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Vision Correction for Computer Users Based on Image Pre-Compensation with Changing Pupil Size

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Abstract—**Many computer users suffer varying degrees of visual impairment, which hinder their interaction with computers. In contrast with available methods of vision correction (spectacles, contact lenses, LASIK, etc.), this paper proposes a vision correction method for computer users based on image pre-compensation. The blurring caused by visual aberration is counteracted through the pre-compensation performed on images displayed on the computer screen. The pre-compensation model used is based on the visual aberration of the user's eye, which can be measured by a wavefront analyzer. However, the aberration measured is associated with one specific pupil size. If the pupil has a different size during viewing of the pre-compensated images, the pre-compensation model should also be modified to sustain appropriate performance. In order to solve this problem, an adjustment of the wavefront function used for pre-compensation is implemented to match the viewing pupil size. The efficiency of these adjustments is evaluated with an "artificial eye" (high resolution camera). Results indicate that the adjustment used is successful and significantly improves the images perceived and recorded by the artificial eye.**

Index Terms—**Vision Correction, Point Spread Function (PSF), Deconvolution, Pupil Size, Wavefront Transformation.**

I. INTRODUCTION

VISUAL perception in humans can be described as a process that transmits image information from the physical world to the brain by sensing the intensity and color of light. It is a critical means to acquire knowledge since it provides us with rich and direct information about our surroundings. A good visual perception is also necessary for Human-Computer interaction. However, the human eye may have imperfections, which include various visual aberrations. If uncorrected, these aberrations will cause the image formed on the user's retina to be blurred or distorted. Therefore, without vision correction, it will be difficult for these users to interact with computers efficiently. Traditionally, vision correction is mainly achieved by spectacles and contact lenses. Laser vision correction, such as LASIK and LASEK, has also become popular recently. However, spectacles and contact lenses are only effective to correct low-order aberrations, and laser vision correction needs to change the shape of the cornea permanently to compensate the overall aberration of the human eye. All these vision correction methods achieve the correction by changing characteristics of the optical path between the object viewed and the retina. In this paper, a vision correction method in which the correction takes place at the source of a computer image is proposed. Aiming to improve the visual performance of computer users with visual impairments, this method achieves the correction by performing pre-compensation of the images before they are displayed on the computer screen. The pre-compensation is performed to counteract the blurring and distortion caused by visual aberrations in the user's eye and seeks the perception of undistorted images by the user.

The pre-compensation model used in this method is based on the visual aberration of the user's eye, which can be measured by a wavefront analyzer. However, the aberration measured is associated with one specific pupil size. This is because the aberration is usually represented as a set of Zernike coefficients which must be defined on a specific radius. However, in practice the pupil size of a human eye may vary due to accommodation or the change of illumination. In addition, pupil size also depends on other factors such as emotional factors and attentional factors [1], [2]. Therefore, the pre-compensation model can be inaccurate if it is based on a constant pupil size. Thus, readjustment of the pre-compensation model is necessary to ensure the model is matched to the pupil size at viewing. A number of approaches [3], [4], [5] have been developed to recalculate the new set of Zernike coefficients when the pupil size changes. In this paper, the transformation method proposed by Campbell [5] is used to adapt the pre-compensation model from the original one to a new one corresponding to a new pupil size. We also test the efficiency of this adaptation using an "artificial eye" implemented with a high resolution camera.

A. Wavefront Aberration

Most human eyes have varying degrees of aberration. The wavefront aberration function, used to describe the refraction characteristic of the eye, is defined as the difference between the actual aberrated wavefront and the ideal spherical wavefront of light coming into the eye. Any wavefront aberration will degrade the resulting retinal images.

B. Zernike Polynomials

The wavefront aberration is usually decomposed into a set of basis functions and represented as a set of coefficients. The value of each coefficient indicates the amount of that particular aberration (e.g., defocus, astigmatism, coma, etc.). The most popular set of basis functions to represent wavefront aberration is the Zernike polynomials. The

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wavefront aberration function can be represented by Zernike polynomials as:

$$W(\rho,\theta)=\sum_{i=0}^{\infty}c_i Z_i(\rho,\theta) \tag{1}$$

where c_i represent the Zernike coefficients and $Z_i(\rho,\theta)$ represent the corresponding Zernike polynomials. In practice, a wavefront analyzer measures the wavefront aberration of a human eye and reports it as a set of Zernike coefficients.

