Capability of a Liquid-Crystal Adaptive Optics System Based on Feedback Interferometry for Retinal Imaging

Tomohiro SHIRAI
Photonics Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), 1-2-1 Namiki, Tsukuba 305-8564, Japan

(Received August 20, 2004; Accepted January 10, 2005)

A modified arrangement of the adaptive optical retinal imaging system that we described previously is proposed to reduce the intensity loss in the system, so that it works properly even when the intensity of light incident on the eye is very weak. Experiments to verify the system performance were conducted using a conventional artificial eye with a specular reflector as a model retina. We observed that an image of a test target (mimicking a retina) blurred by an aberration plate (mimicking the ocular aberrations) was successfully restored in the adaptive optics fashion even when the intensity of the incident light probing the aberration of the eye became about 1.5% of that required in the previous system. Effect of a more realistic artificial eye with a scattering object as a model retina was also examined experimentally. We found that not only the ocular aberrations, but also the retinal scattering cause the wave-front deformations and that our adaptive optics system compensates for both of them simultaneously. © 2005 The Optical Society of Japan

Key words: adaptive optics, feedback interferometry, liquid-crystal spatial light modulator, aberration correction, retinal imaging

1. Introduction

The idea of adaptive optics was originally proposed to markedly reduce blurring of astronomical images in real time.1,2 It has recently been demonstrated, however, that aberrations of the human eye can be compensated for by means of adaptive optics to improve the quality of retinal images and vision drastically.3 Thereafter, especially in the last few years, a great deal of attention has been paid to the use of adaptive optics beyond astronomy.4 An account of the pioneering work on retinal imaging and vision with adaptive optics is given in some recent review articles.5,6 The basic functions of adaptive optics are to measure the wave-front deformation and to drive a wave-front corrector to correct it in real time. In the astronomical applications, mechanically-actuated segmented or deformable mirrors have played an important role as wave-front correctors.7 It is known, however, that such mirror devices generally have drawbacks of great expense, massive structure, high power consumption, and relatively low-resolution correction. Liquid-crystal (LC) spatial light modulators (SLMs) are promising alternatives to the conventional mirror devices and have extensively been studied in the context of adaptive optics,8,9 though recently developed micromachined deformable mirrors may also solve these problems.10-12

We have thus proposed an LC adaptive optics system,13 which may be utilized for medicine and industry rather than astronomy, based on all-optical feedback interferometry,14,15 in which high-resolution correction of the wave-front deformation is achievable without any electronic calculations. We then have applied it to relatively simple front deformation is achievable without any electronic calculations. We then have applied it to relatively simple

2. Low-Loss Arrangement for Adaptive Optical Retinal Imaging

Figure 1 shows a modified arrangement of the previous adaptive optical retinal imaging system described in ref. 18 to reduce the intensity loss in the system, so that the new system works properly even when the intensity of light incident on the eye is very weak, namely, it could safely be applied to the actual human eye. Experimental verification of the system performance is made by use of a conventional, but somewhat refined artificial eye with a specular reflector as a model retina. Finally, we examine the effect of a more realistic artificial eye with a scattering object as a model retina on the performance of our adaptive optics system.

Imaging.18 Experiments to verify the system performance have been conducted by use of an artificial eye, demonstrating that our adaptive optical retinal imaging system could work properly, at least with the artificial eye: a blurred image of a test target (mimicking a retina) due to an aberration plate (mimicking ocular aberrations) was successfully restored immediately after our adaptive optics system was activated. However, the test target employed as a model retina was a specular reflector and thus it was not a proper model for the actual human retina which has a rough surface.

In this paper we first propose a modified arrangement of the previous adaptive optical retinal imaging system described in ref. 18 to reduce the intensity loss in the system, so that the new system works properly even when the intensity of light incident on the eye is very weak, namely, it could safely be applied to the actual human eye. Experimental verification of the system performance is made by use of a conventional, but somewhat refined artificial eye with a specular reflector as a model retina. Finally, we examine the effect of a more realistic artificial eye with a scattering object as a model retina on the performance of our adaptive optics system.
feedback. The key device acting as a wave-front corrector, which is common in both parts, is a high-resolution, nonpixelized, optically addressed, phase-only, parallel-aligned nematic LC SLM (Hamamatsu PAL-SLM), as before.13,16–18)

