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Curvature sensing with a Shack-Hartmann sensor

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Abstract: Shack-Hartmann (SH) sensor, based on sampling of wavefront tilts in subapertures, is a simple, reliable, and widely used in adaptive optics wavefront sensor. A wavefront curvature sensor has the advantage of providing the results suitable for direct control of membrane and bimorph deformable mirrors [1], but requires linear registration of intensity in two planes. SH sensor modifications using astigmatic microlens array [2] and three SH sensors [3] provide measurement both in the form of wavefront gradients and Laplacian curvatures. In this work, we consider a simple arrangement that turns a standard SH sensor into a curvature sensor by moving the camera chip of the SH sensor into the optical plane conjugated to a deformable mirror. This establishes a direct geometric correspondence between the coordinates on the DM surface and the sensor chip. Then, change in the local centroid density corresponds to the Laplacian curvature of the mirror, and the phase at the boundary can be found from the centroid displacements along the edge of the pupil. We investigate the feasibility of this approach for direct control of membrane deformable mirror by measuring the dependence of the calculated centroid density on the control signal applied to the mirror actuators. The experimental results demonstrate a good linear dependence.

Keywords: Adaptive optics; Shack-Hartmann sensor; curvature sensor; membrane deformable mirror

Laplacian curvature from a Shack-Hartmann sensor

Shack-Hartmann (SH) sensor is a popular wavefront sensor (WFS) used in adaptive optics (AO), which measures the averaged over subapertures wavefront gradients $\nabla\phi$, related to the spot shifts in the Hartmann pattern.

The methods based on finding centroids of the spots are low sensitive to the irradiance variation over the pupil and to the linearity of the camera.

A wavefront curvature sensor [1] measures the Laplacian curvature of the wavefront $\Delta\phi=\nabla^2\phi$. This provides a good match with the physics of curvature aberration correctors such as membrane and bimorph deformable mirrors (DM) and can be used directly for control. To deal with intensity variations, the standard curvature sensor registers the intensity in two planes, before and after the focus.

The hybrid curvature and gradient SH sensor modification [2] uses single detector plane; the sensors provides measurement both in the form of wavefront gradients and Laplacian curvatures, but requires special astigmatic microlens array. The differential SH curvature sensor [3] uses three usual SH sensors for measuring twist and Laplacian curvatures. In all SH-based method, the range of the wavefront gradient is limited by the ratio of the microlens array (MLA) pitch to its focal distance *p/f*, or some special algorithms are required to index the spots [*e.g.*, 4]. In this work, we propose a simple arrangement that turns a standard SH sensor into a curvature sensor and also benefits from low *p/f* values.

In a traditional aligned AO system, both the DM and the MLA of the WFS are conjugated to the system pupil. In such configuration, every subaperture corresponds to a particular pupil subaperture and to the corresponding patch of the DM. The beam crosses the MLA in a fixed area (pupil image); the spot pattern can move over the camera chip, but (under certain obvious conditions) contains the same number of spots.

An interesting configuration appears if the focal plane of the MLA, *i.e.* the surface of the camera chip is located in the plane conjugated to the pupil. In this case a direct geometric correspondence exists between the coordinates on the DM surface and the sensor chip. The MLA is now located in front of the aperture, and the beam can cross it in different places, depending on the WF shape. The number of spots in the Hartmann pattern is not fixed anymore, but the region they occupy is fixed. The change in local density of the spots is directly proportional to the local Laplacian curvature, as in the intensity transport sensors [5, 6], but is almost independent of the intensity variations. As a consequence, the control signal (CS) applied to an actuator is proportional to the integral of the spots density over its area. For the Zernike modes having zero Laplacian curvature [7], the boundary conditions are given by the centroids displacements along the pupil edge.

