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Lens sag and diameter measurement of large-size microlenses using sub-pixel algorithm and optical interferometry

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ABSTRACT

In this paper, an automatic optical inspection system is designed specifically to measure the diameter and lens sag of large-size microlenses: 1. The proposed algorithm of measuring lens diameter locates the lens center through the Euclidean distance array, and determines the lens edge along an initiated ray using linear interpolation with sub-pixel accuracy. 2. The lens sag is calculated from a single fringe pattern of large-size microlens, in combination with the measured lens diameter. 3. According to the experiment results, the proposed system has advantages of high applicability, rapid processing speed, and good accuracy with the RMS error≤1% of measuring a large-size microlens, but without the requirement of prior training. The system architecture of non-contact measurement would not cause scratches on the lens surface and is inexpensive, thus, which is particularly suitable for the in-line inspection of industry field.

1. Introduction

Due to increasingly advanced semiconductor manufacturing technology, microlens molds can be produced by electroforming and became easy to be reproduced. However, poor mold manufacturing and non-uniform thermal expansion and contraction will cause defects in the microlens. Hence, an automatic optical inspection (AOI) system for measuring the diameter and les sag of a large-size microlens is developed in this study. The current methods to measure the size of microlens can be divided into contact measurement and non-contact measurement. The contact measurement is carried by scanning electron microscope (SEM), atomic force microscope (AFM), and stylus profiler [1–3], which are very expensive, tend to cause scratches on the surface of the microlens, and have low measurement speed. Hence, the non-contact measurement method is adopted in this study.

When lens sag is similarly equal to the wavelength of the light source, the interference fringes of the microlens are sparsely distributed and can be clearly observed; therefore, the surface profile of a microlens can be accurately measured through interferometry [4–7]. A 3D profile of such microlens can be reconstructed using the grating projection techniques [8–10] or Fast Fourier Transform methods [11,12]. However, when lens sag is far greater than the wavelength of the light source, only a few central circular fringes of the microlens are clearly distributed, and the surrounding fringes are blurred and difficult to identify due to very high distribution density. Thus, the above method is not suitable for measuring the lens sag of large-size microlenses. Yang et al. [13] calculated the microlens center using the center of area method (COA), then calculated the microlens sag according to the desired diameter. However, the actual diameter is not measured, thus errors existed in the obtained lens sag.

As the lens sag is much larger than the light wavelength, a fuzzy area often arises at the circular edge of large-size microlens, which is due to the low contrast, and the edge points of microlens is unable to be accurately determined. Although there have been many edge detectors proposed [14,15], but they cannot be applied to obtain good results for the circular edge of microlenses. In other words, the diameter of the microlens cannot be directly calculated. The fuzzy theory is also often used for edge analysis [16,17]. Lin et al. [18] determined the edge location of a microlens using fuzzy ratio analysis in order to measure the diameter of the microlens, but the results were easily affected by noise in the image.

To improve the above drawbacks, an innovative method, which combines with the concept of sub-pixel [19,20], is proposed specifically for measuring the diameter of a large-size microlens. Moreover, a second method is designed based on the adaptive neuro-fussy inference system (ANFIS) [21] to verify the superiority and practicality of the proposed sub-pixel algorithm. For measuring the lens sag of a large-size microlens, a mathematical model for rapid estimation of lens sag is also established, and the calculated diameter can be used to determine the microlens sag. By integrating the algorithms for diameter and sag measurement, the proposed AOI system is established with the advantage of fast

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measurement and is particularly suitable for the large-size microlens inspection of industry field.

2. Methods of lens sag and diameter measurement of large-size microlenses

In order to highlight the edge contour of large-size microlenses, a backlight module is used as the light source in this study, as shown in Fig. 1. The sharpness of the circular edge of a microlens is far lower than that of the straight edge; thus, a series of image processing algorithms are proposed to solve this problem. The detailed process is described in the following sections.

2.1. Positioning of microlens center

To measure the diameter, the coordinates of microlens center are calculated first. As dust and other foreign matters may attach to microlens samples, or due to processing defects, the image of a microlens contains noise. The edge contour of the microlens will then be broken and incomplete after binaryzation and filtering operations. In order to solve this problem, a max inscribed circle of the binary image of a microlens is found, and the center of this circle is approximate to the microlens center, which can avoid noise interference.

