OCULAR WAVEFRONT SENSOR: DESIGN AND SIMULATION

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Abstract: We propose a sensor for ocular aberration measurement and validate the design with simulations. It involves the design of a CGH as encoded dots and its holographic reconstruction. The reconstructed dots are imaged on a CCD and a simple normalized intensity difference of the pair of dots gives the information of ocular sphero-cylindrical aberrations. The simulation results have demonstrated simultaneous wavefront detection of lower order Zernike modes with a resolution better than $\lambda/50$ for wide measurement range of $\pm 3.5\lambda$ with much reduced crosstalk.

Keywords: Computer generated hologram, Shack-Hartmann sensor, Ocular aberrations, Zernike polynomials.

1. INTRODUCTION

The correction of higher order ocular aberrations are being aggressively explored in the form of corneal refractive surgery, contact lenses, and intraocular lenses. OSA task force has standardized the normalized Zernike expansion for specifying the ocular aberrations. Performance of ocular optics is most conveniently represented by Zernike aberration contents. Precise knowledge of Zernike contents of wave aberrations of human eye serves as tool in ophthalmic design, wavefront guided corrections (or surgical procedures), and adaptive optics techniques for high-resolution retinal imaging. Several techniques have been proposed to measure the wavefront aberrations of human eye. In one of the method called objective method a light spot is created at the retina that works as point source. The propagated optical wave, coming out of the eye-optical system, is used to estimate the wave aberrations of the eye. Most popular method used is Shack-Hartmann wavefront sensor (SH-WS) that also offers fast estimates of the aberrations under some limitations.

SH-WS is an improved version of classical Hartmann test and offers improved signal to noise ratio. SH-WS is widely used for the measurement of ocular aberrations. It measures local slope errors and then wavefront reconstruction techniques are used to estimate various Zernike contents of ocular aberrations. It involves extensive computation that scales with the spatial resolution of the sensor [2]. Thus need of a wavefront sensing method arises that could directly measure the Zernike contents [3]. Holographic techniques offer wavefront reconstruction directly. In such techniques the information used for aberration detection is present in the Fourier plane of the entire beam width; therefore it is more robust against local losses of information [4]. Recently a multiplexed holographic wavefront sensor has been reported [4] with resolution $\sim \lambda/50$ over the dynamic range of $\pm 2\lambda$, yet this suffers from cross-talk problems. Recording and reconstruction of multiplexed physical holograms suffers with two types of sources of errors, first at recording process and then during reconstruction. The sources of errors due to recording process can be avoided by making Computer Generated Hologram (CGH). CGH is a better option to implement this type of sensor, because it provides the design freedom to optimize the cross-talk problem [5]. Thus we propose a technique of modal wavefront sensing employing CGH. We have given earlier a model to design a CGH based wavefront sensor that could directly detect the Zernike mode [6]. In the proposed work the CGH design is optimized and the number of holograms to be multiplexed is reduced so that the modal cross-talk is reduced. Normalized difference signal between the two spots obtained is proportional to the amplitude of the sensed Zernike modes and is used as the output signal. This significantly increases the detection dynamic range. We call it differential modal Zernike wavefront sensor (MZ-WS). Simulation study of the differential MZ-WS has been carried out for the detection of sphero-cylindrical ocular aberrations.

