SOFTWARE-BASED COMPENSATION OF VISUAL REFRACTIVE ERRORS OF COMPUTER USERS

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ABSTRACT

For human beings, vision is one of the most important senses in interacting with the surrounding environment, as well as with any tools that require visual communication. As such, the ability to interact effectively with computers through typical graphic user interfaces (GUIs), is greatly affected by any refractive errors present in an individual's visual system. If the refractive errors can be mathematically modeled, a system for overcoming these aberrations can be devised, increasing effective human-computer interaction for these individuals. Several methods, such as Adaptive Optics, have been proposed that attempt to solve this problem using electro-mechanical devices. These methods are costly and impractical, preventing most visually impaired individuals from benefiting from their use. In contrast, an image-processing method, based on deconvolution techniques, has recently been proposed for the pre-compensation of images to be displayed in a computer. This method is much more practical, being completely implemented in software, and has achieved encouraging results. Previous results have yielded an average 50% increase in visual efficiency in the compensation of a known artificial aberration introduced into the field of vision of experimental subjects. This paper describes the difficulties encountered with the present software-only compensation and proposes several methods for overcoming these obstacles. The difficulties, as well as the proposed solutions, are described theoretically and followed by examples using a lens system showing the improvement over previous methods.

1. INTRODUCTION

Humans commonly interact with computers through an input/output system consisting of a mouse/keyboard and a visual display, usually a cathode ray tube (CRT) or a liquid crystal display (LCD). Most of the output of the personal computer to the user is in the form of visual information consisting of images, text, or a combination of both. Consequently, the ability to reasonably interpret the information presented in the Graphic User Interfaces (GUIs) directly impacts a human being's ability to use computers effectively. This paper specifically addresses human-computer interface issues in compensation for errors present in the refractive component of the visual system described by the eye's Point Spread Function (PSF).

When refractive errors are present in a user's visual system, the result is a loss of visual acuity, which is an important requirement for basic interaction with the PC [6]. The most common types of refractive aberrations are myopia, hyperopia, and astigmatism. Developments in ophthalmology during the last century have contributed methods of correction, such as contact lenses, glasses, and recently, Laser-Assisted In Situ Keratomileusis (LASIK) surgery. Although very effective, these forms of correction however only apply to these common aberrations and are not suited to deal with high-order aberrations such as keratoconus [8].

Several other attempts have been made at correcting these high order aberrations [5, 7, 11]. These approaches, however, are bulky and require very expensive custom equipment. Although these methods are effective, their complexity and high cost render them impractical for everyday use [1]. Recently, an all-digital solution has been proposed [1] for the correction of visual limitations. This approach is based on applying image processing modifications on the image to be displayed on-screen before it is shown to the user, and assume the knowledge of his/her PSF. Because this method is based on knowing the mathematical representation of the refractive error, it should apply equally well to both low-order (e.g. myopia, hyperopia, etc.) as well as high-order (e.g. keratoconus) aberrations.

The aim of the pre-compensation proposed in this paper is essentially the same; "modify the intended display image in a way that is opposite to the effect of the wavefront aberration of the eye. Once this is achieved, the result is displayed to the viewer so that the wavefront aberration in the viewer's eye will "cancel" the pre-compensation, resulting in the projection of an undistorted version of the intended image on the retina"[3]. The method proposed here, however, overcomes some of the limitations of the previous attempt at an all-digital software solution. The paper is organized as follows: We begin by summarizing the current research and analyzing the limitations encountered. The inverse processing using the PSF is summarized, followed by the description of an improved version of the Weiner filter and post- processing for contrast enhancement of the pre-compensated images. Results using a known aberration introduced by a lens follow, along with the Discussion, and Conclusion.

1.1 Current research

The human eye is an imaging system and behaves in a manner similar to any type of imaging system composed of lenses [10], i.e., it should form an image at it's effective focal length. Any object, when being viewed by the eye, can be thought of as a two-dimensional array of points of varying intensity [12]. Thus, for an eye free of aberrations, each point in the object is represented as a point on the retina. When a human views a computer screen, each pixel can be thought of as a point-source of light, and the corresponding image of that pixel is projected onto the retina [1]. If the eye is unable to project a point source of light onto the retina as a corresponding point, the result is a broad Point Spread Function (PSF).

The PSF of the human eye can be found indirectly through what is known as the wavefront aberration function, which represents the deviation of the light wavefront from a purely spherical pattern as it passes the pupil on its way to the retina [9]. The relationship between the object, (i.e. the digital display device) and the image projected on the retina is described by convolution [9, 10]. Under these same assumptions, the object could be reconstructed from a degraded retinal image through convolution with the inverse PSF. This inverse process is referred to as "deconvolution". If this deconvolution is applied to the undistorted image, a "pre-compensated" image will be created. When viewed through the PSF, this pre-compensated image will be projected onto the retina, free of distortion [1].

