A New Shack-Hartmann Type Wavefront Sensor Using Liquid Crystal Panels

Chen Xiaoxi, Liu Xu
Dept. of Optical Engineering, Zhejiang University, Hangzhou, Zhejiang, China
Phone: +86-571-8595-1187 E-mail: chenxiaoxi1022@hotmail.com

Abstract

In this paper, we present a new and practical method for achieving real-time wavefront measurement, dramatically increasing the resolution, dynamic range of Shack-Hartmann wavefront sensor and improving the wavefront reconstruction quality. In proposal method, a liquid crystal display panel (LCD) for the generation of an array of Fresnel microlenses is used instead of the static microlens array of the conventional Shack-Hartmann type sensor.

An off-axis holographic microlens array is designed instead of the normal microlens array to increase the effective array and then the dynamic range. The focus properties of the off-axis lens are studied.

1. Introduction

The Shack-Hartmann wavefront sensor [1] is used to directly measure the slope (phase gradient) and the amplitude of the optical wavefront. It is a very common device used to measure the distortions introduced by atmospheric turbulence for adaptive optics in Astronomy, to measure the wavefront quality of the laser and laser diode light sources for adapting the profile of laser beam to the needs, to measure the optical aberrations of human eye.

Shack-Hartmann wavefront sensors are very simple systems. Conventional Shack-Hartmann wavefront sensors consist of two main components-a microlens array and a CCD (charge coupled device) detector or some other means for recording the pattern of images formed by the microlens array. The schematic diagram of Shack-Hartmann wavefront sensor is shown in the Fig.1.

The incoming testing wavefront is divided into a two-dimensional array of square or hexagonal subaperture by the array of microlenses. Each microlens produces a focal spot in its focal plane. The position of spots is recorded using the CCD detector. By comparing the position of the spots from the incoming wavefront, with those from the calibration wavefront that is a perfect spherical or plane wavefront, it is possible to measure the slope of the wavefront over each subaperture area, and thus reconstruct the entire wavefront over the full aperture or calculate the polynomials description of a wavefront shape such as the Zernike polynomials [2].

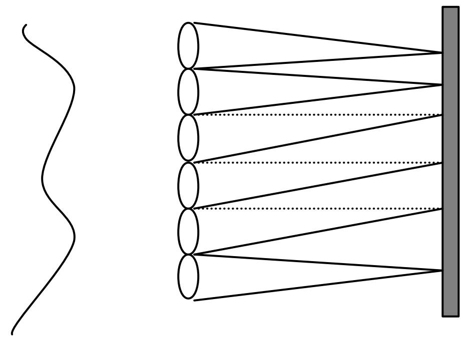


Fig. 1. A schematic diagram of Shack-Hartmann wavefront sensor.

2. The Sensing Data Analysis Process

After the CCD detector grabs the spot image, we need the following steps to reconstruct the wavefront:

- We use the centroid computation approach [3, 4] to determine the center of the spot. The approach optimized thresholding method. The center position of spot (g_x, g_y) can be expressed as:

$$g_x = \frac{\sum_{i,j} x_{i,j} I_{i,j}}{\sum_{i,j} I_{i,j}} \tag{1}$$

for the x-axis,

$$g_y = \frac{\sum_{i,j} y_{i,j} I_{i,j}}{\sum_{i,j} I_{i,j}} \tag{2}$$

for the y-axis.

Here, the computation only includes the position $(x_{i,j}, y_{i,j})$ when the Intensity of the associated position $I_{i,j}$ is larger than the thresholding intensity I_{th}.

- The expression of the slope of the wavefront phase over the subaperture area is equal to the first derivative of the wavefront phase :

$$\begin{pmatrix} \nabla f_x \\ \nabla f_y \end{pmatrix} = \frac{1}{A_{sub}} \int_{sub} \nabla f dxdy = \frac{1}{f} \begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} \qquad (3)$$

where the displacement of the spots $(\Delta x, \Delta y)$ can be calculated from the center position shift of spots between the testing wavefront and the flat wavefront, f is the focal length of the microlens.

