HOWARD: High-Order Wavefront Aberration Regularized Deconvolution for enhancing graphic displays for visually impaired computer users

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Abstract. High-Order Wavefront Aberration Regularized Deconvolution (HOWARD) is a complete closed loop system developed for simulating human visual function with the primary goal of enhancing graphic computer displays for users that have refractive errors (resulting in difficulty interacting with visual displays). Visual function is a primary requirement for a human being to engage in computer usage efficiently. There are situations in which common forms of vision correction, such as contact lenses or glasses are not sufficient to provide the necessary compensation for some users to interact with graphic displays. This paper presents a model for the visual function of an imaging system, the implementation of an artificial eye with high-order wavefront aberrations, as well as a method for providing compensation of the artificial eye through a graphic display.

1 Introduction

Since the development of the Hartmann-Shack sensor for measurement of wavefront aberrations in the human eye [5],[7], it has become possible to characterize the individual refractory limitations of each individual. This capability has been used by emerging techniques such as Adaptive Optics [8] to implement custom vision correction approaches. These methods, however, may be expensive and cumbersome due to the highly specialized hardware needed. The corrective approach we propose requires only the knowledge of the wavefront aberration to create customized pre-compensated images to be displayed in standard PC graphical displays to facilitate the interaction of users with refractory limitations.

1.1 Problem Statement

The goal of this paper is to present an innovative way of providing enhancement of graphic displays to PC users that have high-order visual aberrations. A number of visual impairments, such as keratoconus [10], involve high-order visual aberrations that may not be corrected by using glasses or contact lenses.

The algorithm presented here relies on the linear systems approach to modeling the human visual system, known as Fourier Optics [6]. The human visual system can be thought of as a linear system having an impulse response *H*. In a linear system, the output of the system is the convolution of the input with the impulse response of the system. The impulse response of an ideal optical system, including the human eye, is a delta function. Thus, if the user is free from any visual aberrations, his/her eye impulse response, from here on termed Point Spread Function (PSF), will be a delta, allowing the user to interact more efficiently with the personal computer (PC) via the graphical display. This will result in a clear, undistorted projection of the object onto the retina. If however, the user has a visual aberration, the PSF will not be a delta, and thus the retinal project of the object will be distorted. Fig. 1 shows the Linear Shift Invariant (LSI) model used to describe the optical process.

An object $O(x,y)$ (for example, a picture on a graphical display) is degraded by convolution with the PSF of the user's visual system, $H(x,y)$, resulting in a distorted projection of the object on the user's retina, $I(x,y)$. This is described by

$$I(x,y) = H(x,y) * O(x,y), \quad x = 0,\dots,N-1, y = 0,\dots.M-1 \tag{1}$$

where * denotes convolution.

Given O and H, the High-Order Wavefront Aberration Regularized Deconvolution (HOWARD) algorithm seeks to find an inverse function H^{-1} to produce an enhanced object, *EO*, counteracting the distortion introduced by H, such that when the user views the *EO* on the graphic display, an undistorted version of O will be projected onto the retina.

$$EO(x,y) = H^{-1}(x,y) * O(x,y) \tag{2}$$

$$I(x,y) = H(x,y) * EO(x,y) = H * H^{-1} * O(x,y) \approx O(x,y) \tag{3}$$

This model amounts to a noiseless deconvolution problem. However the ill-conditioned nature of the PSF of the human eye [1] will require a robust method, such as HOWARD, to allow a more efficient interaction between a user that has a refractive error present in his/her visual system and the PC.

2 Background on Fourier Optics

In order to better understand HOWARD, a brief review of Fourier Optics, the foundation for why the human eye can be considered a Linear Shift Invariant System, will be given.

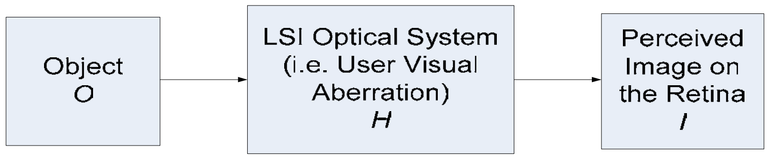

Fig. 1. Simplified Human Visual Model. The image perceived by the user results from the convolution of an object, in this case an image on a graphical display, with the Point Spread Function (PSF) of the user. Under ideal conditions, the perceived image on the retina will be a magnified, but undistorted version of the object. If the user has any type of visual aberration, the resulting image that falls on the retina will be a distorted version of the object.

