Closed-loop aberration correction by use of a modal Zernike wave-front sensor

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We describe the practical implementation of a closed-loop adaptive-optics system incorporating a novel modal wave-front sensor. The sensor consists of a static binary-phase computer-generated holographic element, which generates a pattern of spots in a detector plane. Intensity differences between symmetric pairs of these spots give a direct measure of the Zernike mode amplitudes that are present in the input wave front. We use a ferroelectric liquid-crystal spatial light modulator in conjunction with a $4-f$ system and a spatial filter as a wave-front correction element. We present results showing a rapid increase in Strehl ratio and focal spot quality as the system corrects for deliberately introduced aberrations. © 2000 Optical Society of America

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Optical systems regularly underperform because of the presence of aberrations. These aberrations may be static, for example, owing to low quality or misaligned optics, or dynamic, arising from time-varying optical properties of certain parts the system. Correction of static aberrations is often possible through better design of the optics or, in the case of phase-only aberrations, insertion of a conjugate phase plate. Dynamic aberrations, which by their nature are generally stochastic, require a more versatile method such as inclusion of an adaptive feedback loop in which the wave-front phase distortion is measured and the corresponding conjugate is applied by a wave-front correction element. Adaptive systems using zonal wave-front measurement schemes, such as Shack–Hartmann and curvature sensing, have been demonstrated and are now commonplace in astronomical applications.[1,2] In these schemes, one measures and pieces together information about the local structure of the wave front to find the overall wave-front shape, a process that requires complex calculations. Modal sensing relies on the decomposition of the whole wave front into a set of two-dimensional, usually orthogonal, functions, for example, the Zernike circle polynomials. It has been throught that modal sensing of all but the simplest modes is impractical,[2] but recently we described a new wave-front sensor that measures directly the Zernike mode content of an input wave front and is simple to implement.[3] Here we present results of the incorporation of this sensor in a closed-loop adaptive correction system.

The wave-front sensor consists of a fixed binary-phase element through which the wave front passes, producing a pattern of spatially separated diffraction spots in the back Fourier plane of a lens. In this plane we place an array of pinhole detectors positioned at the center of each spot. In its simplest form the fixed binary element consists of a simple distorted grating pattern, which produced two main symmetric diffraction orders. The positive order can be considered as a uniform-intensity wave front with a phase aberration bias superimposed on it according to the distortion in the grating pattern. By the nature of the binary element, the negative order is an exact conjugate of the positive order and hence has a superimposed negative aberration bias. The output signal is taken as the difference between the intensities of the two spots. If the input wave front itself has a positive aberration of the same type as that introduced by the binary element, then it adds to the bias aberration in these two diffraction orders, increasing the intensity in the focused negative order and reducing that in the focused positive order. If, on the other hand, the input has an aberration that is in some sense orthogonal to that introduced by the binary element, then it will affect both orders equally and merely reduce the intensity at the center of each spot by an equal amount. Indeed, it can be shown that for certain sets of orthogonal modes, such as Zernike polynomials, a sensor for a particular mode is insensitive to all other modes when the intensities at the center of each spot are considered.[3] When finite-sized pinholes are used to maximize the detected optical power, only limited cross talk between modes is found. The output signal exhibits an approximately linear response to the design mode, together with good

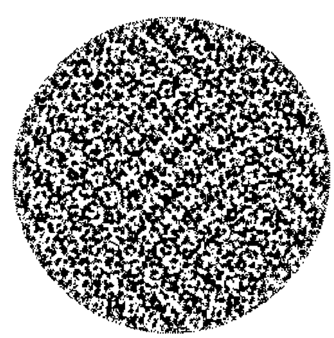

Fig. 1. Binary-phase plate computer-generated hologram (transmission values: white, 1; black, -1).

rejection of other modes, and is therefore ideal for incorporation into a closed-loop adaptive system.

In a further development of this concept the binary-phase element can be designed with standard optimization techniques, such as direct binary search, to produce a multiplexed pattern of pairs of spots, where each pair is sensitive to a separate Zernike mode. Figure 1 shows the binary-element design that was used as a sensor. It produces the spot pairs corresponding to 16 Zernike modes from defocus (mode 4) to second-order trefoil (mode 19), using the numbering system in Refs. 3 and 4. Tip and tilt measurements are also made possible by use of a zeroth-order diffraction spot introduced either by design or by arranging that the binary-phase modulation is not exactly $\{0, \pi\}$.

