FLORIDA INTERNATIONAL UNIVERSITY

Miami, FL

PROPOSAL FOR DISSERTATION

DOCTOR OF PHILOSOPHY IN ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

Miguel Alonso Jr.

2005

I propose to the Major Professor and to the Committee Members a study of the following topic to be conducted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering: A METHOD FOR ENHANCING DIGITAL INFORMATION DISPLAYED TO COMPUTER USERS WITH VISUAL REFRACTIVE ERRORS VIA SPATIAL AND SPECTRAL BASED PROCESSING

*General Statement of Problem Area*

Normal visual acuity is a pre-requisite for proper usage of most contemporary Graphic User Interfaces (GUIs). Advances in the computer industry have made computers pervasive in our daily life. The common interface for humans to use computers is via visual information, presented on a digital display, such as a cathode ray tube (CRT) or a liquid crystal display (LCD). Consequently, the user's ability to interpret the information presented in the GUIs directly impacts his/her ability to use computers effectively. Persons with limited visual acuity cannot interact properly with GUIs. Visual acuity loss is usually attributed to the three most common forms of visual aberrations: myopia, hyperopia, and/or astigmatism. There are simple approaches, such as contacts, lenses, or even surgery that can easily correct these visual aberrations, allowing the person to regain some or all of the visual acuity loss. Although very effective, these forms of correction only apply to these common aberrations. There exist, however, more complex aberrations that cannot be easily remedied by such means [13]. The point spread function (PSF) is a mathematical model for the visual system and its knowledge allows the simulation of how digital images are viewed by the person. Consequently a method for providing software based compensation can be formulated. In this project, an all digital pre-compensation approach is sought. In contrast with the optical corrections mentioned above, this approach is based on modifying the image at its source, i.e., applying image processing modifications on the image to be displayed on-screen before it is shown to the user, based on the knowledge of his/her own wavefront aberration function (WAF), currently assessable through wavefront analyzers.

*Research Purpose*

The aim this research is to 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. Furthermore, the pre-compensation proposed here overcomes some of the limitations of a previous attempt at an all-digital, software solution.

*Research Problem*

The Research Problem has two main facets:

1. To characterize a fixed and known optical system and provide the compensation for that optical system
2. In order to test the significance of the compensation, characterize several human eyes and provide a custom compensation for each eye, based on the PSF.

Before any of type human subject testing can be carried, it is imperative to test the proposed system of "pre-compensation" in fixed and controlled environment. This will verify the conceptual integrity of the methods developed before the added complexity of testing with human subjects is implemented. The actual testing of the methods with human subjects will take place at Nova Southeastern University's College of Optometry.

*Significance of Study*

Since the proposed method of pre-compensation is entirely digital, i.e., the method is implemented completely in software, any Personal Computer (PC) with an SVGA graphics card could theoretically be used to deliver the pre-compensation. The only other component necessary is the PSF of the user, which can be obtained through wavefront analysis of the user's eye (currently becoming more and more common in ophthalmologists' and optometrists' offices [9]). With these components in place, the interface will then be customized to the aberration present in the user's visual system, allowing him/her to view the display screen as if there were no aberration present. Additionally, an estimated 7 million people in the United States alone have some type of high-order refractive aberration in their eye(s) [10]. Since compensating high-order aberrations is beyond the scope of traditional optical methods, this research has the potential to benefit those people who suffer from high-order aberrations, allowing them to potentially interact with any type of digital display more effectively.

*Theoretical Perspective and Literature Review*

The human eye is an imaging system and behaves in a manner similar to an imaging system composed of lenses [15], forming an image at their effective focal length. An object, when being viewed by the eye, can be thought of as a two-dimensional array of points of varying intensity [17] projected onto the retina, a light sensitive plane that is normal to the optical axis of the eye. Thus, for an eye free of aberrations, each point in the object plane is represented as a point on the retina. Similarly, 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 [2]. 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), which describes the light distribution on the retina caused by each point of light in the object.