The foundation of Fourier Optics lies in the definition of the irradiance pattern that falls at the focal point of an optical system composed of a lens and an aperture:

$$E(X,Y) = \iint_{aperture} A(u,v) e^{ik(Xu+Yv)/F} \, dxdy = H, \tag{4}$$

where *E(X,Y)* is the irradiance pattern (which is, in fact, the point spread function of the system [12],[13]), *A(u,v)* is the pupil function representing how a plane wavefront from a source at infinity exits the pupil towards the imaging plane, and F is the focal distance of the lens [13]. In equation (4) we can see that this is in fact a Fourier transform. The PSF of any optical system is the Fourier transform of the pupil function. We refer the reader to [6], which details the relationship needed to apply linear systems theory to optical systems.

Most optical systems, including the human eye, have a complex aperture that modulates both the intensity and the phase of the incoming plane wavefront. For an ideal optical system, the pupil function will be one (*A(u,v)* = 1) across the entire pupil, causing no modulation of intensity or phase. A user that has refractive errors will not have an ideal pupil function. Instead, the pupil function will be composed of a real and imaginary part, as follows:

$$A(u,v) = D(u,v) e^{-i2\pi n W(u,v)/\lambda}. \tag{5}$$

where *D(u,v)* represents the intensity aberration function and *W(u,v)* represents the wavefront aberration function, n is the index of refraction, and λ is wavelength of the light that is incident on the optical system. For a human eye that only has refractive aberrations, i.e., does not have a disease such as cataracts that disperses the incoming light, $D(u,v) \approx 1$ [12].

The wavefront aberration function provides knowledge of how an optical system distorts the incoming wavefront. In order to proceed with any type of enhancement, knowledge of the wavefront aberration function is necessary on a custom basis for each user. Developments in ophthalmology during the last decade have made access to a user's wavefront aberration in the form of Zernike polynomials possible [14], [7]. Once this is known for the user's eye, the PSF describing the way the user views the graphical display can be calculated.

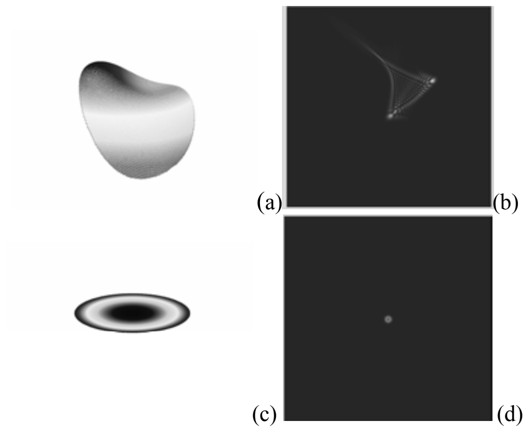

Fig. 2. Wavefront aberration (a,c) and Point Spread Function (b,d) for aberrated and ideal human eye, respectively.

3 Deconvolution Overview

Once the PSF is obtained from the measurement of the wavefront aberration function using equation (4), the next step is to find an H^{-1} such that equation (3) is true.

Classical deconvolution defines H^{-1} in frequency as

$$H^{-1}(fx, fy) = \frac{1}{H(fx, fy)} \cdot \tag{6}$$

It is clear that small values of *H(fx,fy)* will cause singularities in the inverse. Alonso et. all [3] have proposed a method to account for these singularities. Although effective, the parameter selection process for that method is crucial to producing a usable inverse function H^{-1}. These parameters need to be readjusted repeatedly before an acceptable inverse is met.

Additionally, in the model proposed here, noise is not a factor in the deconvolution process, and, therefore, it does not impact the quality of the inverse. We propose a simpler, yet effective form of generating the inverse function, providing regularization for the singularities present in *H*.