Description of the method and experiment

We have used a 15-mm membrane deformable mirror with 39 actuators as show on Fig.1 and a SH sensor with a MLA featuring 12 mm focal length

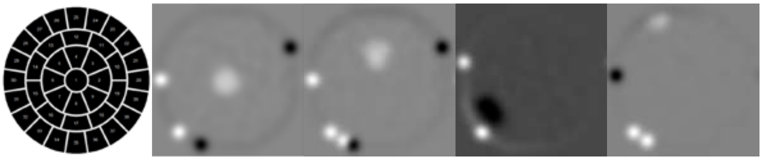

Figure 1. Actuator structure of 39-ch 15-mm MMDM and the response functions (calculated density difference) for actuators 1,2, 13, and 21. The response for the actuator 13 is shown for negative control signal. The edge artifacts do not influence further results.

and 150 um pitch over full aperture of 4.5 mm, and UI1540 camera with 5.2um pixels. A Galilean telescope with 200 mm and 75 mm lenses was used to reimage the mirror to the WFS. The measurements have been done for 10 mm working aperture of the mirror, and full 15-mm aperture. In the last case some parts of the mirror image were clipped by the MLA aperture. The frames corresponding to three reference global curvatures of the mirror (CS = *-1* or *0* or *1* sent to all the actuators simultaneously) have been processed by a usual centroid-finding procedure of a SH-sensor. For the 10-mm working aperture, the total number of found centroids was 500, 532, and 568 centroids respectively. This provides an estimate to the density change range ± 6%. For 19 actuator of approximately equal area this results in 27±1.66 centroid in the actuator.

After that, the frames corresponding to CS = *+1* or *-1* set to the *i*-th actuator and 0 to the rest actuator have been processed to find the centroid array. The next step was to pixilate the centroid arrays by representing each centroid by a group of 4 adjacent pixels having the same center of gravity. This procedure simplifies the further calculations of the spot density.

The spot density was calculated by convolving of the pixelated centroids with a truncated Gaussian kernel of size *4p*, and with $\sigma=1.1p$, where *p* is the pitch of the microlens array expressed in pixel width, and compared with the bias centroid density (technically, it's more efficient to

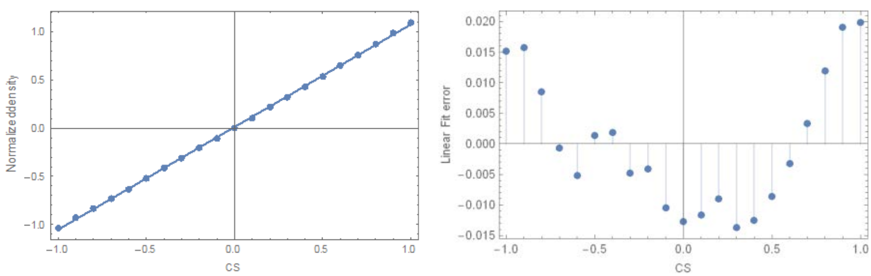

Figure 2. Normalised centroid density difference for a linear control signal applied to actuator 9 and the fitting error from the best-fit linear model.

calculate the difference of the pixelated centroids first and then perform the convolution). The results are present in the Fig.1. One can see the increased centroid density in the regions corresponding to the mirror actuators.

To test the linearity of the calculated density difference with respect to the control voltage, we grabbed and processed 21 frame corresponding to the CS signals *-1,-0.9, ..., 1* to one of the actuators. The pixel values of the obtained density were then integrated over the area of the actuator by multiplying the density image by the mask corresponding to the actuator, summing all values together, and dividing by the actuator area. The obtained results shown in Fig.2 demonstrate linear dependence with 2% accuracy.

Conclusion

In this work we present a simple arrangement that turns a Shack-Hartmann sensor into a curvature sensor. The Laplacian curvature of the wavefront can be found directly by placing the SH sensor camera chip in the plane conjugated to the optical pupil and calculating the local spot density of the spot pattern.

A preliminary tests show good linear dependence between the measured with this method local curvature and the control signal applied to an actuator of a membrane deformable mirror, which makes this method a good candidate for fast adaptive optical systems.

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