Assuming the captured image is an $n \times m$ image, and the black pixels of binaryzation are defined as the basis points. There are a total of r basis points, and the $n \times m$ Euclidean distance matrix $\mathbf{D}$ can be defined as follows:

$$\mathbf{D} = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1(n-1)} & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2(n-1)} & d_{2n} \\ \vdots & \vdots & \ddots & \vdots & \\ d_{(m-1)1} & d_{(m-1)2} & \cdots & d_{(m-1)(n-1)} & d_{(m-1)n} \\ d_{m1} & d_{m2} & \cdots & d_{m(n-1)} & d_{mn} \end{bmatrix} \quad (1)$$

$$d_{ij} = \min_{r}\left(\sqrt{(j - x_{bk})^2 + (i - y_{bk})^2}\right),\ i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n;\ k = 1, 2, \ldots, r \quad (2)$$

where, d_{ij} is the element in ith row and jth column of Euclidean distance array $\mathbf{D}$, and shows the distance from pixel (j,i) to the nearest basis point(x_{bk},y_{bk}).

The value of each element in matrix $\mathbf{D}$ is calculated by Eq. (2). After the Euclidian distance matrix is obtained according to the binaryzation result, the position of the maximum value in the matrix is the center of the max inscribed circle of the binary image, which can be considered as the microlens center, and the maximum value is the radius of the max inscribed circle. The value of each element in the matrix is normalized from 0 to 255, and the red point represents the positioning result of microlens center C, as shown in Fig. 2.

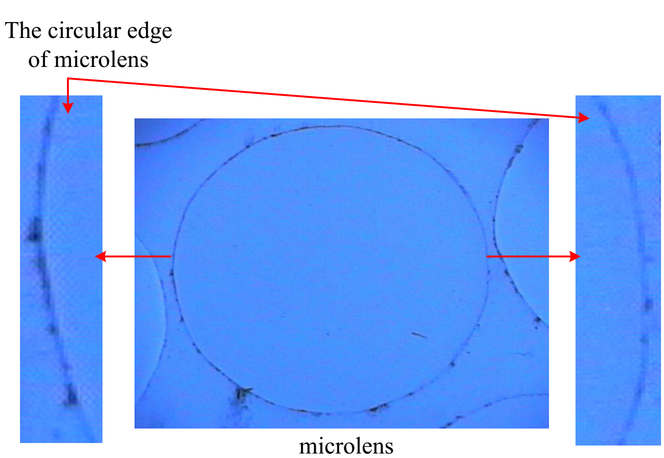

Fig. 1. Image of microlens edge.

2.2. Lens diameter measurement using the concept of a sub-pixel

An initiated ray is made along the edge direction of a microlens with center coordinate $C(x_c,y_c)$ as the starting point, and is rotated each time by fixed angle θ for 360° scanning. $P(x_p,y_p)$ is any point on the initiated ray, as shown in Fig. 3(a), and its coordinate can be expressed as [6]

$$\begin{cases} x_p = x_c + \Delta l \\ y_p = y_c + \Delta l \times \tan\theta \end{cases} \quad (3)$$

where, $\Delta l > 0$ and $\theta \in [0°, 360°)$.

Consider that any point $P(x_p,y_p)$ on the initiated ray must be adjacent to two other pixels, as shown in Fig. 3(b), thus, the gradient G_p of $P(x_p,y_p)$ is defined as

$$G_p = \max(G_1, G_2) \quad (4)$$

where, G_1 and G_2 are the gradient of $P(x_p,y_p)$ and two adjacent pixels, respectively.

According to Eq. (4), the gradients of all pixels on the initiated ray can be calculated. Two points with the maximum gradient are found on this initiated ray, and one of the two points, with a low gray value, is defined as the "initial edge point". For filtering out the improper results of searching the initial edge points, the distance x_{di} from each initial edge point to the microlens center is respectively calculated, and then sequenced in an ascending

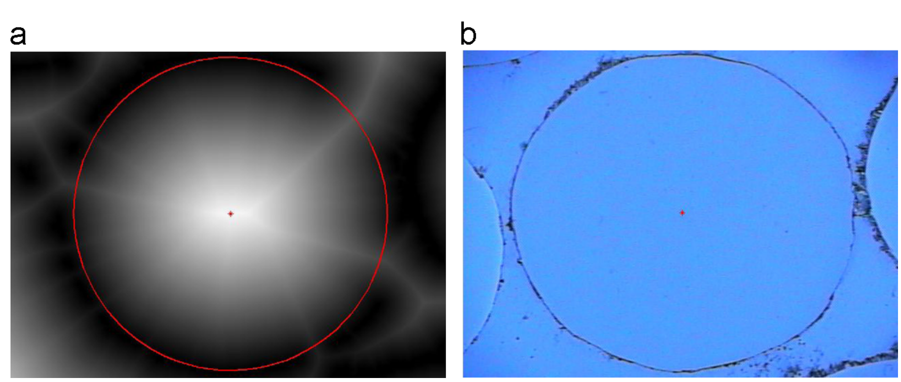

Fig. 2. Result of the maximum inscribed circle and microlens center positioning. (a) Result of Euclidean distance matrix and (b) Result of microlens center positioning.