Given a point spread function, *H*, the inverse, H^{-1} is determined as follows:

$$H^{-1}(fx, fy) = \begin{cases} \dfrac{1}{H(fx, fy)}, & abs(H(fx, fy)) \geq th \\ H(fx, fy), & abs(H(fx, fy)) < th \end{cases} \tag{7}$$

where $0<th<0.1$ specifies a hard threshold to determine the cutoff point for singularity detection.

This threshold yields similar results as in [3], with the added benefit of reducing the sensitivity of the resulting inverse function to the parameter, as well as reducing the problem of parameter choice from three parameters to one.

Unfortunately, the practical implementation of this form of deconvolution necessarily reduces the contrast of *EO* because graphical display devices can only display grayscale values in the range of (0,255). Scaling and shifting of the *EO* is necessary for presentation on modern graphical displays [3], at the cost of the associated loss of contrast.

Although this method of deconvolution yields an adequate inverse, the Fourier domain does not provide a compact form of representing the PSF. Even for the common PSF corresponding to defocus, the associated singularities are spread throughout the frequency domain causing distortion in the form of ringing in the enhanced object, *EO*. This ringing is not necessary to provide adequate enhancement to the user and causes a distortion that is further exacerbated if any attempt at improving the contrast of *EO* is made [1].

The HOWARD algorithm uses wavelet denoising to reduce the presence of the ringing in the enhanced object, *EO*. This has been shown to improve the signal-to-noise ratio (SNR) and mean-square-error (MSE) of signals corrupted by noise [9], [11]. Wavelet image denoising first decomposes an image into l=4, 7, 10…L levels, with wavelet approximation coefficients for each level. In the *Lth* level, the number of wavelet coefficients with a significant amount of energy is typically a subset of all the coefficients calculated, and thus the signal can be reconstructed with an abbreviated number of coefficients [11]. The idea behind denoising is to select the appropriate coefficients to accurately represent the image, while suppressing the noise. In wavelet denoising, one form of selecting the coefficients is by soft thresholding [11], given by

$$w_{soft}(u,v) = \begin{cases} sign(w(u,v))(|w(u,v)| - \tau), & |w(u,v)| > \tau \\ 0, & |w(u,v)| \le \tau \end{cases} \quad \textbf{(8)}$$

where $w_{soft}(u,v)$ are the thresholded wavelet coefficients, $w(u,v)$ are the wavelet coefficients obtained through the decomposition of the image, and τ is the threshold level.

The noise power is assumed to be less than the signal power, thus the noise can be removed from the image. For the enhanced object produced using equation (7), the ringing is assumed to be noise. Thus, for a specified threshold level, the ringing introduced by the regularization is ideally removed from the enhanced object, leaving only the necessary information to satisfy equation (3).

The final step in the algorithm is to apply contrast enhancement to the denoised version of *EO*. HOWARD employs the contrast enhancement method proposed by Alonso et. all [4]. We refer the reader to [4] for a detailed description of the contrast enhancement algorithm. Fig. 3 summarizes the HOWARD algorithm.

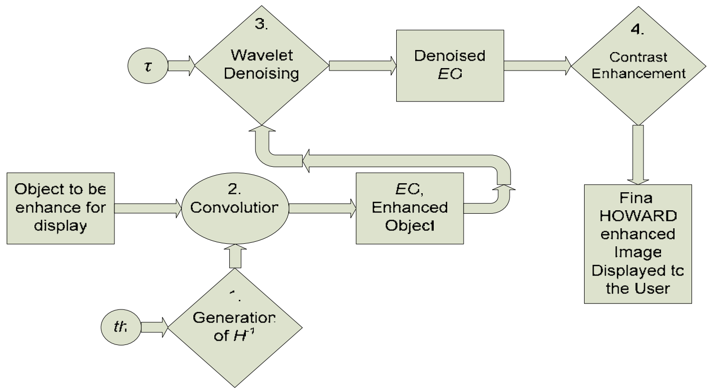

Fig. 3. Summary of the HOWARD algorithm. 1. H^{-1} is generated using the desired threshold, th, and the user's unique wavefront aberration function given in the form of Zernike polynomials. 2. The Object to be enhanced for the user is convolved with H^{-1}. 3. Wavelet denoising is applied to the *EO,* image to produce the denoised version of *EO*. 4. Then contrast enhancement is applied to yield the final, HOWARD enhanced image to be displayed to the user.