- To reconstruct the wavefront from the slope estimation, the wavefront can be expressed as a linear combination of the Zernike polynomials Z_j which are related to the aberrations of wavefront, j is the number of the polynomial.

3. Displaying Off-axis Holographic Lens Array on LCDs

LCDs have become the most frequently used spatial light modulators. They can real-time modulate a wavefront [5]. We use a LCD displaying a phase Fresnel hologram instead of microlens array of conventional Shack-Hartmann wavefront sensor. Thus our new Hartmann sensor can fast change the displaying hologram. We can easily change the parameters of the microlens array like focal length, position, subperture size and number of lenses.

If the LCD displays the on-axis holographic microlens array, the maximum measured displacement of the spots is limited by the center of the micro lens and its size in order to avoid the neighbor spots overlapped. Only when the spot is placed in the cell area can the displacement be measured. The spot S3 in Fig. 2 leaves the associated cell area (the solid line rectangle shown) and the testing wavefront can not be reconstructed correctly. Thus the conventional sensor can not measure the testing wavefront with steep wavefront slope if the long focal length is chosen.

Here, we propose to increase the dynamic range of our new senor through displaying the off-axis holographic lens instead of the on-axis lens. Using the off-axis lens the spot position of the calibration plane wavefront leaves the original place-the center of the associated cell area of the subaperture in focal plane. So we design the holographic lens array with different off-axis value to achieve the longer distance between the near two spots. Fig. 2. shows the effective area of the sensor without and with off-axis holographic lens array.

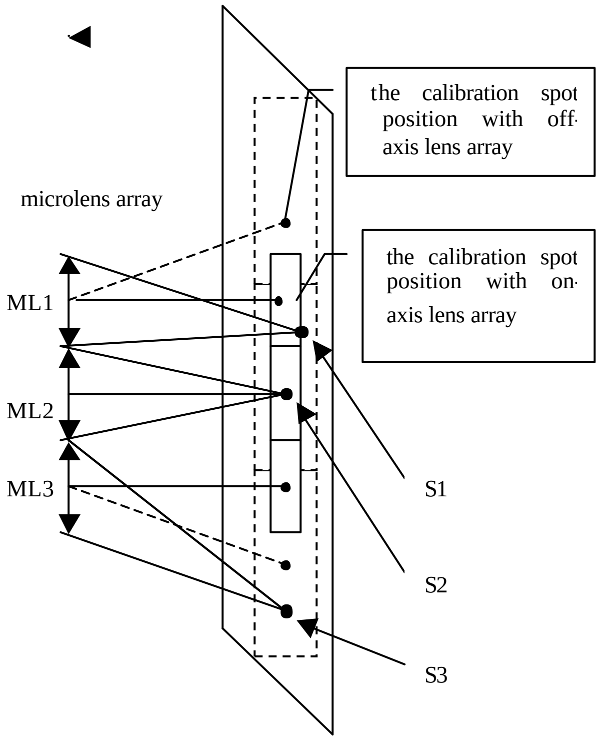
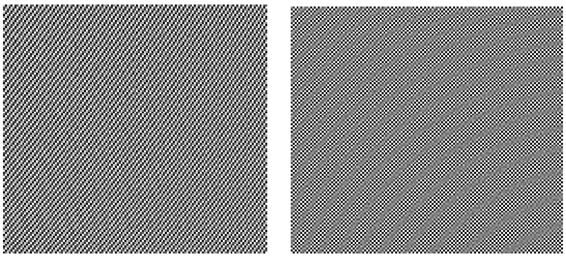


Fig. 2. the effective area of each subaperture with the off-axis lens (dashed line rectangle)and with on-axis lens array (solid line rectuangle).

We can conclude from the Fig. 2 that using the off-axis lens array can increase the effective measure area. The displacement of the spot S3 can be correctly measured by using a suitable off-axis holographic microlens array.

It should be mentioned that we can also design the short focal length lens to improve the dynamic range of the sensor, because the wavefront slope in x/y-axis over the subaperture area A_{sub} is the ratio between the displacement of the spots and the focal length of the associated lens considering Eq. (2). But the long focal length can increase the sensitivity of the sensor.

