Novel Fast Laser-Based Auto-Focusing Microscope

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***Abstract*—In keeping with consumer preferences for ever more high-performance products, a requirement exists for precise and fast auto-focusing microscope systems for the inspection processes in mass production lines. Accordingly, the present study proposes a precise and fast laser-based auto-focusing microscope system in which an auto-focusing capability is achieved by using a position feedback signal from the centroid of the image of the reflected laser beam captured from a CCD sensor. The experimental results show that the proposed auto-focusing microscope system is under a 1 s cycle time and ±3 µm positioning accuracy with a ±500 µm linear working range. Overall, it is shown that the proposed auto-focusing microscope system has both a fast response and high positioning accuracy.**

I. Introduction

Focus adjustment is one of the most basic functionalities in imaging systems, and generally requires the mechanical motion of one or more lenses or mirrors within the system [1]. In recent years, auto-focusing technology in digital image requirement becomes more and more important in automatics optical inspection (AOI) and industrial applications such as LCD plane, TFT arrays, semiconductor components, PCB inspection, solar cells, IC chips, laser scribing, and so forth. Therefore, in mass production lines, there are massive requirements for auto-focusing microscope inspection devices and image identification technologies [2].

The auto-focusing microscopes can be divided into two kinds: one is image-based auto-focusing and another is optics-based auto-focusing microscopes. The image-based auto-focusing microscopes are traditional auto-focusing systems and based on the image sharpness identification or the image spatial frequency function which have calculated the high frequency components of image as focus value (FV) [3]. To the best of our knowledge, the image-based auto-focusing microscopes are the most popular in AOI and industrial applications because they are cheap, reliable, robust, and can get a clear image [4-10]. However, the disadvantages of the image-based auto-focusing methods are time-consuming and insufficient for high positioning accuracy because of the maximum extreme finding process and the limit of field of focus (FOV), respectively. To overcome these difficulties, the literature in the field contains many proposals for optics-based auto-focusing methods [11-14]. In the present study, we propose a novel precise and fast laser-based (one of the optics-based methods) auto-focusing microscope system for opaque and transparent materials. The current study presents the structural properties of the proposed auto-focusing microscope system and a series of experimental trials are conducted to evaluate its response time, positioning accuracy, and working range.

II. Structure of Laser-Based Auto-Focusing Microscope System

A. Layout of the Proposed System

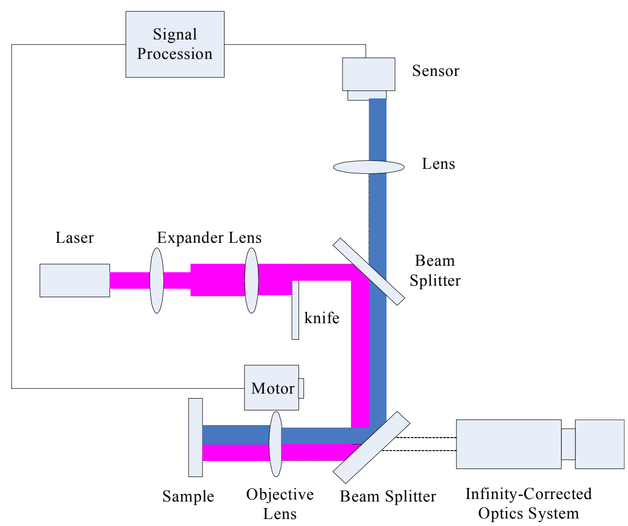

Figure 1. Structure of the proposed laser-based auto-focusing microscope.

The proposed auto-focusing microscope system is established based on geometric optics. Figure 1 illustrates the basic structure of the proposed auto-focusing microscope system. A light beam is transmitted from a laser light source (630 nm), and expanded and collimated through an expander lens. The collimated laser beam is bisected by a knife (or aperture stop) and then passes through two beam splitters. One beam splitter is 50% reflection and 50% transmission for red light. Another beam splitter is high reflection for red light and high transmission for visible light (except for 630 nm). Then the laser beam passes through an objective lens and strikes a sample surface. After traveling the above path, the laser beam is reflected by the sample surface, returns to the objective lens

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and two beam splitters, then passes through an achromatic lens, and finally strikes a CCD sensor. According to the principles of the geometric optics, the shape of the laser's spot (or the centroid of the image) on the CCD sensor is changed according to the distance between the sample surface and the objective lens (see Section B). The variation of the centroid of the image on the CCD sensor is calculated using a built-in algorithm in a signal procession unit. The auto-focusing capability is achieved by using a position feedback signal generated by the variation of the centroid of the image to dynamically adjust the position of the objective lens via a linear motor. Theoretically, the centroid of the image of the reflected laser beam captured from the CCD sensor varies linearly with the microscope's defocus distance, providing a suitable feedback signal for a closed-loop position control system. An infinity-corrected optical system is adopted to observe the real-time image of the sample on line.