2. OCULAR ABERRATIONS

Ocular aberrations are typically described in terms of wavefront error. Wavefront error is the difference between the ideal wavefront and the actual wavefront of the eye-optical system as a function of exit pupil coordinates. Three numbers are typically used to represent the conventional ocular aberrations. Using a lens of pure sphere and pure cylinder with certain angle, one can denote the so-called sphero-cylindrical error of ocular aberrations with the three
numbers: Sphere power, Cylinder power and the Cylinder axis [7]. However when higher order of ocular aberrations is considered, more numbers are needed for representation. For example the three numbers for sphero-cylindrical error are −3.0 D (diopter) of sphere and 1.0 D of cylinder at 45 degree. Even higher order errors can be given as 0.08μm of spherical aberration, -0.12 μm of vertical coma, and 0.09 μm of horizontal trefoil over 6 mm pupil. Wavefront refraction is a good metric often used for evaluating the outcome of vision correction. In paraxial approximation it is simply defined over a unit circle as
\[
WRx(\rho, \theta) = -\frac{1}{R^2} \frac{\partial^2 W(\rho, \theta)}{\partial \rho^2}
\]
where \(R\) is the radius of the eye pupil, \(\rho=r/R\) and \((\rho R, \theta)\) is polar coordinate of any point over the unit circle. \(W(\rho, \theta)\) represents the ocular wavefront errors that is non-rotationally symmetric in nature and can be expanded in terms of orthonormal Zernike polynomials.
\[
W(\rho, \theta) = \sum_{j=1}^{J} c_j Z_j(\rho, \theta)
\]
To consider sphero-cylindrical ocular aberration, defocus and primary astigmatism terms are only taken in the above expansion.
\[
W(\rho, \theta) = c_4 \sqrt{3}(2\rho^2 - 1) + c_5 \sqrt{6}\rho^2 \sin(2\theta) + c_6 \sqrt{6}\rho^2 \cos(2\theta)
\]
Using the transformation
\[
c_5 = \sqrt{c_4^2 + c_5^2} \sin(2\varphi) \quad \text{and} \quad c_6 = \sqrt{c_4^2 + c_6^2} \cos(2\varphi)
\]
estimating the wavefront refraction as [7]
\[
WRx = S + C[1 - \cos(2(\theta - \varphi))]
\]
Under positive cylindrical notation the Sphere power \(S\), Cylinder power \(C\) and Cylinder axis \(\varphi\) can be calculated using the second order Zernike coefficients (e.g. \(c_4, c_5\) and \(c_6\))
\[
S = -4\sqrt{3}c_4 \frac{C}{R^2} \quad C = 4\sqrt{6}(c_4^2 + c_5^2) \frac{R^2}{c_6^2}
\]
\[
\varphi = \frac{1}{2} \tan^{-1}\left(\frac{c_5}{c_6}\right)
\]

3. CGH DESIGN AND SIMULATION

Here we use a concept of recording a hologram of a point object, i.e., bright dot \(d_p\), located in dark plane, with an aberrated wave. This recording we do numerically and generate a CGH encoded with the known aberrated wave. Further if we illuminate the CGH with the similar aberrated wave as used in numerical recording the point object is reconstructed. An aberrated wave with single mode-amplitude combination \(c_j Z_j\), is expressed as
\[
\psi_{abr}^j = \psi_{pln} \exp\left(i \frac{2\pi}{\lambda} \rho Z_j\right)
\]
where \(\psi_{pln}\) is plane wave, \(\lambda\) is the wavelength of monochromatic wave, \(c_j\) is strength of Zernike mode \(Z_j\).

We can compute a single hologram with a reference aberrated wave \(\psi_{abr}^j\) and the Fourier transform of the corresponding dot image \(d_p\) as an object wave. The intensity \(I_j\) at the recording plane of the single hologram is
\[
I_j = |\psi_{abr}^j|^2 + |\psi_{abr}^j|^2 \left[FT(d_p)\right] + \left[\psi_{abr}^j\right]^2 FT(d_p) \quad (6)
\]
The first two terms are DC term and third term represents the conjugate object wave. The third term is well separated due to off-axis position of the bright dot. Only the fourth term of the Eq. (6) is of our interest as it corresponds to the desired object wave. We make the CGH \(h_j\) corresponding to the fourth term of the Eq. (6).

We make two such holograms \(h_{ij}\) and \(h_{i2}\) for two equal and opposite amplitude \(c_{ij}=+\epsilon\) and \(c_{i2}=- \epsilon\) of a particular Zernike mode \(Z_j\) and two corresponding dot images \(d_{ij}\) and \(d_{i2}\) respectively. These dot images are two bright spots in a row representing a particular Zernike mode. Thus
\[
H_j = \left[\psi_{abr}^j\right]^2 FT(d_{ij}) + \left[\psi_{abr}^j\right]^2 FT(d_{i2}) \quad (7)
\]
This requires a suitable encoding technique for amplitude and/or phase and needs to be implemented on an 8-bit amplitude and/or phase SLM. We have encoded the multiplexed CGH simply by taking real part of the multiplexed data from Eq. (7) and scaled it for 8-bit grey levels. Such grey levels can easily be displayed on an amplitude LC-SLM.

