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On-machine multi-directional laser displacement sensor using scanning exposure method for high-precision measurement of metal-works[☆]

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ABSTRACT

We propose a multi-directional triangulation optical system and scanning exposure method for precise height displacement measurement of metal-works. It is difficult to measure metal surfaces precisely with a conventional triangulation-laser displacement sensor due to machining traces. Because reflection characteristics vary by position on the workpiece, measurement errors occur even with positions of the same height. Our multi-directional triangulation optical system performs triangulation using a lens array consisting of four lenses located in a cross. Since our optical system can detect reflected light from four directions, we can achieve high-precision measurement even if the reflection characteristics vary. In addition, our scanning exposure method accumulates reflected light from many positions by scanning a projection beam onto a workpiece during the image sensor's exposure time. Because the shape of a spot image on an image sensor is the sum of the reflected light from many positions, measurement error due to measurement position is reduced. Our proposed methods can achieve on-machine deflection measurement of metal-works with a target accuracy of ± 1 µm.

1. Introduction

Automatic three-dimensional metal-work measurement is increasing in factories using machine tools. An on-machine sensor measures the position and tilt of a workpiece in the machine tool before machining and measures the machining results for comparison with the design. A sensor is required for precise measurement of the edge position and height displacement of the workpiece. ± 1-µm accuracy is in high demand with high-precision machining. Contact-type sensors, such as a touch probe sensor or dial gauge, have been conventionally used on machine tools [1–4]. However, the contact-type sensor takes a long time to measure because it must move toward the workpiece slowly so as not to break the sensor. Additionally, there is a risk of scratching the surface of the workpiece. Hence, non-contact-type sensors have been necessary, along with increasing the speed of on-machine measurement.

An optical sensor has been developed as a non-contact-type sensor on a machine tool [5–8]. A triangulation-laser displacement sensor is often used to measure displacement of the workpiece [6,8]. The triangulation-laser displacement sensor has several advantages over other displacement sensors, such as low cost and high-speed measurement [9]. The general scatter-type triangulation sensor projects a laser beam onto the workpiece and concentrates the light scattered and reflected in the oblique direction on a detector [10]. When the distance between the sensor and the workpiece changes, the spot image's centroid on the detector shifts geometrically toward the in-plane direction. Therefore, we can estimate the workpiece displacement from the shift of the spot image. However, the laser displacement sensor is not used widely as an on-machine sensor presently because it is difficult to measure the metal surface precisely. Although a method using several displacement sensors for high precision has been demonstrated, this method increases the size of the measurement system, making the sensor system cumbersome for the machine tool [11–13].

The reason why the triangulation displacement sensor cannot measure metal-works precisely is due to the cutting machining traces. A picture of a metal surface is shown in Fig. 1(a). Because there are many machining traces on the surface, accuracy decreases due to the speckle noise [14]. Furthermore, measurement error occurs even if we measure identical height positions on the workpiece because the reflected direction characteristic varies by measurement position. For example, the two points shown in Fig. 1(a), P1 and P2, are the same height. The intensity distribution of the spot image on the detector is shown in Fig. 1(b); the solid line is the ideal, and the dashed line and dotted line are the measurements for P1 and P2, respectively. The dashed line of P1 differs from the solid ideal line because the reflected light intensity by scattered direction becomes non-uniform due to the roughness of the

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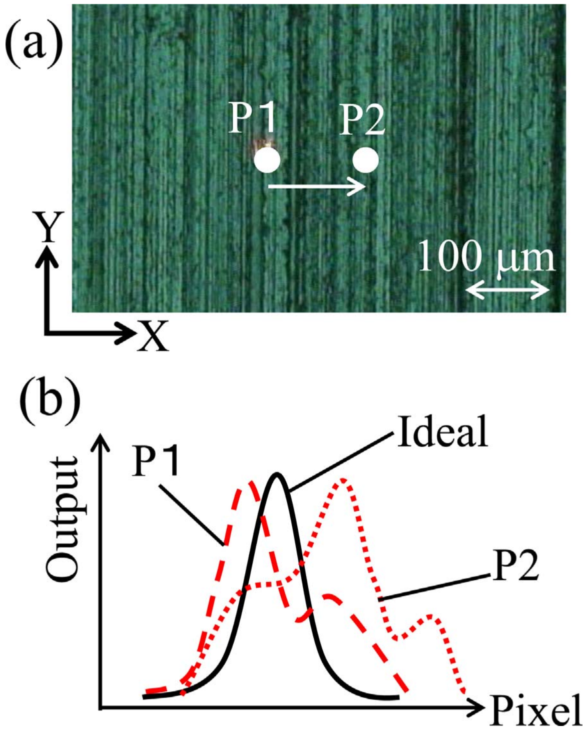

Fig. 1. Metal-work surface and intensity distribution of spot images on an image sensor: (a) the metal-work surface: (b) the intensity distribution of the two positions shown in (a).

machining traces. Hence, an error occurs in the displacement estimated from the centroid. On the other hand, the dotted line of P2 differs from both the solid line and dashed line because the scattered distribution is not the same as the position on the workpiece. Therefore, it is difficult to measure the displacement of equal height positions precisely because the centroids of the spot images are not the same despite the identical height. For example, when we measured a metal-work using a triangulation displacement sensor, the error in measurement positions was approximately 50 μm (peak to peak) [15].