Excessive breadth of the PSF introduces a distortion in the projected retinal image, degrading the usable information. In order to provide the proposed compensation, the PSF of the human eye must be known and its effects should be modeled mathematically in the PC. The PSF can be found indirectly through the WAF, which represents the deviation of the light wavefront from a purely spherical pattern as it passes the pupil on its way to the retina [14]. The instrument used to measure the wavefront aberration of the human eye is termed a wavefront analyzer, which is becoming more and more common in Optometrists' and Ophthalmologists' offices [9]. This enables a person suffering from any type of aberration to obtain their own personal WAF. Pre-compensated digital images for display on their PCs can then be created based on their custom WAF.

The WAF is represented by Zernike polynomials; two-dimensional functions that form a complete orthogonal basis set defined on the unit circle [5, 12]. Modern ophthalmic wavefront analyzers provide an approximation to the WAF measured from the subject as a combination of Zernike polynomials. This characterization of the optics of the eye can be used to determine its PSF and optical transfer function (OTF), thus enabling the implementation of the mathematical pre-compensation concept. Each term in the Zernike basis set corresponds to various commonly termed aberrations in optical system such as piston, tilt, defocus, astigmatism, coma, etc.

The relationship between the object, (i.e. the digital image displayed on the LCD or CRT) and the image projected on the retina is described by convolution [14, 15]. The object could be reconstructed from the degraded retinal image through convolution with the inverse PSF. This inverse process is referred to as "deconvolution". If the deconvolution is applied to the undistorted image, a pre-compensated image will be created. It is hypothesized that, when viewed through the PSF, this pre-compensated image will be projected onto the retina, free of distortion [2]. Previous attempts at correcting these high order aberrations [11, 16] are bulky and require very expensive custom equipment. Although these methods provide some positive results, their complexity and high cost render them impractical for everyday use [2].

*Research Questions and Hypotheses*

| | |
|---|---|
| Question #1 | Will the proposed method for pre-compensation provide an improvement in visual acuity for an artificial eye if its WAF is known a priori? |
| Hypothesis #1 | The proposed method for pre-compensating images will provide an improvement in visual quality. The visual quality metric will be implemented as a numerical measure equivalent to the visual acuity measure for a human subject. It will be implemented as a sum of square of the frequency content of the original image vs. the pre-compensated image, since perceived visual acuity is related to the frequency content of images. |
| Question #2 | Will the proposed method for pre-compensation provide an improvement in visual acuity for human subjects if their customized WAF is known a priori? |
| Hypothesis #2 | The proposed method for pre-compensating images will provide a statistically significant increase in visual acuity as measured by a standard visual acuity test thereby increasing the user's ability to reasonably interpret textual information presented in a GUI. |

*Methods*

In linear systems, the inverse of an impulse response is given by the inverse Fourier transform of the reciprocal of its Fourier transform. It was discovered, however, that for this particular use of the inverse processing, a straight application of the convolution with the inverse does not yield a meaningful pre-compensated image [2]. Using straight deconvolution to achieve the pre-compensation is essentially dividing the Fourier transform of the Object by the Fourier transform of the PSF (the OTF). Values of the

OTF near zero will produce disproportionately high amplitude noise at the frequencies where these zeros occur. Several alternatives for deconvolution were explored, and the only method found to be well suited for this application was the Weiner Filter or Minimum Mean Squared Filter [2-4]. There are however two unwanted side-effects of the processing: the apparent loss of contrast and the introduction of low-frequency artifacts.

*Design and Instrumentation*

*Proposed Improvement to the Pre-compensation Process*

The Weiner filter is typically used in the presence of Gaussian noise. The parameter K in this algorithm should ideally represent the spectrum of the signal to noise ratio. But often, the noise is not known, and its spectrum cannot be calculated. Thus, a constant value can be used in place of the spectrum of the signal to noise ratio [8], yielding acceptable results.

This is the approach taken in [1, 2]. 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.

*Proposed Improvement #1: Spectrally Enhanced Weiner Filter*

As K approaches zero, the Weiner filter converges to the ideal inverse filter [8]. Similarly, as the value of K increases, the effect of very small values in the OTF diminishes. The drawback of increasing the value of K is that the resulting 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. To achieve this, a K that varies smoothly according to frequency is necessary. As part of the work for this dissertation, a spectrally enhanced weiner filter has been developed and is currently being tested.