The entire sequence of convolution and pre-compensation using the methods described in [3] assumes that the object displayed to the user is in fact a digital image that can be presented on a digital display. The PSF is a spherical aberration, or defocus. There are however two unwanted side –effects of the processing in the final, "distortion free", retinal projection: the apparent loss of contrast and the introduction of low-frequency artifacts.

1.2 Contrast loss

The performance of this approach is ultimately influenced by the ability of the computer monitor to accurately reproduce the required intensities. Given that all digital displays can only reproduce positive intensities in the range of [0, 255], a suitable adaptation to the method must be implemented.

The direct result of using the method described by [3] produces a pre-compensated image that contains both negative and positive values. The solution explored in [2] is to shift and scale the intensity values to lie in a range of [0 1], or for display on a digital screen, [0 255]. This can be accomplished using equation 1:

$$PCS = \frac{\left(PC - \min(PC)\right)}{\max\left(PC - \min(PC)\right)} \cdot 255 \tag{1}$$

where PC is the pre-compensated image generated using equation 11 (from [2]), min and max are the absolute minimum and maximum of the pre-compensated image, respectively, and PCS is the scaled pre-compensated image. However, this shifting and scaling of the pre-compensated image results in an evident reduction of its contrast.

1.3 Low frequency artifacts

Additionally, this form of pre-compensation introduces unwanted low frequency artifacts that will hinder any attempts at post-processing the pre-compensated image to enhance its contrast. Those artifacts will be disproportionately amplified by the contrast enhancement transformations. Using straight deconvolution to achieve the pre-compensation involves dividing the Fourier transform of the Object by the Fourier transform of the PSF. For values of the PSF near zero this will produce disproportionately high amplitude noise at the frequencies where these small values of the Fourier transform of the PSF occur.

The remedy is to use the Weiner filter approach, which provides for a parameter K that can be adjusted to minimize the impact of these rogue frequencies [2, 4]. This constant value K works well for high frequencies, but does not adequately provide control of lower frequency artifacts. Therefore, a constant K will not produce the ideal result: having a pre-compensated image that is free of the unnecessary low-frequency artifacts while preserving the necessary frequencies that will allow the object to be perceived without blur by the user.

2. METHODS

2.1 Modified Weiner Filter

The Weiner filter is traditionally used in the presence of Gaussian noise. The parameter K should ideally represent the spectrum of the signal to noise ratio. But often, the noise is not well characterized, and its spectrum cannot be estimated. Thus, a constant value can be used in place of the spectrum of the signal to noise ratio [4], yielding acceptable results, [2] and [1]. If instead, a variable value of K, based on frequency, is used, it is possible to reduce the introduction of noticeable low-frequency artifacts that are unavoidable with a constant K. As K approaches zero, the deconvolution using the Weiner filter converges to the ideal inverse filter [4]. Similarly, as the value of K increases, the effect of zeros in the PSF diminishes. The drawback of increasing the value of K is that the ideal inverse PSF is less accurate as the value of K increases.

In order to provide for a more accurate inverse PSF, while simultaneously reducing the appearance of low-frequency artifacts, a compromise between the values of K at high-frequencies and low-frequencies must be implemented.

In order to achieve this, a K that varies smoothly according to frequency can be proposed:

$$K(f\theta, fR) = \begin{cases} a \cdot b \cdot e^{-\alpha R} + b & fR \neq 0 \\ 0 & fR = 0 \end{cases} \tag{2}$$

with

$$fR = \sqrt{fx^2 + fy^2} \tag{3}$$

and

$$f\theta = \tan^{-1}\left(fy/fx\right) \tag{4}$$

where *fr* and *fθ* represent the frequency in polar coordinates, assuming that the zero frequency is in the center of the spectrum, a is the span of K and b is the baseline value of K.

The value of K, at zero frequency is zero allowing the deconvolution at zero frequency to be ideal. For frequencies other than zero, K is equal to a decaying exponential function that varies with frequency, ranging from 0.0009 for low frequencies, and approaching an asymptote at 0.0001. The steepness of the decaying exponential is controlled by the parameter α. Notice that the value of K remains fairly constant from fs/8 to fs/2. This preserves the high frequency deconvolution with a value of K=0.0001. For low frequencies, however, the value begins to increase as the frequency decreases towards zero. This has the effect of toning down the low-frequencies in relation to all of the other frequencies.

2.2 Single sided contrast enhancement

While the use of a frequency varying K eliminates the low-frequency artifacts, the issue of the contrast loss still remains. A traditional histogram equalization method can be used, but it is too general. A better solution would be to incorporate knowledge of the original digital image and use that information to do post-processing contrast enhancement. This idea was implemented in the contrast enhancement proposed in [2] in processing the image of a white letter on a black background. The idea is to separate the letter from the background in the pre-compensated image. Once this separation takes place, the background is then replaced by the background in the original image. Although this method provided some contrast enhancement, it introduced a 'halo' around the final simulated retinal projection [2].

