the five light spots, which are arranged as one central spot that is surrounded by four peripheral spots 90° apart, as shown in Fig. 1. These five positions of the light spots can be interpolated to two crossed curves that intersect at the central point. The normal vector of the central point can then be computed as the cross-product of the two tangent vectors of these two curves [19–21].

2. Measurement methodology

The triangulation probe system is based on a trigonometric principle: if the length of one side and two interior angles of a triangle are given, then the lengths of the other two sides and the other interior angle can be determined.
Fig. 2 presents the simplest configuration of a triangulation measuring system. A laser projects a light spot onto an evaluating surface and a one-dimensional position sensor detector (PSD) captures its location. One interior angle is $90^\circ$. The horizontal distance $B$ (OC) between the laser beam and the center of the focus lens C, and another interior angle $\alpha$ between the laser beam and the optical axis of the focus lens, are known. The vertical distance $L + \Delta z$ between the center of the focus lens C and the measuring surface M can be evaluated from the location $D_u$ of the light image spot on the PSD or the two-dimensional CCD, according to the following formulas.

$$L + \Delta z = \frac{B}{\tan(x - \delta)}$$

(1)

The only unknown in the above equation is the angle $\delta$, which can be determined from the position of the image spot $D_u$ and the focal distance $F$, as given by,

$$\delta = \arctan\left(\frac{\Delta u}{F}\right)$$

(2)

The vertical distance $L$ is between the right-angled vertex O in the triangulation system and the intersection point Q of the laser beam and the optical axis of the focus lens. This intersection point Q is assumed to be the origin of this triangulation system. The measuring height $\Delta z$ from this origin Q is represented by the following equation.

$$\Delta z = \frac{G \times \Delta u}{F \times \cos(90 - x)} = \frac{G \times \Delta u}{F \times \sin(x)}$$

(3)

The distance $G$ is between the origin Q and the center C of the focus lens. The horizontal distance $\Delta x$ measured from the origin Q is given by,

$$\Delta x = \Delta z \times \tan(x) = \frac{G \times \Delta u}{F \times \cos(x)}$$

(4)

Similarly, the distance $\Delta y$ measured from the origin Q can be determined from the position $\Delta v$ of the image spot, along the direction V on the CCD, which is parallel to the Y axis. The distance $\Delta y$ is thus defined as,

$$\Delta y = \frac{(G + \Delta G) \times \Delta v}{F} = \frac{(G + \Delta z \times \cos(x)) \times \Delta v}{F}$$

$$= \frac{(G + \Delta u \times \cot(x)) \times \Delta v}{F}$$

(5)

The distance $\Delta G$ is much smaller than the distance $G$ and can be neglected. Therefore, the equation for $\Delta y$ can be simplified to,

$$\Delta y = \frac{G \times \Delta v}{F}$$

(6)

3. Configuration of measurement probe

The measuring probe system consists of two main components – a five-laser-beam projector and a CCD camera. Figs. 1, 3 and 4 present the configuration and the prototype. The angle between the optical axis of the CCD camera and the laser beams is set to $45^\circ$. This five-laser-beam probe is mounted on a three-axis platform, which is controlled by a personal computer, on which is loaded software for processing the surface position and orientation.

The five-laser-beam projector comprises a laser diode as a light source with a collimating lens, a light mask and a projecting lens, which are aligned coaxially. The light mask has five pinholes that are arranged as one in the center with four around the periphery. The four pinholes are
separated by 90° from each other. The five laser beams are generated by a laser diode with a collimating lens, and pass through the five-pinhole mask. The five beams are then transmitted through the projecting lens and projected onto a measuring surface, forming the image of five laser spots that is shown in Fig. 5. The distance between the central spot and each peripheral spot is approximately 0.7 mm.

The CCD camera has a 2/3" format CCD sensor (JAI CV-M4 + CL) and a commercial focus lens. The CCD has a horizontal dimension of 8.9 mm and a vertical dimension of 6.6 mm, with a resolution of 1280 \times 1024 pixels per image. The physical size of each pixel is 6.45 \mu m. The specifications of the focus lens are working distance WD = 65 mm with optical magnification 1.2× and measuring range.
2.4 mm. The pixel resolutions in the X, Y and Z directions are 7.5, 5.3 and 7.5 μm respectively.