*Proposed Improvement #2: Single-Sided Contrast Enhancement*

While the use of a frequency varying K should reduce 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 and disproportionately amplifies unnecessary parts of the image. A better solution would be to incorporate knowledge of the original digital image and use that information to do post-processing contrast enhancement. The fact that the shifting and scaling of the pre-compensated image (which is needed for display on a computer monitor) does not affect the non-zero frequencies can be used to aid the contrast enhancement. 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, 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 the focus 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 is necessary. As part of the work for this dissertation, a single-sided contrast enhancement transform has been developed and is currently being tested.

*Proposed Improvement #3: Parameter Minimization*

The inherent processing necessary to achieve a useable pre-compensated image requires several levels of processing, each with several parameters that require manual adjustment. In order to provide a uniform, repeatable experiment, a method for automatically setting the various parameters will be developed based on several automated methods such as neural networks or fuzzy logic.

*Preliminary Results: Physical Emulation and Simulation*

*Artificial CCD Eye*

In order to verify and close the loop of the proposed processing, a method of verifying the results in a physical optical system is necessary. The requirements of the optical system are as follows:

- Interchangeable lenses
- Adjustable Iris
- Adjustable focal length
- Removable CCD Retina
- Simulated Retina (Reflective surface to measure the system in the wavefront analyzer)
- Similar dimensions to a human eye, e.g. focal distance, size of iris, etc.)

A preliminary version of the Artificial CCD Eye has been custom built using various parts from several manufacturers including Edmund Scientific. This eye will be used to provide several testing conditions allowing for variation of several parameters including pupil diameter, focal length, and various types of wavefront aberrations introduced via lenses. The removable CCD retina along with the simulated retina will allow for both objective measurement/characterization of the optical system (i.e. assessment of the WAF of the system via the wavefront analyzer) as well as the ability to 'see' through the optical system via the CCD.

*Simulation Results*

As the development of the original pre-compensation approach progressed, it was found that there are two sources for potential error in the method of processing due to the inherent nature of the measurement device as well as the fact that the human eye is a dynamic optical system. According to Campbell, the defocus term has a very high variability among different wavefront analyzers, making it difficult to predict the actual value for the defocus term in the WAF [7]. Thus, during the testing phase of the dissertation work, a suitable method for varying the defocus from the measured value must be implemented to 'track' the true value of the defocus term for each subject.

Additionally, Campbell states in fact, that the actual WAF Zernike terms vary with pupil diameter for the same optical system [6]. Thus, if there are any variations in the pupil diameter from the time of measurement to the time of the testing, there will be a Zernike term mismatch, degrading or altogether destroying the pre-compensation process. Fortunately, he provides a method for producing a new set of Zernike terms for a given change in pupil diameter. It is thus necessary to build into the testing system a way to account for any variations in the pupil diameter.

*Scope of the Proposed Work*

The dissertation work will occur in the following modules:

- Further Develop the Method of Pre-compensation to improve final projected retinal image
- Develop testing with a fixed and controllable optical system (artificial CCD eye)
- Subject recruitment and testing at NSU
    - Phase 1 and 2
    - Phase 3 and 4
- Subject testing data analysis

Subject recruitment and testing will occur in two main phases each with two sub-phases. For each main phase, 1 and 2, there will be a sub-phase for subject recruitment and wavefront analysis data collection, and a sub-phase for testing visual acuity with the proposed pre-compensation method.

*Data Analysis*

The data analysis will be conducted by using the statistical package SPSS for windows. The data analysis will consists of analysis of the frequency distribution of the subjects score before and after pre-compensation. Additionally, a test of significance will be performed on the data using a matched pair t-test because the statistics of the population of low-vision users is unknown. The assumptions are as follows: the difference of scores before and after the pre-compensation follows a normal distribution with similar variances, and the visual acuity scores are continuous. A Shapiro-Wilk W-test will be performed to verify the normality of the distribution. The matched pair t-test will give a measure as to how much of an improvement is shown by using the method proposed of pre-compensation.