The expression of the holographic lens is the expression of a spherical wavefront coming from a point light source. The hologram pattern is shown as in Fig. 3.



(a) (b)

Fig. 3. Part of the Fresnel holographic lenses: (a) off-axis value 1.5mm, and (b) off-axis value 3mm with a focal length of 500mm.

4. Experimental Setup

We have designed an experimental setup to study the focusing properties of the Fresnel holographic lens array. As shown in Fig. 4, the output beam of the He-Ne laser was magnified by two lenses with the focal length of 50 mm and 350 mm, respectively. A pinhole with 30 µm diameter was positioned at the focal point of the first lens as a spatial filter. The beam diameter was expanded to ~3cm larger than to cover the opening area of LCD. A polarizer was placed before LCD with its polarizing direction parallel to the LCD rubbing direction. Light focusing properties of the Fresnel holographic lens array was recorded using a CCD camera connected to a computer. The CCD camera was situated at the focal plane of the Fresnel lens.

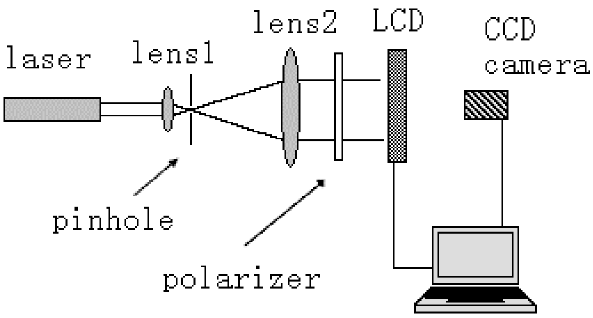
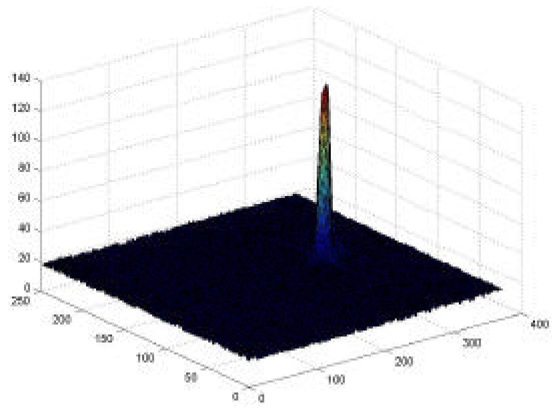


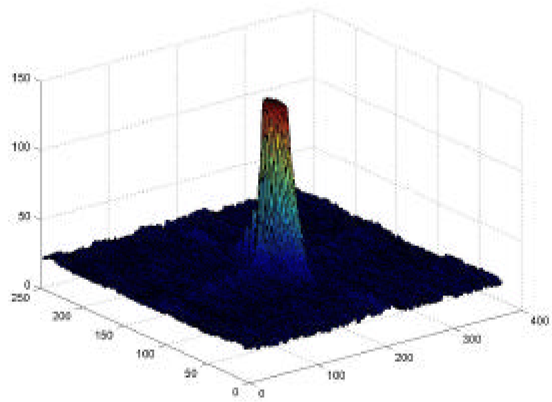
Fig.5 the optical setup

5. Results and Discussions

Fig. 6. plots 3D light intensity profiles of the produced spots using a digital CCD camera when the off-axis value is 5mm and 10mm with the focal length of 500mm. increasing the off-axis value would lead to the spot size suppressed. The small size of spot would increase the accuracy for determining the center position of spots.



(a)



(b)

Fig. 6. The 3D light intensity profiles of the spots using the holographic lenses of (a) off-axis value 5mm and (b) off-axis 1cm by at the focal plane (f=500mm).

6. References

[1] R.V. Shack, B.C. Platt, J. Opt. Soc. Am. 61 (1971) 656.

[2] F.Zernike, Opt. Image Evol. Circular.(1954)526

[3] J. Arines, J. Ares, Opt. Lett., 27(2002) 497-199.

[4] R. Irwan, R. G. Lane, Appl. Opt., 38 (1999) 6737-6743.

[5] G.D. Love, Appl. Opt., 36 (1997) 1517-1524.