C. Point Spread Function

Any object, when viewed by any optical system, including the human eye, can be considered as a two-dimensional array of point sources with variable intensity. The image mapped by the optical system for a point source is called the point spread function (PSF), which is analogous to the two-dimensional impulse response function of the imaging system. The PSF can be derived from the wavefront aberration function and other eye parameters, through Fourier transformation [6]. The process of forming a retinal image can be represented by the convolution of the object image and the PSF.

II. PRE-COMPENSATION ALGORITHM

The purpose of pre-compensating the images to be displayed on the screen is to counteract the blurring and degradation caused by visual aberrations of computer users. Our method achieves this pre-compensation through deconvolution.

A. Deconvolution

Deconvolution is commonly used to restore the original image from a degraded image with a known degradation model. However, instead of applying deconvolution to a degraded image, deconvolution here is to be implemented at the source of the image.

In the context of our vision correction for computer users, images are displayed on the computer screen. Due to the visual aberration of users, images perceived by them will be degraded, in a way described by the known PSF of their eyes. Let us say an image $O(x,y)$ is degraded by the PSF of the user's vision system which is represented as $PSF(x,y)$, resulting in a blurred image on the user's retina $I(x,y)$. This can be described as a convolution process:

$$I(x,y)=O(x,y)*PSF(x,y) \tag{2}$$

The optical transfer function (OTF), another important function for describing visual performance, is calculated by applying the Fourier Transform to the PSF as:

$$OTF(fx,fy)=F\{PSF(x,y)\} \tag{3}$$

Therefore, in order to remove the degradation introduced by the PSF, the frequency-domain representation of the pre-compensated image, $RD(fx,fy)$, should be calculated as:

$$RD(fx,fy)=\frac{O(fx,fy)}{OTF(fx,fy)} \tag{4}$$

Accordingly, the pre-compensated image to be displayed on the screen $RD(x,y)$ can be obtained through inverse Fourier Transform:

$$RD(x,y)=F^{-1}\left\{\frac{O(fx,fy)}{OTF(fx,fy)}\right\} \tag{5}$$

However, the formula shown in (5) is not practical since noise distortions will result when the value of $OTF(fx,fy)$ is close to zero. Additionally, the OTF derived from a measured wavefront aberration may deviate from the actual one due to measurement error. Thus, regularization is introduced to solve this problem as:

$$RD(fx,fy)=\frac{O(fx,fy)}{OTF(fx,fy)}\frac{|OTF(fx,fy)|^2}{|OTF(fx,fy)|^2+K} \tag{6}$$

where K is the regularization parameter that limits the amplification of unknown noise components, $N(x,y)$. Therefore, the expected retinal image formed after pre-compensation can be considered as:

$$P(x,y)=F^{-1}\{RD(fx,fy)OTF(fx,fy)+N(fx,fy)\} \tag{7}$$

In practice, the image displayed on the screen to be viewed is $RD(x,y)$ which can be obtained by applying Inverse Fourier Transform to $RD(fx,fy)$. From (6), it is easily found that $RD(x,y)$ always has a wide range. Therefore, for displaying on the computer screen, values of $RD(x,y)$ need to be shifted to the intensity range that the display terminals are able to manipulate [7]-[10]. Unfortunately, during this shift process, the image will lose part of its contrast.

B. Pupil Size of Computer Users

When the aberration of the human eye, represented as a set of Zernike coefficients, is calculated, the pupil size in which the Zernike coefficients and functions are defined must be specified. Therefore, the pre-compensation introduced above is strictly associated with a particular pupil size. However, in practice the pupil size of the human eye is quite sensitive to illumination. Once the ambient illumination increases, the pupil may quickly constrict. It has been reported [11] that the mean pupil size of 250 volunteers under room light was 3.86mm and in near-total darkness was 6.41mm.

C. Readjustment of Pre-compensation

If the user's pupil size at the time of viewing the images is the same as the pupil size during the measurement by the wavefront analyzer, the pre-compensation model can maintain its performance without readjustment. Otherwise the pre-compensation model should be adjusted. In this paper, the transformation method proposed by Campbell is used to recalculate the Zernike coefficients and rebuild the pre-compensation model from the original one to the new one corresponding to the current (viewing) pupil size.