This CGH is employed for developing the MZ-WS. Hologram reconstruction is the process in which reference test wave \(\psi_{ref}\) is allowed to pass through the CGH and then inverse Fourier transform of the field is taken. The test wavefront may be taken as
\[
\psi_{ref} = \psi_{pln} \exp\left(i \frac{2\pi}{\lambda} \sum h_k Z_k\right)
\]
As illustrated in Fig.(1), the two spots corresponding to each Zernike mode appear at the Fourier plane during hologram reconstruction. These spots correspond to the locations of the bright pixels.
of the dot images. The intensity difference between two spots of the corresponding pair is the output signal of the sensor and it is proportional to the amplitude of the sensed Zernike mode present in the test wavefront. Thus sensor output signal for $j$th mode is

$$I_j = I_1 - I_2$$

where $I_1$ and $I_2$ are the intensities of the two spots at the reconstructed plane. Similarly many pair of holograms can be computed for various Zernike modes, and are multiplexed to get the desired CGH.

In the present work, Inverse Fourier transform of the product of test wave $\psi_{test}$ and CGH $H_j$ is used to reconstruct the hologram numerically. All the simulation work was realized using MATLAB environment. This simulation is equivalent to propagating the signal up to the detector plane via an on-axis FT lens as shown in the Fig.(1). The reconstructed hologram is a set of rows of spots with bright dots. Depending on the Zernike modes under consideration spots appear in several rows at one corner of the observation plane, with each row corresponding to a particular Zernike mode. Particular Zernike mode is sensed as the intensity difference of the spots of the corresponding row and is calibrated.

Figure 1. Ocular Aberration measurement sensor

For simulation we have taken an aberrated test wave with the known ocular aberrations. This test wave is used to reconstruct the pair of spots with the multiplexed designed CGH. The normalized intensity difference between the two spots in a row is used to plot the response curve for the detection of particular Zernike mode. Multiplexed CGH is designed by coding Zernike defocus and Zernike astigmatisms as shown in the Fig.(2a). Reconstructed set of dots obtained by simulation is shown in the Fig.(2b).

Figure 2. (a) Multiplexed CGH (b) Reconstruction

Figure 3. Zernike coefficient vs. cylinder axis

4. SCHEMATIC OF THE SENSOR

The sensor would consist of a multiplexed CGH, a Fourier transforming lens, CCD, beam splitter, LED source and a collimating lens, as shown in the Fig.(1). The LED source is focused by the eye lens at the retina. The scattered light is collimated by the collimating lens and used for the wavefront sensing. Collimated light from eye has the wavefront error information of the eye-optical system. Sensor involves multiplexed CGH of encoded dot images and its holographic reconstruction as shown in the Fig.(1). These set of reconstructed dots are imaged on a CCD and by a simple normalized intensity difference of the pair of spots the amplitudes of various Zernike modes are estimated. Two spots in a row correspond to a particular Zernike mode and the no. of rows correspond to the different Zernike modes considered during CGH design. As no. of modes increases some intermodal cross-talk could appear whereas intramodal cross-talk [6] is almost eliminated in our present design. Further, very simple software can be developed to display the strength of ocular sphero-cylindrical errors. Method is very well scalable for the higher order ocular aberration that is required for the wavefront-guided LASIK and other refractive surgery applications.

5. RESULTS AND CONCLUSION

First we have plotted astigmatic coefficients with the cylinder axis for cylinder power of 5 D (one of the extreme case). As shown in the Fig.(3) the two astigmatisms are complementary to each other. Further we studied the Zernike coefficients versus the spherical and cylindrical powers (in conventional unit diopter). As shown in the Fig.(4) the extreme cases of the powers, i.e., 8 D the coefficient variations is less than 2 micron. This supports the City data for 93 eyes used in simulation [2].
Sensor response curves have been generated for simultaneous detection of second-order Zernike aberrations (defocus and the two orthogonal astigmatism). Response curves for the various modes are shown in Fig. (6).

Simulation was performed for a test beam consisting of sphero-cylindrical power corresponding to coefficients 1.5 micron and cylinder axis of $3\pi/8$. The phase map of this typical ocular aberration is shown in the Fig. (5). In our earlier work we found that the sensor could detect Zernike modes with resolution better than $\lambda/50$ for wide measurement range of $\pm 3.5\lambda$ with much reduced crosstalk.

Test wave consisting of sphero-cylindrical aberrations were detected in terms of normalized intensity difference and the Zernike coefficients were estimated by the sensor response curve. Further the corresponding sphero-cylindrical powers and axis are estimated from the variations given in the Fig. (3) and (4). Here we presented only the case of detection of sphero-cylindrical error but the proposed sensor is scalable to higher order aberrations.

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