4. Algorithm for processing position and orientation

The coordinates of the five light spots can be obtained by processing the image captured from the CCD, following the procedure that is presented in Fig. 6, and described below.

a. Fetch image from CCD camera (Fig. 5).
b. Binarize image by applying threshold value.
c. Find five laser spots and neglect smaller blobs (noise).
d. Identify the five centers (u and v from the CCD coordinates) of the five laser spots.
e. Compute Δx, Δy and Δz of the five laser spots, according to the above measurement methodology.
f. Calculate the position of the five spots by adding Δx, Δy and Δz to the coordinates of the three-axis platform.
g. Compute the normal vector at the central spot (explained in detail below).

The 3D position of the five light spots is composed of the coordinates of three-axis platform and this five-laser-beam probe. Thus, the positioning accuracy of three-axis platform is same effects as the accuracy of this probe for the overall measuring accuracy.

The normal vector of the central position can be computed from these five coordinates (points) using numerous methods [9,19,20]. The cross-curve method is employed herein to calculate the normal vector of the central point and is described in detail below.

These five points can be interpolated to two crossed curves, one longitudinal and one latitudinal, using the quadratic Bezier method, as presented in Fig. 7. A quadratic Be-
zier curve (degree 2/order 3) that passes through three points $P_0$, $P_1$, and $P_2$ can be expressed as \[ P(u)(1-u)^2B_0 + 2u(1-u)B_1 + u^2B_2 \] \[ \text{(7)} \]
where $B_0$, $B_1$, and $B_2$ are control points and are derived as,

\[ B_0 = P_0, \quad B_2 = P_2, \quad \text{and} \]

\[ B_1 = \frac{(-1-u_1)^2P_0 + P_1 - u_1^2P_2}{2u_1(1-u_1)} \] \[ \text{(8)} \]
respectively. At central point $P_1$, $u = u_1$.

Hence, the tangent vector $P'_1$ at the central point ($u = u_1$) can be expressed as,

\[ P'_1(u_1) = -2(1-u_1)B_0 + 2(1-2u_1)B_1 + 2u_1B_2 \] \[ \text{(9)} \]
\[ P'_1(u_1) = 2(1-u_1)P_0 + 2(1-2u_1) \]
\[ \times \frac{(1-u_1)^2P_0 + P_1 - u_1^2P_2}{2u_1(1-u_1)} \] \[ \text{(10)} \]

Similarly, the other tangent vector $P'_1(w_1)$ at the central point of another curve can also be evaluated.

The unit normal vector $N_c$ at the central point $P_1$ can be calculated as the cross-product of two the tangent vectors $P'(u_1) \times P'(w_1)$ of the two crossed curves at the central point. The formula for the unit normal vector is

\[ N_c = \frac{P'(u_1) \times P'(w_1)}{|P'(u_1) \times P'(w_1)|} \] \[ \text{(11)} \]

5. Calibration

Before this optical non-contact probe can be used in measurement, the whole system must be calibrated because both the components and their assembly affect the accuracy of the system. The CCD sensor and the five laser beams must both be calibrated. The calibration involves determination of the parameters the CCD sensor and each laser beam.

First, the CCD sensor must be calibrated to determine the position of pixels that can be mapped onto 3D world coordinates. The CCD sensor is calibrating using a small pinhole ($\phi/0.2$ mm) on a flat plane that can be placed in 27 positions, as shown in Fig. 8. These 27 positions are arranged in three levels, at depths in the $Z$ direction of 1.2 mm, 0 mm and $-1.2$ mm, and each of the nine positions in the $X$–$Y$ plane separated by 1.2 mm in both the $X$ and the $Y$ directions. The nine points on each level cover the main area of the CCD sensor. These 27 positions in the three levels form the sensing volume of the CCD. Using the least square method, the coordinate system of the CCD is mapped onto 3D real world coordinates. The calibration of more levels and positions results in more accurate overall calibration. For example, 125 positions, arranged in five levels along the $z$-axis and at five points along each of the $x$ and $y$ axes, with a pitch distance of 0.6 mm, are calibrated.

Then, the five laser spots are also mapped onto the 3D world coordinate system. These five laser beams are pro-
jected onto the same flat plane at each of the three depths used in the CCD calibration. Using more depth levels yields more accurate calibration of the laser spots. Based on the results of CCD calibration, the CCD pixel coordinates of the five laser spots are mapped to a 3D real world coordinate system using the least square method. Thus, the $\Delta x$, $\Delta y$ and $\Delta z$ coordinates of the five laser spots in the measuring range can be easily be determined.