B. Theorem

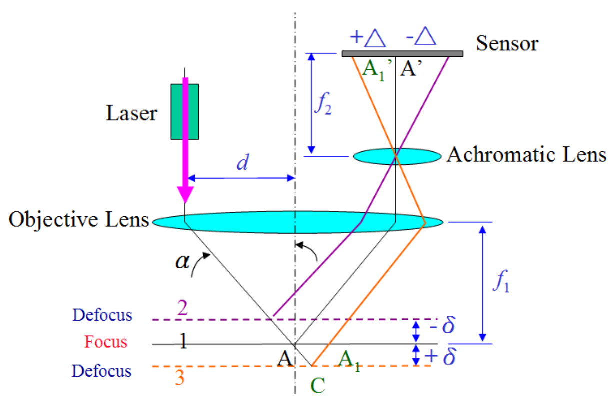

Figure 2. Schematic diagram of the optical path for the proposed auto-focusing microscope system.

The schematic diagram of the optical path for the proposed auto-focusing microscope system is depicted in Fig. 2 [15]. When the laser beam strikes point A on the sample surface placed at the focal plane of the objective lens, the laser beam reflects from point A and falls on point A' on the CCD sensor. According to the geometrical relation, the following equation can be obtained:

$$\tan\alpha = d/f_1, \tag{1}$$

where, α is the maximal incidence angle of the laser beam, d is the radius of the collimated laser beam, and f_1 is the focal length of the objective lens. When the sample surface is moved from plane 1 to plane 3 with a distance δ, the laser beam strikes point C on the sample surface and is then reflected. The reflected laser beam intersects plane 1 at point A_1 and falls on point A_1' on the CCD sensor. Also from the geometrical relation, the following equation can be obtained:

$$\overline{AA_1} = 2\delta\tan\alpha. \tag{2}$$

According to the geometric optics, the displacement Δ on the CCD sensor can be obtained as:

$$\Delta = K\overline{AA_1}, \tag{3}$$

where, Δ is the distance between the point A' and point A_1', and K is the total magnification of the objective lens and the achromatic lens. K can be represented as:

$$K = f_2/f_1, \tag{4}$$

where f_2 is the focal length of the achromatic lens. Substituting (1), (2), and (4) into (3), the distance Δ can be expressed as:

$$\Delta = \delta\frac{2df_2}{f_1^2}. \tag{5}$$

Equation (5) indicates that the distance Δ and the defocus distance δ have a linear relationship.

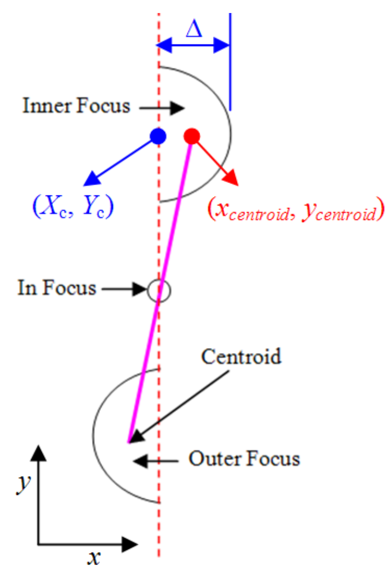

Figure 3. Image of the reflected laser beam captured from the CCD sensor.

Figure 3 illustrates the shape of the laser's spot on the CCD sensor. As shown in Fig. 3, (X_c, Y_c) and ($x_{centroid}$, $y_{centroid}$) represent the positions of the geometrical image center and the centroid of the image captured from the CCD sensor, respectively. The geometrical image center (X_c, Y_c) is constant, and the centroid of the image ($x_{centroid}$, $y_{centroid}$) can be expressed as:

$$x_{centroid} = \frac{\sum\sum(x - X_c)P_{xy}}{\sum\sum P_{xy}}, \tag{6}$$

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$$y_{centroid} = \frac{\sum\sum (y - Y_c) P_{xy}}{\sum\sum P_{xy}}, \tag{7}$$

where, x and y are the row number and column number of the CCD sensor, respectively, and P_{xy} denotes the image intensity registered by a pixel at the crossing of the row x and column y. Assuming image intensity P_{xy} is uniform for the overall image, there is a linear relationship between the centroid of the image on the CCD sensor and the defocus distance δ from (5)-(7).

