Optimized restoration of wavefront coded images

C. Toxqui-Quitl[a], Eva Acosta[b], Justo Arines[b], and A. Padilla-Vivanco[a]

[a] Universidad Politécnica de Tulancingo, Ingenierías 100, 43629 Hidalgo, México.

[b]Universidad de Santiago de Compostela, Departamento de Física Aplicada, Santiago de Compostela 15782, Spain

ABSTRACT

Wavefront coding (WFC) uses a special aspheric optics and digital image processing to extend the depth of focus in imaging systems. An intermediate blurred image is generated by the spatial convolution of the image with the point spread function (PSF) of a cubic phase mask. Restoration tests are performed on an optically encoded image. The best option to restore an image is not always given by a deconvolution method using the PSF of the imaging system. Due to it is limited by the perfect PSF of the system. In this study, the restored image is given by a deconvolution method using the numerical PSF. As the quality of the image is depended of the pupil diameter and strength of the wfc phase plate, an optimization was achieved by means of measuring the decoded image contrast. Results shows a high resolution decoded image.

Keywords: image restoration, wavefront coding, genetic algorithms, focus invariant

1. INTRODUCTION

The wavefront coding imaging systems use an aspheric surface to code an image in order to make it insensitive to misfocus related aberrations.[1] The detected image will be decoded by means of focus independent digital filtering. This technique allows that: A) focus related aberrations can be controlled, B) misfocus information can be preserved, C) the depth of focus increases by a factor of ten, D) the MTF contains no zeros or nulls, and others advantages. Some applications of this technique involve high-resolution imaging of the retina and other structures in the eye.[2] In this paper is presented the use of wavefront coding to compensate eye aberrations such as sphere and astigmatism. Restoration tests are performed on an optically encoded image. This work is organized as follows: section 2 gives a brief review of the theory of wavefront coding. In Section 3 is described the image acquisition system and the results of restoration. Finally, conclusions are given in section 4.

2. METHODOLOGY

A family of cubic phase pupil functions is used to have an invariant Defocus Transfer Function[3] (DFT) in order to extend the depth of focus of a system. It is given by,

$$P(x,y) = e^{A(x^3+y^3)}, \tag{1}$$

with A the phase deviation defined as,

$$A = \frac{2\pi OPD}{\lambda}, \tag{2}$$

and OPD is the Optical Path Difference.

Further author information: (Send correspondence to C. Toxqui-Quitl.)
C. Toxqui-Quitl: E-mail: ctoxqui@upt.edu.mx, Telephone: +51(775) 7558202

Current Developments in Lens Design and Optical Engineering XV, edited by R. Barry Johnson, Virendra N. Mahajan, Simon Thibault, Proc. of SPIE Vol. 9192, 91921J · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2065848

The cubic phase element expressed in terms of the Zernike polynomials $Z_{n,l}(r,\theta)$ is,

$$W(r,\theta) = e^{-iAZ_{n,l}(r,\theta)}, \tag{3}$$

where $Z_{n,l}(r,\theta)$ is given by,[4]

$$Z_{n,l}(r,\theta) = R_{n,l}(r)e^{-il\theta}, \tag{4}$$

and

$$R_{n,l}(r) = \sum_{s=0}^{\lfloor\frac{n-|l|}{2}\rfloor} (-1)^s \frac{(n-s)!}{s!(\frac{n+|l|}{2}-s)!(\frac{n-|l|}{2}-s)!}(r)^{n-2s}, \tag{5}$$

for $n \geq 0$, $l = 0, \pm1, \pm2, ...$ Some conditions more are that, $n - |l|$ must be an even number and $|l| \leq n$.

In general, the Zernike polynomials are used in describing wavefront aberrations.[6] Some of them are shown in Figure 1.