We propose a new optical sensor that can measure the height and edge of metal-works precisely with one projection beam. We proposed an edge-measurement method that measures the light intensity of reflected light when the sensor moves across the edge of a workpiece with an accuracy of nearly ± 1 μm [16]. Our new methods for precise height measurement at an accuracy of ± 1 μm are a multi-direction triangulation and a scanning exposure method. The multi-directional triangulation displacement sensor projects a laser beam onto the workpiece perpendicularly and measures height by triangulation using four lenses located at four directions around the projected beam. Additionally, our scanning exposure method decreases measurement errors quickly and easily by averaging the dispersion of the reflected light intensity by the position on the workpiece. In this paper, we demonstrate the deflection measurement of a metal-work using this new optical system and measurement method, achieving ± 1-μm accuracy.

2. Optical design

We propose the multi-directional laser displacement sensor shown in Fig. 2(a). The projecting lens converts the emitted laser into parallel light, which is then reflected onto a workpiece by beam splitter 1. We designed a 5.5-μm spot diameter (full width $1/e^2$), which is focused onto the surface of the workpiece by an objective lens. The spot diameter includes some unevenness from the machining traces on the workpiece's surface, whose pitch is 2 or 3 μm, as shown in Fig. 1(a). The objective lens captures the dispersed reflected light from the workpiece and a concentrating lens focuses the light through beam splitter 1. Beam splitter 2 separates the light for the height displacement and edge position measurement. The light reflected by beam splitter 2 focuses on a photo diode (PD). The lens array for triangulation from four directions is shown in Fig. 2(b). The light through beam splitter 2 is separated into four beams by an aperture array with four apertures located in a cross. The imaging lens array, consisting of four lenses laid flat in a cross, focuses each beam at a different position. Here, we locate the central axis of each imaging lens outside the optical axis of the beams shown in Fig. 2(c). This allows each beam to be imaged on a different position onto the image sensor by deflecting the rays outward. We used an image sensor with a pixel size of 1.67 μm (3840 by 2748 pixels).

Fig. 3 illustrates the spots on the image sensor. Fig. 3(b) shows the spot images on the image sensor when the workpiece is at a focused position of the sensor. The focused position on the image sensor of each beam moves the in-plane by triangulation when the distance between the sensor and the workpiece changes. Each spot moves outward when the workpiece approaches the sensor, as shown in Fig. 3(a), and each moves inward when the workpiece moves away from the sensor, as shown in Fig. 3(c). Consequently, we can calculate the height displacement from the focus position by using the shift quantity of the four spots on an image sensor. The spot shift ΔP is written by triangulation approximately as

$$\Delta P = S \cdot \Delta Z$$

$$S = M \cdot \tan\theta, \tag{1}$$

where S is the sensitivity of displacement measurement, ΔZ is displacement from the focus position that is sufficiently smaller than the focal length of the objective lens, M is the transverse magnification of the optical system, and θ is the optical axis angle of the reflected light from the workpiece. In our optical system, sensitivity S is 0.25 because magnification M is 1.35 and optical axis angle θ is 10.6°. Therefore, we have to estimate the spot shift on the image sensor by 0.25 μm, in other words, 0.15 pixels, to achieve the target accuracy of displacement measurement of ± 1 μm.

Fig. 4(a) and (b) show the experimental spot images on an image sensor when the height of the workpiece has changed. Fig. 4(a) shows spot images of "Spot A" and "Spot C", Fig. 4(b) shows spot images of "Spot B" and "Spot D" shown in Fig. 3. We confirmed that the position of the spot image moves inward when the workpiece moves away from the sensor and moves outward when the workpiece approaches the sensor. We estimate the displacement of a workpiece from the four spot images shown in Fig. 3(b) as follows: First, we calculate the centroid of the four spots as P(Xi, Yi), i = A-D. Second, we respectively estimate the distances Lx, Ly between the centroid of the opposite two spots in the X and Y directions as

$$Lx = XB - XD \tag{2}$$

$$Ly = YC - YA. \tag{3}$$

Finally, we calculate the displacement of workpiece ΔZ from the average distance L_{ave} of Lx and Ly and the sensitivity S in Eq. (1).

$$\Delta Z = Lave/2S \tag{4}$$

Fig. 4(c) shows the result of the spot shift versus the displacement of the workpiece. We calculated L_{ave} from four spots shown in Fig. 4(a) and (b). The experimental result of L_{ave} corresponds to the design within a displacement of ± 50 μm. Although the result differs from the design outside ± 50 μm, this range is outside the projection beam's depth of field. Because the projected spot diameter is larger outside this range, the spot size on the image sensor also increases. Hence, an error occurred in estimating the centroid. In addition, average position P_{ave} of $X_C - X_A$ and $Y_B - Y_D$ shows in Fig. 4(c). The centroid of vertical direction to spot moving direction is almost same value when the displacement is changed.