ADAPTIVE OPTICS SYSTEM TO COMPENSATE COMPLEX-SHAPED WAVEFRONTS

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Free-form lenses are being continuously introduced in the market due to their superior performance when compared to classical designs. The fabrication of accurate free-form lenses depends strongly on the possibility and accuracy of measurement. We present an adaptive optics (AO) system within an open-loop configuration to accurately measure in a single shot lenses that have a complex shape. Once the compensation capabilities in open-loop have been demonstrated, we tested a commercial progressive addition lens by compensating the whole transmitted wavefront.

1. Introduction

The continuous improvements in optical design and manufacturing capabilities are allowing new lenses with complex shapes to become real-world options to many recent commercial products. The introduction of wild aspheric lenses to enhance the optical performance and weight in complex optical systems, the new generation of more comfortable ophthalmic progressive lenses following the market trend of a lens design personalized to the user [1], and the novel imaging systems based on folded lenses which extremely reduce the volume and weight of traditional imagers [2], are just some examples that involve new complex-shaped lenses. In the lens fabrication process, iterative steps of testing and repolishing are typically needed to ensure a high quality product. Therefore, the fabrication of accurate free-form lenses depends strongly on the possibility and accuracy of measurement. Measurements are commonly done with contact profilometers due to the large dynamic range required, despite the extremely high measurement time taken to get a good spatial resolution. Non destructive high speed sensing solutions are also nowadays available, like the classical

Shack-Hartmann optical wavefront sensor, although its more limited dynamic range can not typically deal with very complex wavefront shapes.
Following this reasoning, we present an adaptive optics (AO) system within an open-loop configuration to accurately measure in a single shot lenses that have a complex shape, by means of compensating the whole transmitted wavefront.

2. Adaptive Optics System

The AO principle is based on the local modification of the phase of a distorted wavefront to compensate for its aberrations. Although AO systems can be rather complex, the basic principle is quite simple. In conventional AO, the distorted wavefront is measured with a wavefront sensor and compensated by introducing its conjugate in the phase correcting device by means of a control system. As mentioned, two optical elements are involved in every AO system to perform the wavefront compensation: a wavefront sensor and a phase correcting device.
Figure 1 shows the AO system that we have constructed. A 635 nm point light source obtained from a laser diode coupled with a monomode optical fiber is collimated using a diffraction limited achromat. The resulting plane wavefront passes through a linear polarizer, crosses the optical system of interest (an ophthalmic lens), and is directed towards a liquid crystal programmable phase modulator (PPM) by means of a pellicle beam-splitter (BS1) which does not alter the optical path length. The aberrated wavefront is compensated and reflected by the PPM [3], which is conjugated with a proprietary cylindrical Shack-Hartmann sensor (CSHWS) through a 4:1 telescope system [4]. The sensor, formed by two identical arrays of microcylinders (NA=0.02) oriented along the vertical and horizontal directions, samples the wavefront (previously divided by a second pellicle beam-splitter BS2) in the form of a vertical and horizontal focal line pattern simultaneously recorded by two identical CCDs. By processing the patterns, the average wavefront slope across the microlenses is computed following the usual Shack-Hartmann principle, and, from these data, the wavefront is finally reconstructed in terms of the circular Zernike polynomial decomposition [5].
Because of the non temporal dynamics of the samples to be tested and the excellent linear response of the PPM (as demonstrated later in Sec.3.1) we have chosen to work in an open-loop adaptive configuration (i.e. active compensation), with the important advantage of a very fast measurement process.