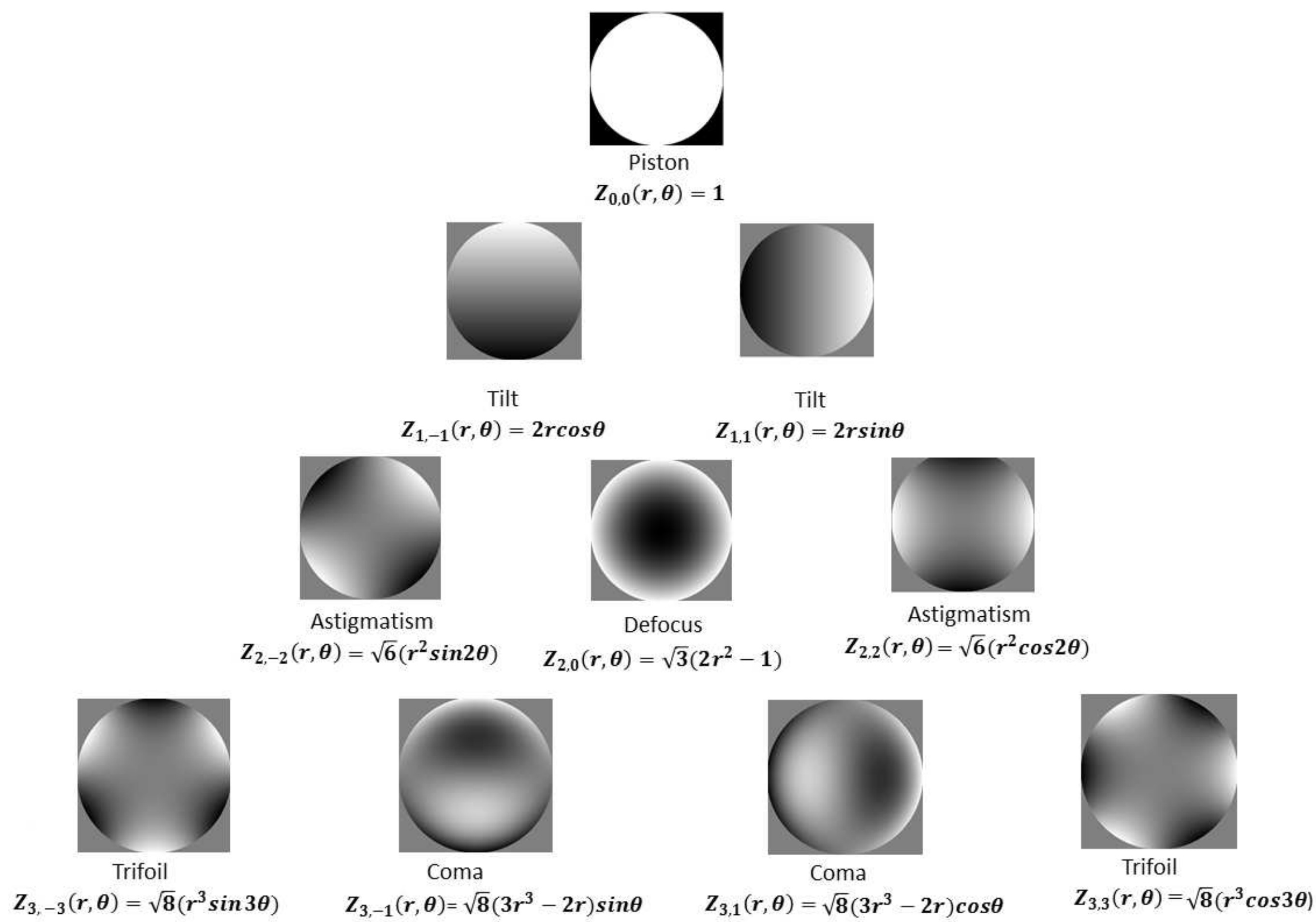

Figure 1. **Some wavefront aberrations expressed in terms of Zernike polynomials.**