C. *Optical Design*

Having established a basic design structure of the proposed auto-focusing microscope system (see Fig. 1), a series of finite element simulations were performed to verify the practicality of the proposed structure and determine the suitable values of the major design parameters (i.e. d, f_1, and f_2, and so on). Table I summaries the selected values of each design parameter for the case where the proposed auto-focusing microscope system has a linear working range of ±500 µm. Figure 4 illustrates the optical model built using the optical design software, ZEMAX. Figure 5 shows the numerical results for the shape of the laser's spot on the CCD sensor. It can be seen that there is a linear relationship between the centroid of the image ($x_{centroid}$, $y_{centroid}$) on the CCD sensor and the defocus distance δ, agreeing with the theoretical analysis.

TABLE I. DESIGN PARAMETERS OF PROPOSED AUTO-FOCUSING MICROSCOPE SYSTEM

Variable	Corresponding value
Wave length of laser	630 nm
d	2.5 mm
f_1	10 mm
f_2	100 mm

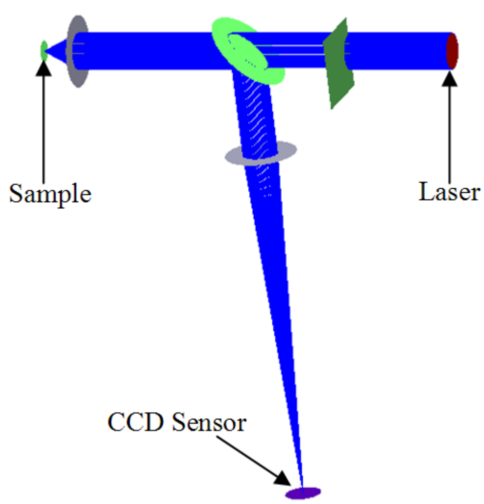

Figure 4. Optical model built using ZEMAX.

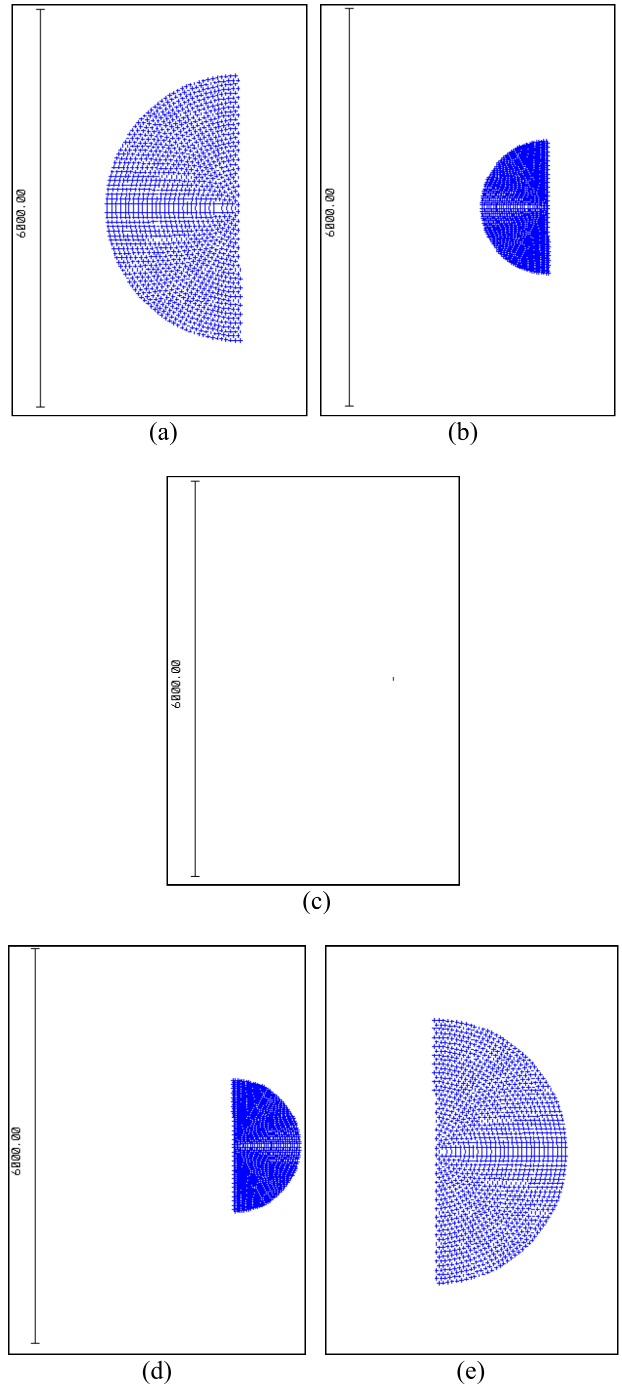

Figure 5. Simulation results for the shape of the laser's spot on the CCD sensor: (a) defocus -200µm, (b) defocus -100µm, (c) in focus, (d) defocus +100µm, and (e) defocus +200µm.

