Wavefront detection with an irregular diffractive lens array

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In this work we present a realized low-cost wavefront sensor based on the classical Shack Hartmann principle enhanced by an irregular diffractive lens array. By using an irregular lens patterns in combination with a positive lens small image sensors can be used.

1 Introduction

Shack Hartmann Sensors are commonly used wavefront sensors in research and industrial applications. They offer robust and precise wavefront detection not only in astronomy and adaptive optics but also in ophthalmology, optical testing, laser beam analysis, and semiconductor manufacturing.

In general, Shack Hartmann sensors consist of a sampling device (lens array) and an image detector (see Fig. 1). Incoming light will be sampled by the lens array and locally focused on the image detector. Local wavefront gradients within the subapertures of single lenses are shifting the foci out of their central position. Knowing the focal length of the microlenses, a detection of wavefront tilts is possible. An integration of these tilts over the whole lens array finally leads to a phase distribution of the incoming wavefront.

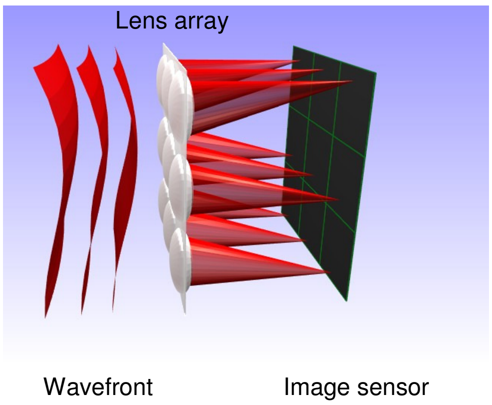


Fig. 1 *Basic principle of Shack Hartmann Sensors. Incoming light is sampled by a lens array and the resulting spot positions are detected by an image sensor.*

Unfortunately, the size of the measured wavefront is directly connected to the size of the image sensor. Using smaller image sensors while maintaining the same measuring aperture requires specially designed microlenses but can lead to reduced total costs for a wavefront sensor.

2 Design of the irregular diffractive lens array

Using a diffractive lens array instead of a refractive one the array layout and lens pattern can be nearly arbitrarily chosen [1].

In a first step of the design process a lens distribution and spot allocation was performed. The used image sensor (Sony ICX098AK 1/4'' VGA CCD) provides an area of 40x40 pixel for each of the chosen 192 spots. The resulting 192 microlenses were positioned in an axially symmetric pattern to provide uniform spacial resolution over a ∅ 20 mm aperture. For ensuring small optical path lengths between the lens array and the image sensor the array layout and spot allocation (see Fig. 2) onto the rectangular CCD was developed.

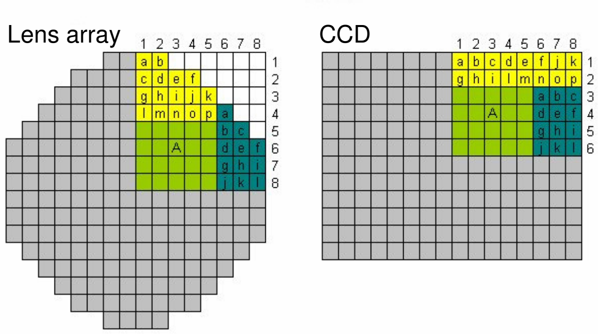


Fig. 2 *Spot allocation between lens array (∅ 20 mm) and CCD (1/4'') for 192 microlenses. Each coloured letter on the lens array will form a spot in the corresponding CCD area of the same colour and letter. The layout is axially symmetric and only shown for the 1st quadrant.*

As the lens array is more than double the size of the CCD the outer focused beams have to be redirected to the CCD. Simulations and numerical calculations have shown that a direct beam redirection caused by the diffractive microlenses would result in a diffractive structure size less than 5 µm with a preferred distance of 13 mm between lens array and CCD.

3 Improvement of diffractive structure sizes

To overcome the small diffractive structure sizes of the needed microlenses a positive lens was positioned behind the diffractive lens array. Placing the CCD shortly in front of the focal plane of the introduced lens the beam redirection will mainly be accomplished by the positive lens (see Fig. 3).