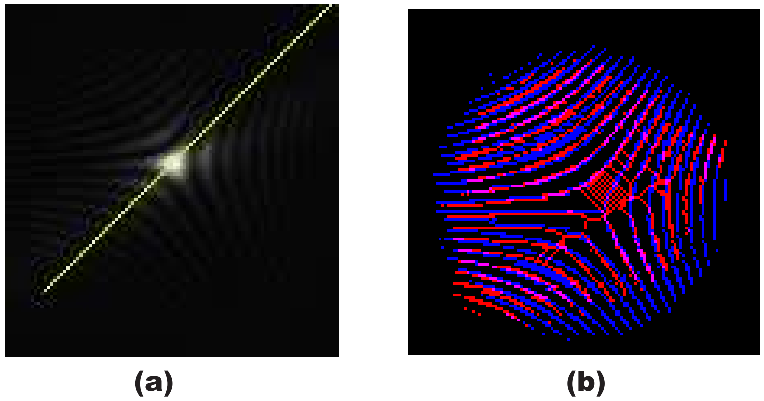

Figure 2. **(a) Numerical PSF and (b) RED Experimental PSF and fitting BLUE numerical PSF of the wfc system.**

3. IMAGE ACQUISITION SYSTEM AND RESTORATION

For the experimental setup, we have used a wavefront coding phase plate of dimensions $10X10mm^2$ with maximum sag of about 1.8 mm. The WFC presented here has 16 microns peak to valey in a pupil diameter of 5mm. The optical parameters of the wavefront coding system[2] are listed below.

Table 1. Optical parameters of a afocal 4f system

wavelength	625nm
pupil diameter	5mm
focal length	10cm
pixel size of a CCD sensor	6.45 μm
eye aberrations	-1.5D of sphere and -1.5D of astigmatism
trefoil aberration by wfc	30 λ

3.1 Encoder using a WFC phase plate

The wavefronts are transmitted from an object and encoded by the cubic phase plate. The USAF chart 1951 is used as an artificial eye. The input image is convolved with the PSF of the optical system with the parameters given by the Table 1. Figure 2 shows the experimental PSF and the fitting numerical PSF. The image blurred by aberrations are shown in the Figure 3.