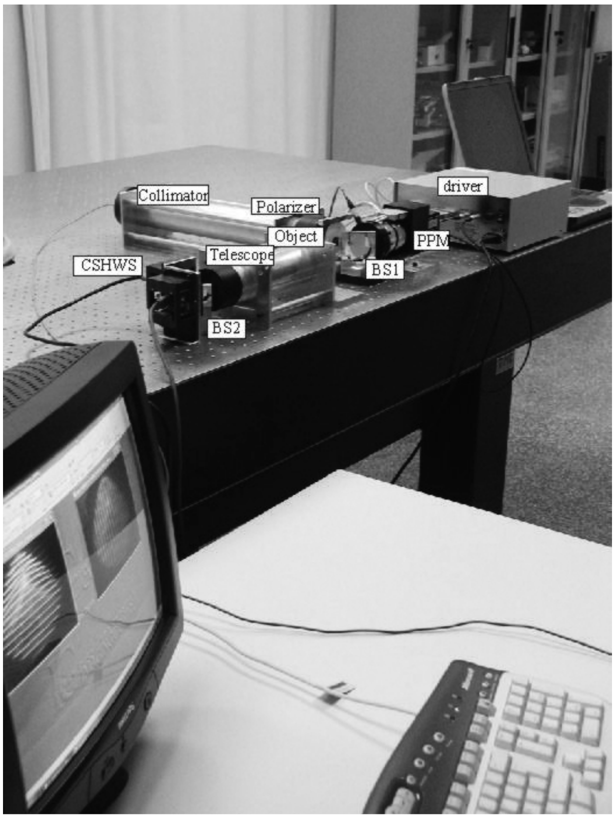
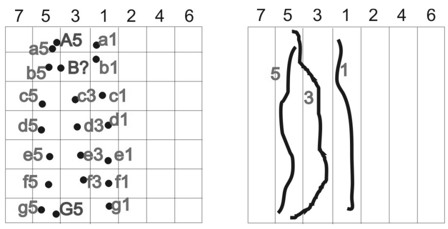


Figure 1. AO system constructed to test commercial lenses with complex shapes.

2.1. *Wavefront sensor*

A novel Shack-Hartmann wavefront sensor based on a cylindrical microlens array (CSHWS) has been developed in order to extend the dynamic range of the classical Shack-Hartmann sensor (SHWS) with a good vertical resolution of measurement (λ/25 at λ=635 nm used). The microcylinders focus the wavefront to be measured onto the CCD in the form of focal lines instead of focal spots of a classical Shack-Hartmann sensor. By easily tracking connected data along the continuous lines, a correct localization of all the data is achieved, even where the wavefront has steep curvatures or abrupt shape changes. The expansion of dynamic range using the CSHWS is illustrated in Figure 2. As it may be seen, the part of the wavefront which is less aberrated and passes through the central column of the array of spherical microlenses (numbered as 1) or through the central microcylinder (1), is properly localized in both cases. However, in the wavefront area where steep phase changes appear, it may be noticed how in the conventional SHWS the spots tagged with capital letters leave their corresponding subapertures in area 3 and merge with those belonging to area 5. This implies an uncertainty in the assignment of spots a5 and A5, b5 and B?, and g5 and G5. The use of the CSHWS solves this problem as all the wavefront samples refracted by each microcylinder are connected in the same focal line and may be easily tracked with a simple algorithm. Thus, samples within lines number 5 and number 3 are unequivocally assigned to microcylinders 5 and 3, respectively.



(a) (b)

Figure 2. Example to illustrate the detected patterns of a complex wavefront with: (a) a conventional SHWS with spherical microlenses which has an uncertainty on the localization of spots a5 and A5, b5 and B?, and g5 and G5; and (b) our sensor based on an array of microcylinders from which all the data are correctly localized.

3. Results

3.1. *Wavefront generation performance of the PPM*

To validate the compensation capabilities of the system in open-loop, the wavefront generation performance of the PPM was analyzed in terms of the amount of aberration considered. Spherical wavefronts of different curvatures (0.25 D, 0.5 D, 1 D and 1.5 D) were introduced in the 768 x 768 pixelated LCD of the PPM in wrapped phase map representation over the whole 20 x 20 mm liquid crystal active area. The incident plane wave in the PPM was modified and reflected as an output beam which should take the spherical shape introduced, and was measured by the CSHWS. Table 1 shows the comparison between the theoretical wavefront written on the PPM and the measured wavefront for the 20 mm pupil. In all the cases, a very good correlation between the desired and real wavefronts has been found (relative rms error below the 0.15%), demonstrating the linear response of the PPM and its suitability for active compensation in open-loop.

Table 1. Comparison between the ideal and real spherical wavefronts created by the PPM.