The response of the wave front can be characterized by a sensitivity matrix $\mathbf{S}$ whose element S_{ik} represents the sensitivity of the sensor designed for the Zernike mode i to the input mode k. This matrix can be calculated or measured experimentally. If the measured difference signals derived from the intensities of each spot pair form a vector $\mathbf{w}$, then to a linear approximation the modal content of the input wave front can be determined as

$$\mathbf{a} = \mathbf{S}^{-1}\mathbf{w}\,. \tag{1}$$

Closed-loop aberration correction can then be realized by implementation of the following algorithm to find new values of the Zernike coefficients, $\mathbf{a}_{n+1}$, generated by the wave-front correction element from the current coefficients $\mathbf{a}_n$ and the measured sensor output signals $\mathbf{w}_n$:

$$\mathbf{a}_{n+1} = \mathbf{a}_n - \mu\mathbf{S}^{-1}\mathbf{w}_n\,, \tag{2}$$

where μ is a gain. However, to demonstrate the simplicity of this approach we use the fact that the sensitivity matrix is both sparse and largely diagonal[3] to approximate it by the identity matrix. This greatly simplifies the calculations that must be performed at each step to

$$\mathbf{a}_{n+1} = \mathbf{a}_n - \mu\mathbf{w}_n\,. \tag{3}$$

We implemented a closed-loop adaptive system as shown in Fig. 2. Illumination was provided by an expanded 532-nm laser beam. The optical system consisted of a wave-front correction element, an aberrating medium, and the modal wave-front sensor. The wave-front correction element consisted of a Displaytech SLM-256 ferroelectric liquid-crystal spatial light modulator (FLCSLM) configured as an arbitrary wave-front generating device.[5,6] This device operates as a correcting element by preaberrating light before it passes through the aberrating medium, a piece of low-quality glass in our experiment. The static binary element for the wave-front sensor was also implemented with a second FLCSLM for flexibility. In practice, we note that it would be preferable and equivalent to use a fixed, etched, or molded plate for the sensor and a deformable mirror as the correction element when optical throughput is important. The diffraction spots produced in the focal plane of the output lens were projected onto a CCD video camera. Camera frames were grabbed with an 8-bit video-rate frame grabber, and the detector pinhole array and signal measurement were implemented in software, again for flexibility. The speed of operation of the whole system was limited by the video system and software to approximately three iterations per second. It is noted that, ideally, the system requires just 16 photodetector pairs in the sensor plane and that much higher operation speeds are possible with considerably less-complex electronics.

The detector plane pattern before correction is shown in Fig. 3(a). Intensity differences in the spot pairs are clearly visible; it is these differences that give rise to the output signals. The central, zero-order spot is present because of deliberately introduced misalignment of PBS2 to disrupt the exact $\{0, \pi\}$ phase modulation of the second FCLSM. This position of this spot was used to measure tip and tilt; the intensity of this order was also used to calculate the relative Strehl ratio as a measure of correction efficiency.

The intensity distributions in the detector plane after the first and final correction cycles are shown in Figs. 3(b) and Fig. 3(c), respectively. As the correction cycles progressed, we saw the equalization of the intensities in each spot pair. Figure 4 shows the variation in Strehl ratio, measured from the central, zero-order spot, as a function of iteration number. It can be seen that the quality of the zeroth-order central spot increased considerably as the correction cycles progressed. In the final corrected image, Fig. 3(c), the characteristic spot patterns of the various sensor aberration modes are visible.

We have described the implementation of a new design of modal wave-front sensor that responds directly to the amplitude of Zernike modes contained in an

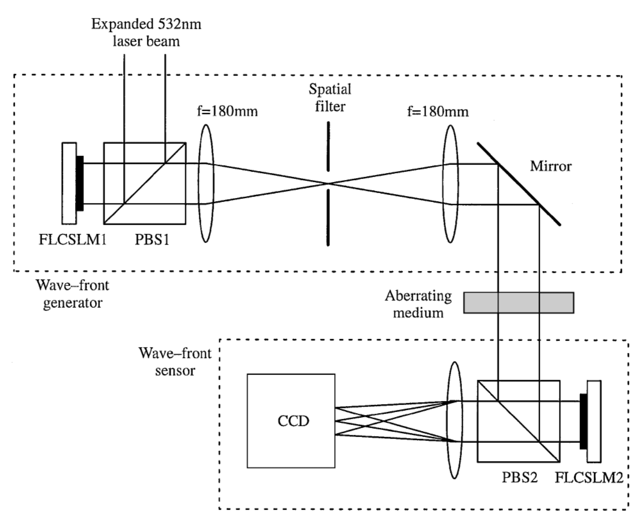

Fig. 2. Experimental configuration of optical system: PBS 1, PBS2, polarizing beam splitters; FLCSLM1, FLCSLM2, ferroelectric liquid-crystal spatial light modulators.