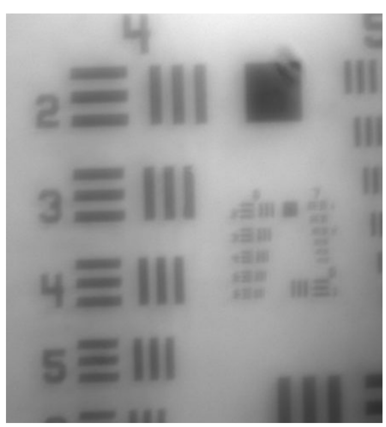

Figure 3. **(a)Image blurred by -1.5D of sphere and -1.5D of astigmatism.**

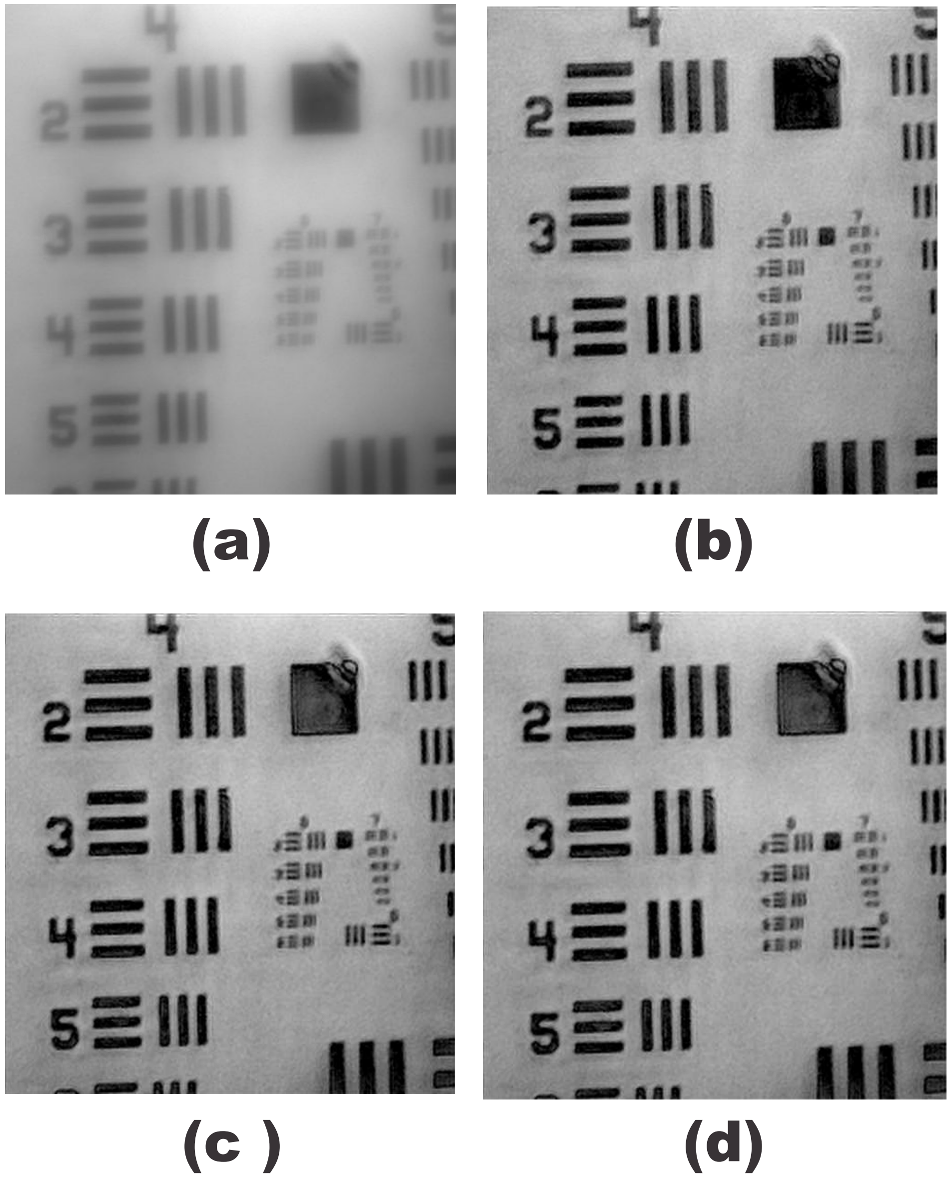

Figure 4. **(a) Coded image and decoded image with pupil diameter (b) d=4.5mm, (c) d=5mm and (d) d=5.5mm. As we can see, when the pupil diameter increases, the image becomes sharper.**

3.2 Decoding

In order to restore the coded image, a spatial filtering is implemented. The deconvolution is done with a Wiener filter given by,[7]

$$F(u,v) = \left[\frac{|H(u,v)|^2}{H(u,v)|H(u,v)|^2 + S_\eta(u,v)/S_f(u,v)} \right] G(u,v), \tag{6}$$

where $H(u,v)$ is the OTF of the system, $G(u,v)$ is the blurred image in the Fourier space, $S_\eta(u,v)$ and $S_f(u,v)$ are respectively, the power spectrums of the noise and the undegraded image. $F(u,v)$ is the restored image in the frequency plane. In the Figures 4 and 5 are shown the results of restoration for different pupil diameters and strengths.