*Project Schedule*

| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Futher Develop of Method | | | | | | | | | | | | | | | |
| Invitro testing and development | X | X | X | | | | | | | | | | | | |
| Subject recruitment | | | | | | | | | | | | | | | |
| Phase 1 | | | X | X | | | | | | | | | | | |
| Subphase 1 DONE | | | | | | | | | | | | | | | |
| Subphase 2 | | | X | X | | | | | | | | | | | |
| Phase 2 | | | | | | | | | | | | | | | |
| Subphase 1 | | | | | X | X | X | | | | | | | | |
| Subphase 2 | | | | | | | | | | | | | | | |
| Data Analysis | | | | | | | | | | X | | | | | |
| Preparation of Dissertation | | | | | | | | | | | | | | | |
| Dissertation Defense | | | | | | | | | | | | | | | X |

*References*


[1] M. Alonso Jr. and A. Barreto, "An Improved Method of Pre-Deblurring Digital Images Towards the Pre-Compensation of Refractive Errors," *WSEAS Transactions on Computers*, vol. 3, pp. 487-492, 2004.

[2] M. Alonso Jr., A. Barreto, J. G. Cremades, and J. A. Jacko, "Image pre-compensation to facilitate computer access for users with refractive errors," *Behaviour and Information Technology Journal*, vol. 24, pp. 161-173, 2005.

[3] M. Alonso Jr., A. B. Barreto, M. Choudhury, and J. A. Jacko, "Software-based Compensation of Visual Refractive Errors of Computer Users," *Biomedical Sciences Instrumentation*, vol. 41, pp. 229-234, 2005.

[4] M. Alonso Jr., A. B. Barreto, J. A. Jacko, M. Choudhury, and M. Adjouadi, "Improving Computer Interaction for Users with Visual Acuity Deficiencies through Inverse Point Spread Function Processing," presented at The 2005 IEEE SoutheastCon Conference, Fort Lauderdale, FL, 2005.

[5] M. Born and E. Wolf, *Principles of optics: electromagnetic theory of propagation, interference and diffraction of light*, 6th ed. New York: Pergamon Press, 1980.

[6] C. E. Campbell, "Matrix method to find a new set of Zernike coefficients from an original set when the aperture radius is changed," *Journal of the Optical Society of America*, vol. 20, pp. 209-217, 2003.

[7] C. E. Campbell, "A Test Eye for Wavefront Refractors," *Journal of Refractive Surgery*, vol. 21, pp. 127-140, 2005.

[8] R. C. Gonzales and R. E. Wood, *Digital Image Processing*. New Jersey: Prentice Hall, 2002.

[9] J. Hjortdal, "Book Review: Wavefront and Emerging Refractive Technology," *ACTA Ophthalmologica Scandanavia*, vol. 81, pp. 681, 2003.

[10] R. Leonard, "Statistics on Vision Impairment: A Resource Manual", 2002.The Lighthouse Inc., from the World Wide Web:http://www.lighthouse.org/downloads/researchstats.pdf.

[11] J. Liang, D. R. Williams, and D. T. Miller, "Supernormal vision and high-resolution retinal imaging through adaptive optics," *Journal of the Optical Society of America*, vol. 14, pp. 2884-2892, 1997.

[12] D. Malacara, *Optical shop testing*, 2nd ed. New York: Wiley, 1992.

[13] J. N. Parker and P. M. Parker, *The official patient's sourcebook on Keratoconus: A revised and updated directory for the internet age*. San Diego: Icon Health Publications, 2002.

[14] T. O. Salmon, "Corneal Contribution to the Wavefront Aberration of the Eye," in *School of Optometry*. Bloomington: Indiana University, 1999.

[15] L. N. Thibos, "Formation and Sampling of the Retinal Image," in *Seeing: Handbook of Perception and Cognition*, K. K. D. Valois, Ed., 2 ed. San Diego: Academic Press, 2000, pp. 1-54.

[16] L. N. Thibos, X. Qi, and D. T. Miller, "Vision through a liquid crystal spatial light modulator," presented at 2nd International Workshop on Adaptive Optics for Industry and Medicine, Singapore, 1999.

[17] R. G. Wilson, *Fourier Series and Optical Transform Techniques in Contemporary Optics: An Introduction*. New York: John Wiley and Sons, Inc., 1995.