Ideal Spherical Wavefront [diopters]	Ideal Spherical Wavefront PV [waves]	Measured Spherical Wavefront [diopters]	RMS difference [waves]
0.25	19.68	0.252	0.022
0.5	39.36	0.499	0.013
1	78.72	0.986	0.062
1.5	118.08	1.513	0.080

3.2. *Compensation of the wavefront transmitted by a commercial PAL*

To show the capabilities of the AO system, we tested a commercial progressive addition lens (PAL) which had a nominal null distance power and +2.5 D power addition. A 20 mm diameter area was scanned in a single shot, covering the whole power progression corridor of the lens. The intersection of the vertical and horizontal line patterns detected by the CSHWS and the reconstructed wavefront are shown in Figures 3a and 3b, respectively. As expected, in the near vision region where there is a higher power, the width of the focal lines increases from the diffraction-limited size and are also displaced outside the corresponding microcylinder area of the CCD array. In order to improve the measurement accuracy, the conjugate of the measured wavefront was placed in the active device for compensation. As a result shown in Figure 3c, several additional points (within the white circles) appear now to compute for wavefront reconstruction and the width of the focal lines reduces close to the diffraction-limited size. The original wavefront of more than 60 µm peak to valley becomes flat after the compensation with a RMS deviation of 71 nm (Figure 3d). Unfortunately, the line pattern also clearly shows the diffractive behaviour of the PPM device. When a large aberration is written on it, the period of the wrapped optical path function is shortened, and the diffraction efficiency noticeably decreases; i.e. the intensity of the first diffraction order (which is the phase-modulated) becomes highly reduced relative to the zeroth order (which is the non-modulated original wavefront). This undesired zeroth order light is superimposed to the compensated pattern, making the image processing task more difficult and time-consuming. At present, two alternatives are under study to overcome it: either the introduction in the system of a filter element to block the zero order light, or to tilt the PPM while adding to the desired wrapped phase map the opposite tilt.

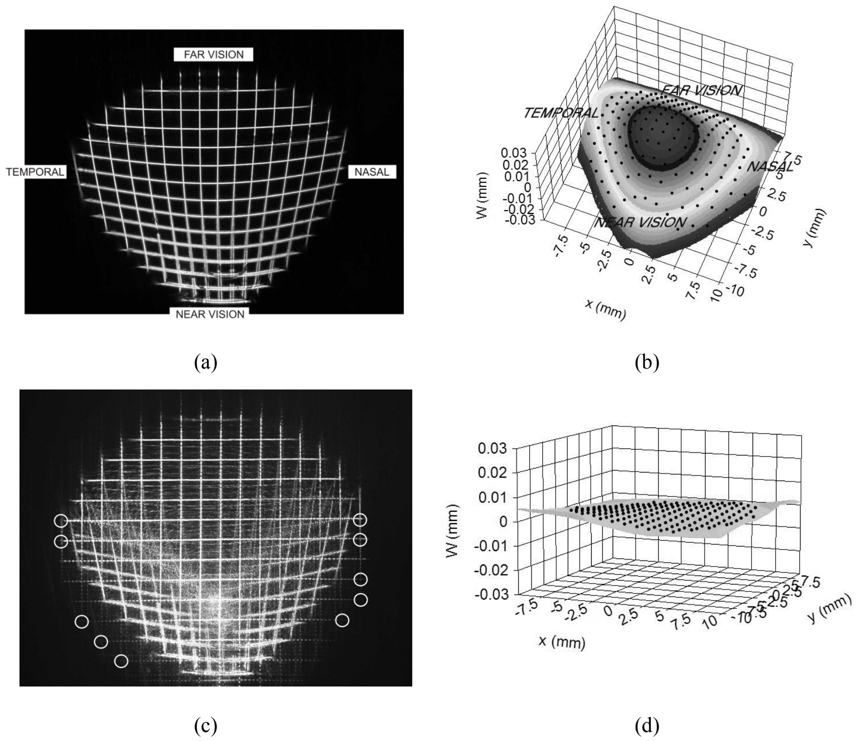


Figure 3. PAL tested with the AO system: line pattern detected and reconstructed wavefront before (a) (b), and after (c) (d) the AO compensation.

Acknowledgments

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