The basic idea in Campbell's method is that the same area of a surface will be described by different sets of Zernike coefficients if a different aperture radius is used to find the coefficients. With the information available only in the form of a set of Zernike coefficients related to a given aperture radius, Campbell developed a conversion matrix $[C]$, that will properly convert the vector of one Zernike coefficient set $|c\rangle$ corresponding to an original aperture radius to the vector of another Zernike coefficient set $|c'\rangle$ corresponding to a new aperture radius as:

$$|c'\rangle = [C]|c\rangle \tag{8}$$

The conversion matrix $[C]$ is derived as [5]:

$$[C] = [P]^T [N]^{-1} [R]^{-1} [\eta][R][N][P] \tag{9}$$

where the "T" and "-1" superscripts mean matrix transposition and inversion respectively. Besides, $[P]$ represents the permutation matrix, $[N]$ indicates the normalization matrix, $[R]$ indicates the weighting coefficient matrix and $[\eta]$ indicates the powers of ratio matrix [5].

It must be noted that attempting to reshape the aberration at a pupil size that is larger than the measured one is not feasible since the aberration information outside the measured pupil area is unknown. In our context, this is not a problem as the aberration measurement is always conducted under dark illumination while computer users usually view the screen under regular room light.

III. RESULTS AND DISCUSSION

In this preliminary work, an "artificial eye", implemented with a high-resolution camera (PixeLINK A782, 6.6 mega-pixels) with adjustable focal length and aperture, is used to simulate the human eye of computer users. This makes it possible for us to evaluate the results in an objective manner since the image formed by the artificial eye can be accessed directly for viewing and for objective quality evaluation. For our tests, the defocus aberration of a human eye is simulated by adjusting the focal length and the pupil size variation is simulated by modifying the camera aperture size.

For our experiment, two pictures, one with text and the other with an icon, are used as the source images displayed. First, the camera was oriented to view the pictures displayed on screen. Fig. 1 shows the images captured by the camera with proper focusing (no aberration is simulated). Next, the focal length of the camera was increased by the adjustment of the focusing barrel. This generates an aberration similar to the defocus aberration of the human eye. The blurred pictures captured by the camera with the defocus aberration in place are shown in the first column of Fig. 3. Based on the aberrations of the defocused camera measured in a wavefront analyzer, the pre-compensation is performed on the original images. Fig. 2 demonstrates the results after the initial pre-compensation. Then the defocused camera is pointed to view these pre-compensated pictures. The images captured at this time are shown in the second column of Fig. 3. As expected, these images exhibit more details and sharper edges than those in the first column.

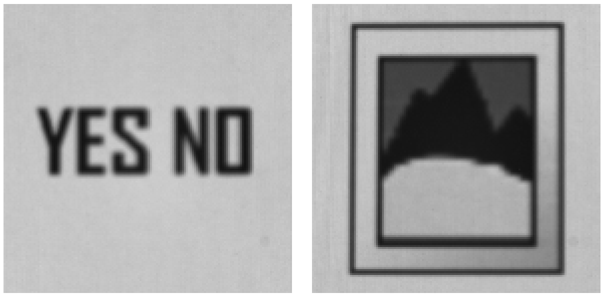

Fig. 1. Images captured by the correctly focused camera.

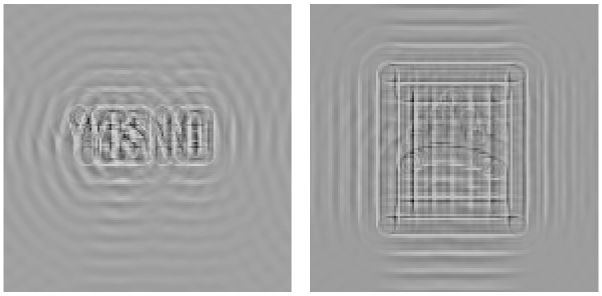

Fig. 2. Images pre-compensated to be displayed on screen.