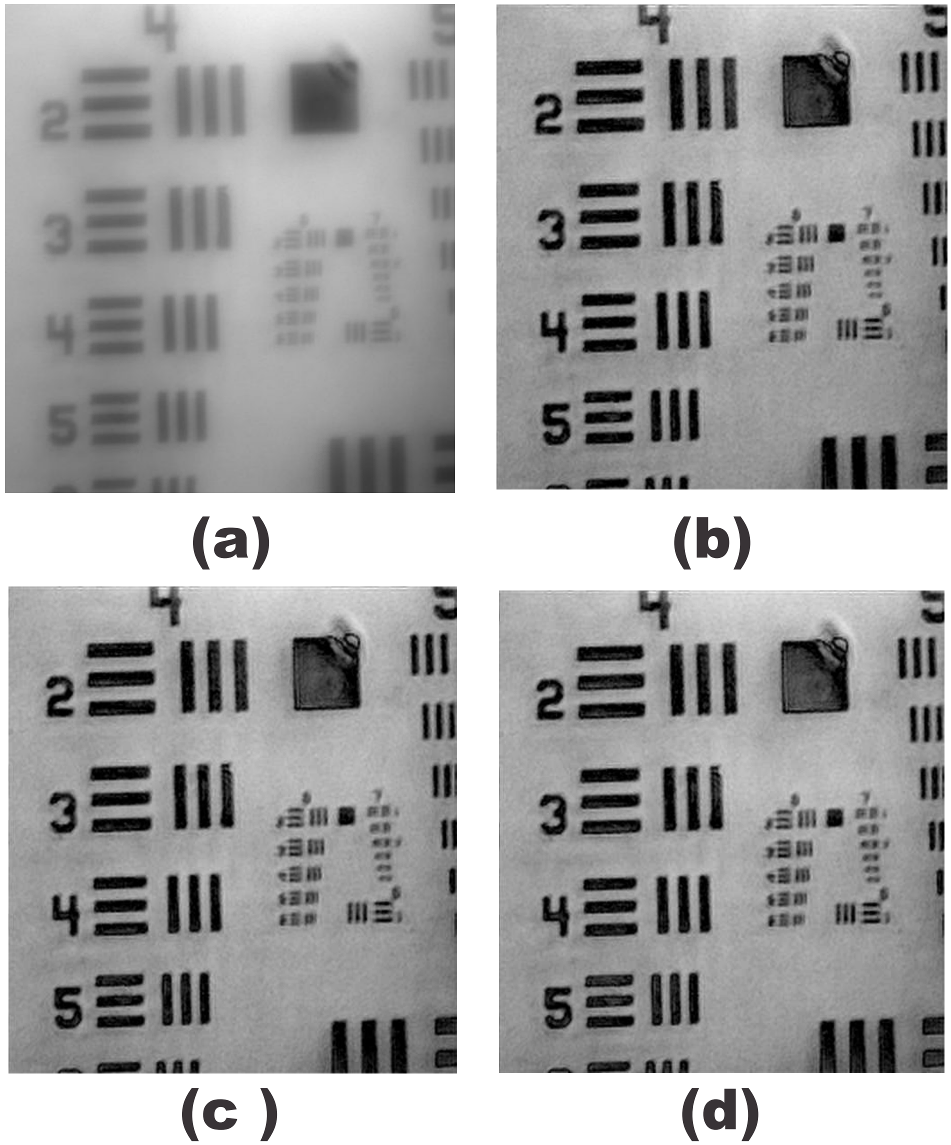

Figure 5. **(a) Coded image and decoded image with (b) OPD=-14.4 λ , (c) OPD=-17.5 λ and (d) OPD=-19.4 λ peack to valey in a pupil diameter of 5 mm.**

The restored image $f(x, y)$ has been evaluated by using the spatial frequency defined as,[5]

$$SF = \sqrt{(RF)^2 + (CF)^2}, \tag{7}$$

where,

$$RF = \sqrt{\frac{1}{MN} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} [f(x, y) - f(x, y-1)]^2}, \tag{8}$$