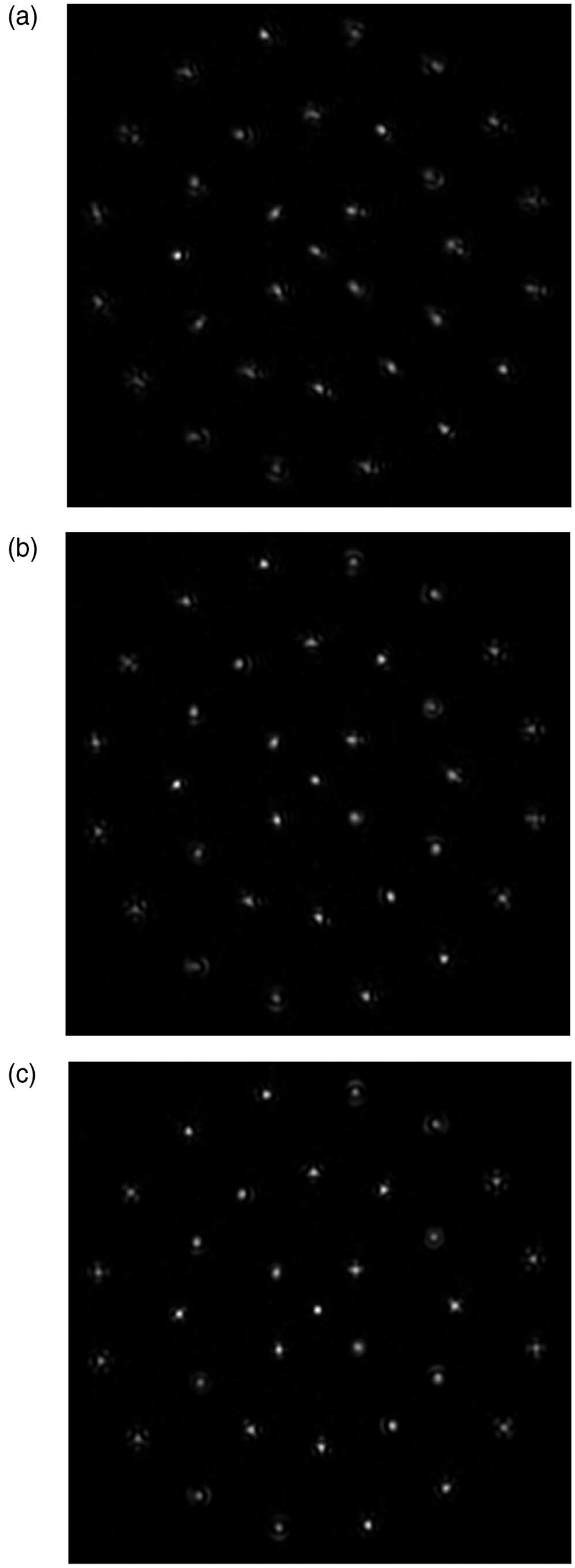

Fig. 3. Intensity pattern in the detector plane (a) before correction, (b) after one cycle, and (c) after nine cycles.

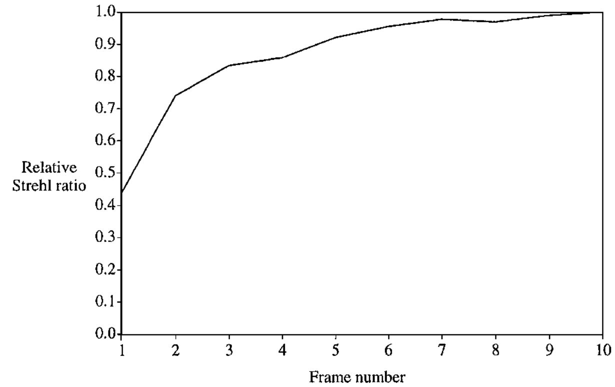

Fig. 4. Improvement in Strehl ratio (relative to final frame) as a function of frame number.

input wave front. We have presented results that show the operation of this sensor in a closed-loop system, using an extremely simple feedback algorithm. The system corrects both system and introduced aberrations to increase the Strehl ratio substantially.

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