For the steps described above, the aperture of the camera was kept fully opened and constant. Thus no readjustment of the pre-compensation model was needed. In order to verify the need for readjustment of the pre-compensation model when the pupil size changes, the aperture radius of the artificial eye was then constricted to 65% of the original one. The constriction amount here is well within the range possible for a human eye. After that, without any other changes, the camera is oriented to view the display images that were pre-compensated based on the original model. The images captured in this fashion are significantly distorted, which proves that the original model is not appropriate anymore. This is illustrated in the third column of Fig. 3. At this point, the measured Zernike coefficients are transformed through (8) to new ones which correspond to 65% of the original aperture radius. The PSF used for compensation is recalculated and the pre-compensated model is rebuilt based on the new Zernike coefficients yielding new pre-compensated images. Finally, the images captured when the camera is used to view these new pictures, which are pre-compensated by the adjusted model, are shown in the fourth column of Fig. 3. In them the distortion caused by inappropriate pre-compensation model disappeared although

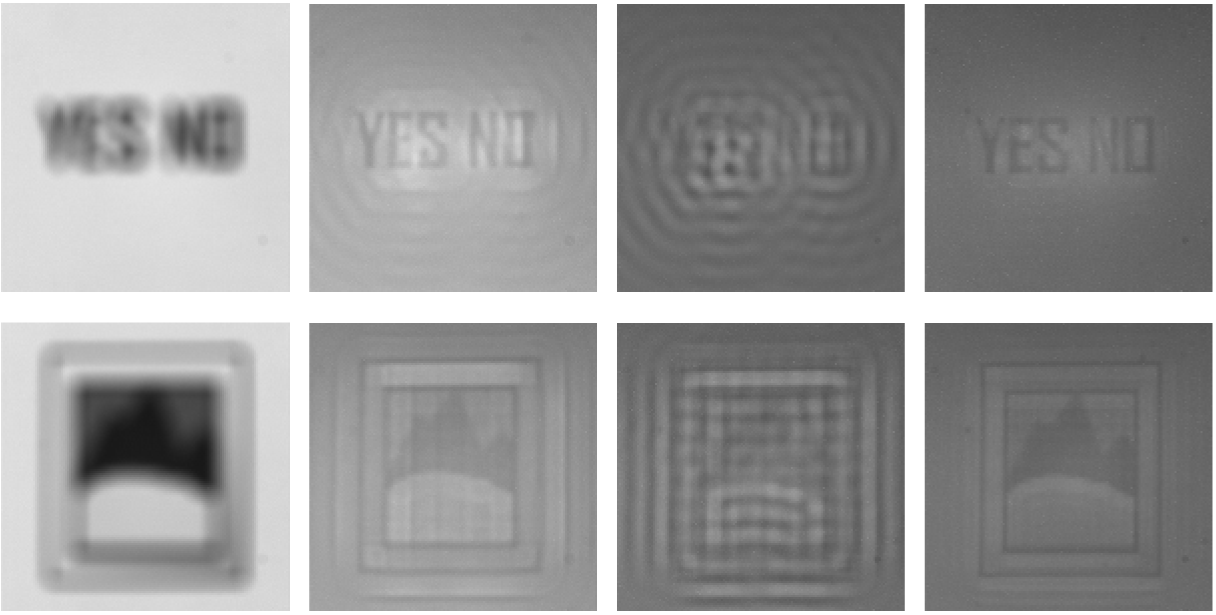

Fig. 3. First column: images captured by defocused camera without pre-compensation. Second column: images captured by defocused camera with pre-compensation. Third column: images captured by defocused and aperture-constricted camera with unadjusted pre-compensation. Fourth column: images captured by defocused and aperture-constricted camera with readjusted pre-compensation.

these captured images are darker than the ones in the second column. This is because the constricted aperture reduces the amount of light reaching the imaging device of the camera.

IV. CONCLUSION

In order to improve the visual perception of computer users with visual aberrations, this paper proposes a correction method based on image pre-compensation. The pre-compensation model used is adjusted according to the pupil size of computer users during viewing to avoid the degradation of the correction process that would occur otherwise. Experiments conducted with an "artificial eye" (high resolution camera with adjustable iris) showed that images captured by the artificial eye are significantly improved when the images displayed on the computer were pre-compensated using Zernike coefficients adapted to the correct viewing pupil diameter. Our next efforts will focus on the online implementation of this adaptation of the pre-compensation model based on real-time measurements of the pupil diameter of human viewers that are obtained from an eye gaze tracking system.

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