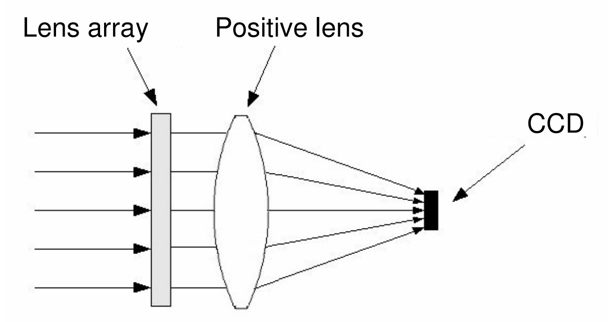


Fig. 3 *Reduction of the diffractive structure size of the microlenses by introducing a positive lens behind the lens array. Placing the CCD close to the focal plane of the positive lens will lead to increased structure sizes of the microlenses.*

As a result of the positive lens the subsequently calculated structure sizes of the microlenses were above 10 µm. After performing a position optimization for all components the lens array was fabricated (see Fig. 4) and the sensor constructed.

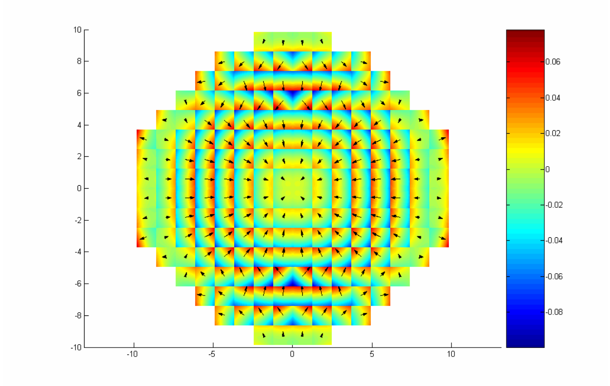
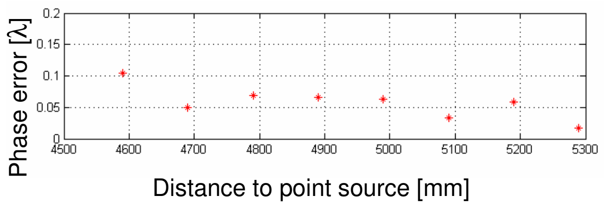


Fig. 4 *Resist layout of the irregular diffractive lens array. Each microlens contains a focus compensation and a small tilt factor to redirect the incoming light through the positive lens and form a narrow spot in the specified CCD area.*

4 Measurements and calibration

In combination with a predetermined look-up table for spot positions and wavefront gradients spherical waves were measured and reconstructed. The reconstruction error over different radii of curvature was in the area of less than $\lambda/10$ (see Fig. 5) and shows the potential of this principle.

The sensor resolution of $\lambda/10$ is covered over a dynamical range of up to ±0.3° wavefront tilt. Higher gradients will result in overlapping spot positions on the CCD but compensation should be possible by iterative spline fitting methods [2].



A resolution improvement can still be achieved by calibrating the complex sensor dynamics with predefined plain or spherical wavefronts and creating a system adapted look-up table for spot positions and local wavefront gradients.

At the moment calibrations with a dynamic light source are being tested [3].

5 Summary

We have shown that wavefront detection with an irregular diffractive lens array allows the use of small image sensors while covering a large measurement area. The additional use of a positive lens behind the lens array extensively increased the needed diffractive structure sizes and reduced accuracy requirements for the sampling device.

References

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[2] S. Groening, B. Sick, K. Donner, J. Pfund, N. Lindlein, J. Schwider, "Wave-front reconstruction with a Shack–Hartmann sensor with an iterative spline fitting method" in Applied Optics Vol. **39**, No 4 (2000)

[3] J. Liesener, H.J. Tiziani, "Interferometer with dynamic reference" in Proc. SPIE **5252**, 264 (2004)