Let us first summarize the behavior of light in the retinal imaging system. A planar object T is uniformly illuminated by spatially incoherent white light originating from a halogen lamp (equipped with a collimation lens system) by way of wedge plate WP1, beam splitter BS1, circular aperture CA1, aberration plate AP, and lens Le. Here and hereafter, the wedge plate WP1 (and WP2, 3 below) is employed as a beam splitter to avoid ghosts and to minimize the intensity loss of the laser light used in the adaptive optics system to be discussed below. The four elements CA1, AP, Le, and T, mimicking respectively a pupil, ocular aberrations, a crystalline lens, and a retina, form an artificial eye in which T is located at the back focal plane of Le.19) and AP and CA1 are located just in front of Le, as shown in Fig. 1. The reflected light from T is imaged by four lenses Le, L1, L2, and L10 onto CCD camera CCD3 via polarizer P1, the phase modulating side of the PAL-SLM, and wedge plate WP2. Here the phase modulating side of the PAL-SLM is conjugate with AP by the effect of afocal two-lens imaging system L1 and L2. The LC molecule directors in the PAL-SLM are aligned vertically so that only the vertically polarized component of the light incident on the phase modulating side of the PAL-SLM is phase modulated. The polarizer P1 is inserted to separate the vertically polarized component of light from the initially unpolarized light and, consequently, the image-bearing light after passing through P1 can be fully phase modulated by the PAL-SLM. This retinal imaging system is essentially the same as the previous one (see Fig. 1(a) of ref. 18), except for the slightly inclined setting of the PAL-SLM and for dispensing with a beam splitter accordingly.

The image of T captured by CCD3 is necessarily blurred by the effect of AP. This means that the retinal image captured by a fundus camera is generally blurred by the effect of ocular aberrations in its clinical application. The blurred image can be restored when the PAL-SLM behaves so as to cancel out the effect of AP.

To do this, we drive the adaptive optics system. A vertically polarized plane wave of light originating from a He-Ne laser (equipped with beam expander BE) is incident on CA1, via WP1 and BS1, and tightly focused on the artificial retina T by Le. The focused spot on T, which is generally blurred by the effect of AP, is reflected and goes back along the same path to BS1, and eventually arrives at CCD camera CCD1, after passing through BS1 and reflecting on the phase modulating side of the PAL-SLM. In this arrangement, the phase modulating side of the PAL-SLM and the CCD camera CCD1 are located at the image plane of AP by afocal two-lens imaging system L1 and L2, and afocal four-lens imaging system L1-L4, respectively. According to the theoretical analysis given in Appendix A of ref. 18, the complex amplitude distribution of the laser light just in front of the phase modulating side of the PAL-SLM and, hence, that on CCD1 is approximately given by

\[ U(\rho, \omega) = C a(\rho, \omega) a(-\rho, \omega), \] (1)

under the conditions that the artificial retina T is a specular reflection object, the reflectance of T is locally uniform, and the aberrations of AP are not too strong. Here \( a(\rho, \omega) \) denotes the complex amplitude transmittance of AP (assumed to be a purely phase object), and \( C, \rho, \) and \( \omega \) denote a constant, a position vector across the plane in question, and the frequency of the light, respectively. Equation (1) characterizes the wave-front deformation (due to AP) to be corrected.

A circular aperture, CA2, is located at the conjugate plane of CCD1. Moreover, lens L5 is located just behind CA2 and CCD camera CCD2 is located at the focal plane of L5. This is to evaluate the wave-front deformation to be corrected, before and after correction, qualitatively by means of the Strehl ratio. Here the Strehl ratio is defined as the ratio between the peak intensity of the aberrated image (more precisely, the diffraction pattern produced by a circular aperture on which an aberrated wave-front to be evaluated is incident) and that of an ideal diffraction-limited image.

In the adaptive optics system based on feedback interferometry, an interference fringe pattern carrying complete information about the wave-front deformation to be corrected is required. To produce it, a vertically polarized plane wave of light originating from the same He-Ne laser is guided to CCD1 as a plane reference wave, through BS1, four lenses L6-9, polarizer P2, and via polarizing beam splitter PBS, as shown Fig. 1. This plane reference wave and the preceding deformed wave characterized by eq. (1) are combined by beam splitter BS2 and the resultant interference fringe pattern is captured by CCD1. The combination of the two polarizing elements P2 and PBS serves as an attenuator to balance the intensities of these two waves for high-contrast interference fringes. Moreover, two pinholes PH1 and PH2 are located at the focal planes of lens L6 and lens L3, respectively, to prevent the image-bearing light from entering CCD1. A shutter, S, placed between BS2 and CCD1 was left open during the present experiments.