III. EXPERIMENTAL CHARACTERIZATION OF PROTOTYPE MODEL

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The validity of the proposed auto-focusing microscope system was verified by constructing a laboratory-built prototype with a sample of TFT arrays and developed algorithm programming using commercial software, LabVIEW, a platform and development environment for a visual programming language (see Figs. 6 and 7). The proposed auto-focusing microscope system was designed for Mitutoyo 20x objective lens (f_1 = 10 mm) and integrated with the infinity-corrected optics system (see Table I).

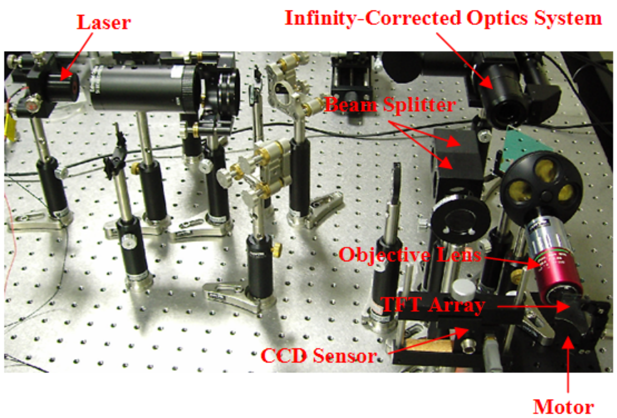

Figure 6. Photograph of the proposed auto-focusing microscope.

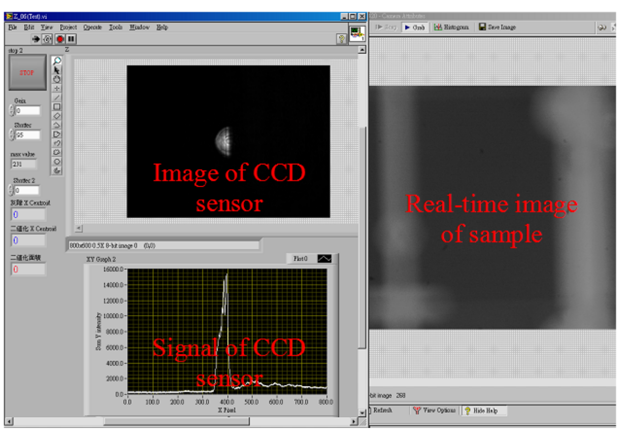

Figure 7. Develpoed algorithm and interface for singal procession.

Figure 8 shows the experimental shape of the laser's spot on the CCD sensor. It can be seen that the centroid of the image on the CCD sensor is demonstrated to vary linearly with the microscope's defocus distance δ. It is noted that the section inside the red dash line in Fig. 8(a) has an image of another laser's spot, which is reflected by the lower surface of the transparent sample of TFT arrays. The image is disturbing and can be filtered by the developed algorithm. Figure 9 shows the real-time image of the sample via the infinity-corrected optical system. It can be seen that the images of the TFT arrays are not clear except for in focus distance, indicating the excellent auto-focusing capability.

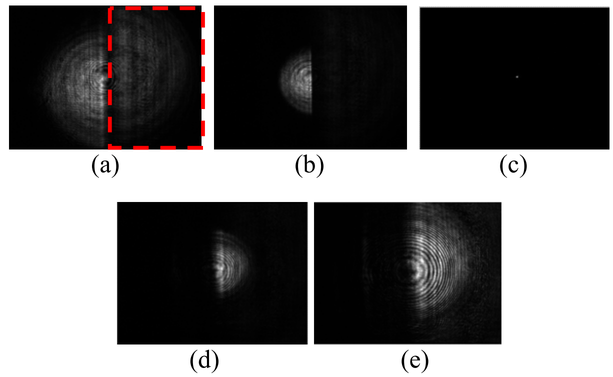

Figure 8. Experimental results for the shape of the laser's spot on the CCD sensor: (a) defocus -200µm, (b) defocus -100µm, (c) in focus, (d) defocus +100µm, and (e) defocus +200µm.