4 Considerations for the verification of the method

The HOWARD algorithm derives its ability to enhance objects on the graphic display from knowledge of the wavefront aberration function of each user. In order to test the validity of the compensation, an assessment of the image quality perceived by the user is needed to verify the enhancement. Evidently, we do not ordinarily have access to the image that forms on the retina of the user. Thus, in order to provide verification of HOWARD, we expanded upon previous work [2] on developing an artificial eye that can: 1) be measured on a wavefront aberrometer, and 2) provide image capture to verify the processing. The scope of the remaining portion of the paper is dedicated only to this form of validation of HOWARD with example images demonstrating results from the HOWARD algorithm.

A high resolution PixeLINK A782, 6.6 mega-pixel camera was used to capture experimental images through a compound lens composed of a 72mm focal length plano-convex lens, a 10mm adjustable iris, and a 90mm achromat lens, mounted in a standard c-mount lens mount (Edmund Optics). High-Order aberrations were achieved by layering a UV cured Optical Adhesive with a non-uniform surface approximately 0.2mm thick. This created high order aberrations approximately commensurate with those found in some aberrated human eyes. This setup allows images to be captured at 6.6 mega-pixels, while simultaneously providing a measurable, high-order wavefront aberration function.

Lastly, because wavefront aberrometers measure the wavefront aberration function using approximately parallel light rays for viewing conditions [12],[7], the PSF they measure simulates how an object at infinity would appear to the user. Most graphic displays are intended for much shorter distances (~ 50 cm). Thus, an adjustment of the measured Zernike polynomials is necessary to accurately simulate near vision. This is achieved by re-referencing the wavefront from a plane wavefront, to a wavefront that originates at a finite distance from the user.

5 Results

Examples using the digital image of a letter from a standard Early Treatment Diabetic Retinopathy Study (ETDRS) eye test chart are shown in fig. 4. Two display images are used, one un-enhanced, and the other enhanced by HOWARD. Each image is then captured through the high-resolution artificial eye with the high-order wavefront aberration function and corresponding PSF, as shown in fig. 4.

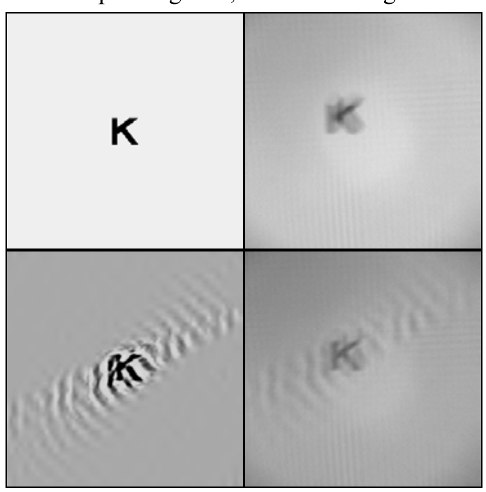

Fig. 4. Top Left- Original Display Object. Bottom Left- HOWARD Enhanced Object. Top Right- Original Display Object captured through the artificial eye. Bottom Right – HOWARD Enhanced Object captured through the artificial eye.

6 Conclusion

In this paper, we propose an efficient method, the High-Order Wavefront Aberration Regularized Deconvolution (HOWARD) algorithm that creates custom enhanced objects for computer users with high-order aberrations in their visual system. The motivation for this stems from the fact that high-order aberrations are not correctable using current ophthalmic methods, making the use of PCs through graphical displays difficult for users with these types of refractive errors. Additionally, existing methods to provide enhancement of vision for high-order wavefront aberrations are costly and inaccessible for the average user.

Upon further development, software-based custom pre-compensation approaches, such as HOWARD, may provide users with otherwise uncorrectable high-order refractory aberrations a way to use GUIs more efficiently in their interaction with computers.

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