and

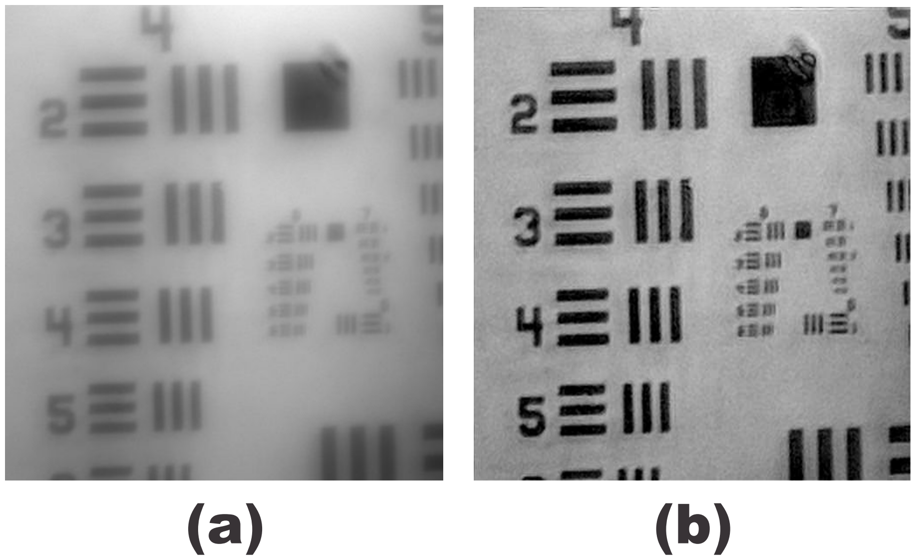

Figure 6. **(a) Blurred image by aberrations (b) Decoded image by means genetic algorithms.**

$$CF = \sqrt{\frac{1}{MN}\sum_{x=0}^{M-1}\sum_{y=0}^{N-1}[f(x,y) - f(x-1,y)]^2}. \tag{9}$$

As we can see, the restored image is depended of the pupil diameter d, the OPD and the value of the parameter $K = S_\eta(u,v)/S_f(u,v)$. By means of Genetic Algorithms (GA) we maximize the contrast metric SF. So that, the objective function is given by,

$$MaxContrast(d, OPD) = SF[f_{d,OPD}(x,y)]. \tag{10}$$

Figure 6a shows the image blurred by the eye aberrations and figure 6b shows a high contrast image that is recovered with WFC after the deconvolution is applied.

4. CONCLUSIONS

This work analyze the use of wavefront coding to compensate eye aberrations in order to obtain high-resolution images of the retina and other structures in the eye. An imaging system is implemented for coded the image affected by aberrations. Restoration tests are done on the optically encoded image. The PSF is constructed numerically from the optical parameters of the system. The restored image is given by a deconvolution method using the numerical PSF. As the quality of the image is depended of the pupil diameter and strength of the wfc phase plate, an optimization is achieved by means of measuring the decoded image contrast. Results shows a high resolution decoded image.

REFERENCES

1. E. R. Dowski, Jr., and W. T. Cathey, "Extended depth of field through wavefront coding," Appl. Opt. **34** (1995).

2. J. Arines, C. Almaguer, C. Toxqui, and E. Acosta, "Retinal imaging with wavefront coding," 23rd. ICO conference, Santiago de Compostela (2014).

3. H. Bartelt, J. Ojeda-Castaeda, and E. S. Enrique, "Misfocus tolerance seen by simple inspection of the ambiguity function," Appl. Opt. **23**, 2693-2696 (1984).

4. Z. Ping, H. Ren, J.Zou, Y. Sheng and W. Bo, "Generic Orthogonal moments: Jacobi Fourier moments for invariant image description," Pattern Recognition 40, 1245-1254 (2007).

5. C. Toxqui-Quitl, A. Padilla-Vivanco and G. Urcid-Serrano, "Multifocus image function using the Haar wavelet transform,"Proc. of SPIE 6748, 555812-112 (2004).

6. Virendra N. Mahajan, "Aberration theory made simple,"SPIE Press **TT93**, Second edition, (2011).

7. Rafael C. Gonzalez and Richard E. Woods, "Digital image processing,"Prentice Hall, Second edition, (2002).