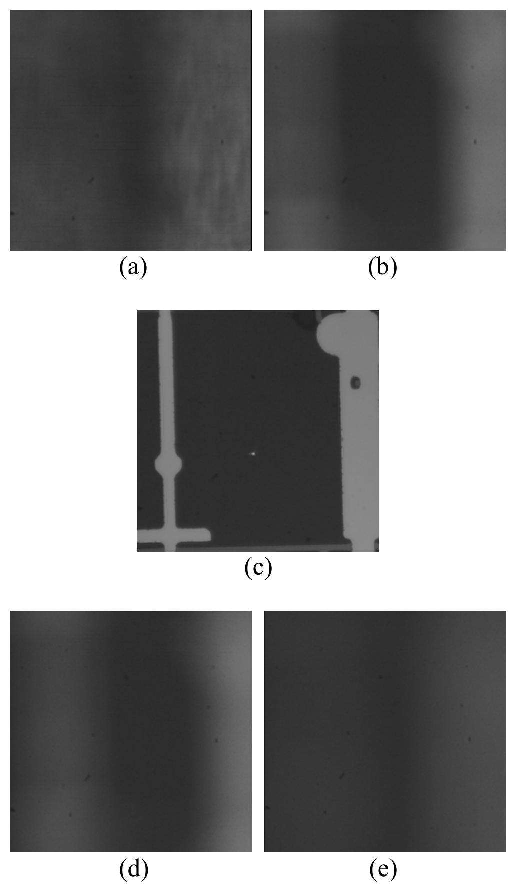

Figure 9. Photo of auto-focusing test for TFT arrays: (a) defocus -200µm, (b) defocus -100µm, (c) in focus, (d) defocus +100µm, and (e) defocus +200µm.

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In order to verify the stability of the proposed auto-focusing microscope system, an experiment was conducted to observe the variation of the centroid of the image ($x_{centroid}$, $y_{centroid}$) of the reflected laser beam captured from the CCD sensor with the time. Figure 10 illustrates the experimental results, in which a measured value of 1 pixel variation was equivalent to a positioning accuracy of 3 μm. It can be seen that the variation of the centroid of the image ($x_{centroid}$, $y_{centroid}$) is about 3 μm within 1 hour and therefore it demonstrates the stability of the proposed system. The experimental results show that the proposed auto-focusing microscope system has a faster response (less than 1 s) and a high positioning accuracy (less than ±3 μm) with a ±500 μm linear working range. As a result, the proposed auto-focusing microscope system can work very well, and it confirms the potential of the proposed auto-focusing microscope system for commercial applications.

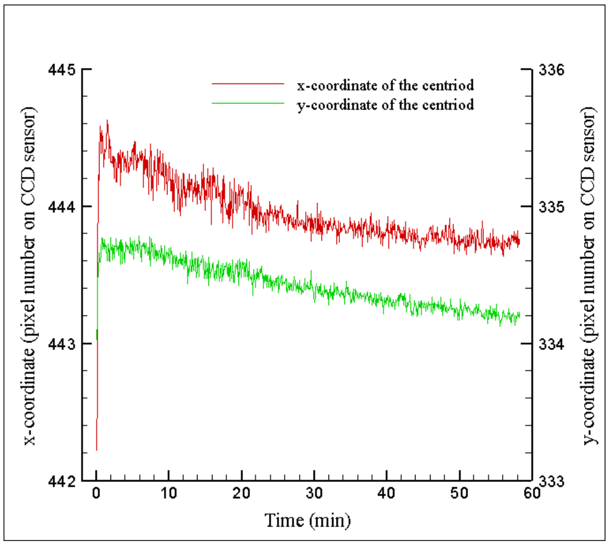

Figure 10. Variation of measuredcentroid of the image of the reflected laser beam captured from the CCD sensor ($x_{centroid}$, $y_{centroid}$) with the time.

IV. Conclusions

This study has presented a novel precise and fast laser-based auto-focusing microscope system for opaque and transparent materials. In the proposed approach, the auto-focusing capability is achieved by using a position feedback signal from the centroid of the image of the reflected laser beam captured from a CCD sensor. The auto-focusing performance of the proposed device is then demonstrated using the laboratory-built prototype with the sample of TFT arrays. The experimental results show that the proposed auto-focusing microscope system has both a fast response and high positioning accuracy to satisfy the industrial applications.

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