6. Experimental results

To evaluate the accuracy of the measurement of the height in the Z direction of the five laser spots in the measuring range (−1.2 to +1.2 mm), the plane of a sine-bar is measured using this five-laser-beam probe at a fixed height, as shown in Fig. 9. The sine-bar (Grade B) is constructed from a gage block (Grade B) with a height of 5 mm. The −1.2 to +1.2 mm measuring range can be created by moving sine-bar from −23.97 to 23.97 mm in X direction. The height deviation of this five-laser-beam probe is about −10 to 30 $\mu$m, and the details are as shown in Fig. 10. According to the experimental results, the accuracy is better approximately −5 to 10 $\mu$m when the measuring range is limited to −0.3 to +0.3 mm. This limited measuring range can be adopted in an automatic measure procedure to improve the overall accuracy.

To appraise the angular accuracy of this five-laser-beam probe, the slant planes are determined using the sine-bars with gage blocks of various heights. The sine-bars are various inclined at angles 8.627°, 17.458°, 26.744° and 36.870°, and are constructed using gage blocks with heights 15, 30, 45 and 60 mm, respectively. The sine-bars are posed in 24 different arrangements on the X–Y plane, separated by 15° from 0° to 360°. Fig. 11 depicts six arrangements of the sine-bar. Fig. 12 shows the error of the angular measurement of the normal to the sine-bar plane. The mean angular error is approximately 0.2° and the angular standard deviation is about 0.35° (Fig. 13).

A spherical surface (sphericity 2 $\mu$m) is utilized to evaluate the performance of the measurement of a freeform surface using this developed five-laser-beam probe. A sphere is the best shape to choose because its surface is analytically defined and also can be used to simulate various features of a freeform surface. Therefore, a sphere with radius of 25 mm is applied to evaluate the effectiveness of
Using CAD system, these 315 points can be constructed a spherical surface of radius 25.0066 mm. The radius deviates by only 6.6 μm. The maximum position deviation is 30 μm and the standard deviation is 8.2 μm. Fig. 14 presents position deviation.

The angular deviation between the ideal normal vector and the measured normal vector at the central spot on a spherical surface is also investigated. The ideal normal vector at the central spot is defined as the vector from the center of a spherical surface to the position of a central spot. Fig. 15 displays the angular deviation of 9 × 7 locations on the spherical surface: the mean angular deviation is about 0.846° and the angular standard deviation is 0.364°. This angular deviation is worse than the angular deviation of the sine-bar above, because a freeform surface increases the distortion of the images of the five laser spots.

This five-laser-beam probe can be employed in reverse engineering. A personal computer mouse was chosen as the target object and data points for its 3D geometry were automatically digitized (Fig. 4). The total number of mea-

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**Fig. 12.** Angular deviation of measurement of variously oriented sine-bars.

**Fig. 13.** Angular deviation of measurement of sine-bar.

**Fig. 14.** Deviation of measurement of position on sphere.

**Fig. 15.** Deviation of measurement of normal vector on sphere.

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this probe. The total number of measured locations was 9 × 7 in the X and Y directions, respectively, with a distance pitch of 3 mm; the number of measured points is 315.
sured locations was 12 × 11 in the X and Y directions, respectively, with a distance pitch 3 mm; 660 data points were measured to re-construct the surface, as shown in Fig. 16. A total of 132 normal vectors on the surface of a PC mouse were obtained and the angles between these normal vectors and the Z-axis are as presented in Fig. 17.

7. Conclusion

A novel optical non-contact probe for measuring the position and orientation (normal vector) of a freeform surface was developed. The probe consists of a five-laser-beam projector and a CCD camera. The five-laser-beam projector was designed to be very compact and low-cost. The probe can be easily integrated with a commercial motion platform and image processing system. The image of the five laser beams projected onto measured surface is captured and processed. The position and orientation can then be evaluated in a single measurement. The system can be employed when information on the position and orientation of measuring surfaces is required, such as in manufacturing processes. It can be also adopted by reverse engineering, surface inspection and other areas. Its depth measuring range is 2.4 mm and the angular measuring range is 40°. The overall measurement accuracy of the system is about 30 μm for position and 1.8° for orientation.

This five-laser-beam probe system included only one CCD camera. To improve the measuring range and the accuracy of the system, two CCD cameras can be applied. An accurate three-axis motion platform can also improve the overall precision and accuracy of the measuring system.

Beyond the image pattern of five spots projected by five laser beams, such image patterns as those with nine laser spots, cross hairs, cross lines and others can be used in further research and to improve the whole measurement system.

References