The shifting and scaling procedure was found to affect only the DC value (in the shifting) and the amplitudes of the non-zero frequencies uniformly (in scaling). This can be used to aid the contrast enhancement. This can be used to change the amplitude and DC of the pre-compensated image in order to aid in the contrast enhancement process. Ideally, the intensity of the background of the pre-compensated image should be somewhere near the intensity of the background in the original image. Thus, once the pre-compensated image is generated, it can be shifted and scaled in such a way that the mean is a gray level closer to the original background gray level. It is not advisable to replace exactly the background gray level of the original image because if the gray level is for instance white (as in figure 1-a) the remaining values of the pre-compensated image that lie above the mean would be shifted to values that are larger than 255, which cannot be displayed.

Since the restoration of acuity is governed by non-zero frequencies, the transients in the pre-compensated image should be preserved through the entire contrast enhancement process. Thus, a one sided, or single-sided method of contrast enhancement can improve the contrast, while preserving the non-zero frequencies.

This can be implemented as follows:

$$s(r)=\begin{cases} r & r>l \\ \dfrac{1-e^{-\beta\left(\frac{r-u}{l-u}-1\right)}}{1+e^{-\beta\left(\frac{r-u}{l-u}-1\right)}}\cdot l+l & r\leq l \end{cases} \tag{5}$$

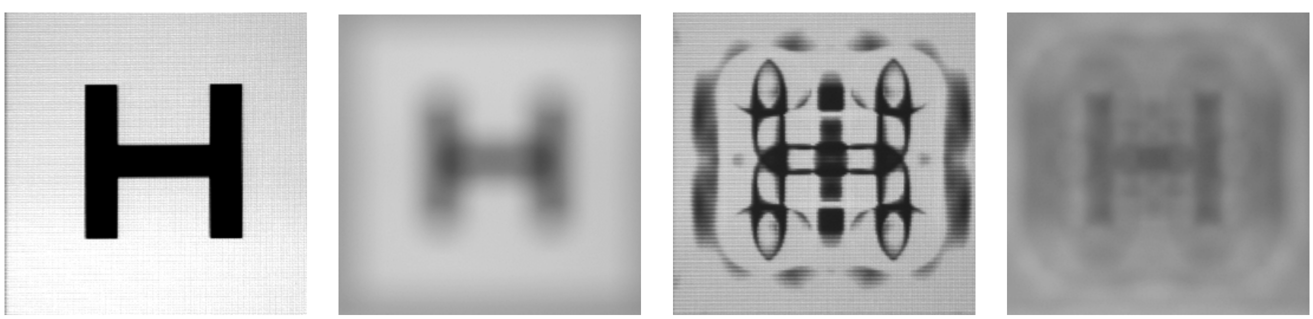
where s(r) is the transformed gray level, r is the original gray level, β is the parameter controlling the steepness of the transformation, l is the threshold level, and u is the minimum value of the pre-compensated image after it has been shifted and scaled to have a mean near the background gray level. In brief, this transformation essentially raises the background level of the pre-compensated image close to white.

Notice that for gray levels above l, the transformation is a one to one transference, but for gray levels that lie below l, the negative half of a bipolar sigmoid function is used. This allows for a smooth, controlled gray level transformation.

The values for β, l, and u will depend on the pre-compensated, scaled and shifted image. The value of l should be sufficiently below the mean of the pre-compensated, scaled and shifted image so as to minimize the transformation of unwanted low-frequency noise.

3. RESULTS

Figure 1 shows the pre-compensated images and projected retinal images when both the enhance Weiner filter, and the single-sided contrast enhancement algorithms are applied to the original letter 'C'.



(a)(b)(c)(d)

Figure 1. (a) Image of Letter H (b) Figure 1-a as seen through a spherical aberration introduced into the field of view of a 6 mega-pixel camera (c) Image of Pre-compensated Letter H (d) Figure 1-c as seen through a spherical aberration introduced into the field of view of a 6 mega-pixel camera

DISCUSSION

Figure 1-a shows the reduction of the low-frequency artifacts that the normal Weiner filter introduces. This reduction is a pre-requisite for post-processing to increase the contrast of only areas that have transients present. Once this image is generated, it is then shifted and scaled to a mean value near white. For the images in figure 1, the shifting and scaling produced a pre-compensated image with the mean

gray level at 222, the maximum at 255, and the minimum at 195. This image was then processed using the single-sided contrast enhancement algorithm with $\beta=10$, $l=195$, and $u=221$. Figure 1-c is a simulation of the resulting projected retinal image that a user having a spherical aberration (defocus) would perceive when viewing Figure 1-b.

CONCLUSIONS

The results shown above have illustrated the potential of the image pre-compensation approach proposed to revert the degradation on the perception of images presented on digital displays. Improvements on the Weiner filter along with the proposed gray level transformation resulted in higher contrast in the final retinal image than with prior research. The next stage of our work will use the methods developed to generate the pre-compensation for participants with targeted visual impairments, particularly those of high-order. This will allow verification of the general applicability of the algorithms. We foresee that this pre-compensation approach will be applicable to users with severe refractive errors whose individual wavefront aberration functions are known.

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