Vision-Simulated imaging

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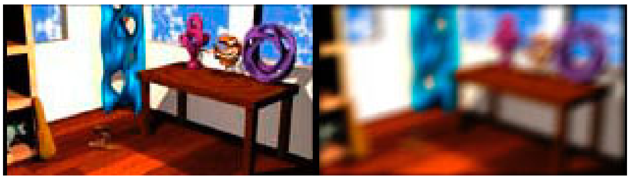
Abstract

Vision-simulated imaging (VSI) is the computer generation of synthetic images to simulate a subject's vision, by incorporating the characteristics of a particular individual's entire optical system. Using measured aberration data from a Shack-Hartmann wavefront aberrometry device, VSI modifies input images to simulate the appearance of the scene for the individual patient. Each input image can be a photograph, synthetic image created by computer, frame from a video, or standard Snellen acuity eye chart -- as long as there is accompanying depth information. An eye chart is very revealing, since it shows what the patient would see during an eye examination, and provides an accurate picture of his or her vision. Using wavefront aberration measurements, we determine a discrete blur function by sampling at a set of focusing distances, specified as a set of depth planes that discretize the three-dimensional space. For each depth plane, we construct an object-space blur filter. VSI methodology comprises several steps: (1) creation of a set of depth images, (2) computation of blur filters, (3) stratification of the image, (4) blurring of each depth image, and (5) composition of the blurred depth images to form a single vision-simulated image.

VSI provides images and videos of simulated vision to enable a patient's eye doctor to see the specific visual anomalies of the patient. In addition to blur, VSI could reveal to the doctor the multiple images or distortions present in the patient's vision that would not otherwise be apparent from standard visual acuity measurements. VSI could educate medical students as well as patients about the particular visual effects of certain vision disorders (such as keratoconus and monocular diplopia) by enabling them to view images and videos that are generated using the optics of various eye conditions. By measuring PRK/LASIK patients pre- and post-op, VSI could provide doctors with extensive, objective, information about a patient's vision before and after surgery. Potential candidates contemplating surgery could see simulations of their predicted vision and of various possible visual anomalies that could arise from the surgery, such as glare at night. The current protocol, where patients sign a consent form that can be difficult for a layperson to understand fully, could be supplemented by the viewing of a computer-generated video of simulated vision showing the possible visual problems that could be engendered by the surgery.

***Keywords**: vision realistic rendering**,** vision simulation, blur, optics, LASIK, PRK, corneal refractive surgery, cornea, visual acuity, visual performance, depth of field, optometry, ophthalmology, wavefront aberrometer, pupil, fovea.*



(left) Image simulating the vision of an aberration-free model eye. (right) Image simulating the vision of a patient with the vision disorder of keratoconus.

1. OPTOMETRY AND OPHTHALMOLOGY

In practice poor visual performance is often attributed to simple blur; however, our technique[1][2] enables the generation of vision-simulated images andanimations that demonstrate specific defects in how a person sees.Such images of simulated vision could be shown to an individual's eye care clinician toconvey the specific visual anomalies of the patient.Doctors and patients could be educated aboutparticular vision disorders by viewingimages that are generated using the opticsof various ophthalmic conditions such as*keratoconus*and *monocular diplopia*.

One of the most compelling applications is in the contextof vision correction using laser corneal refractive eye surgeries such asPRK (photorefractive keratectomy) and LASIK (laser in-situ keratomileusis).Currently, in the United States alone, a million people peryear choose to undergothis elective surgery.By measuring subjects pre-operatively and post-operatively,our technique could be used toconvey to doctors what the vision of a patient is like before and aftersurgery.In addition, accurate and revealing medical visualizations of predicted visual acuity andof simulated vision could be providedby using modeled or adjusted wavefront measurements.Potential candidates for such surgery could view these images to enable them tomake more educated decisions regarding the procedure.Still another application would be to show such candidatessome of the possible visualanomalies that could arise from the surgery, such as glare at night.With the increasing popularityof these surgeries, perhaps the current procedure which haspatients sign aconsent form that can be difficult for a layperson to understand fully could besupplemented by the viewing of a computer-generated animation ofsimulated visionshowing the possible visual problems that could be engendered by the surgery.

2. ALGORITHM

The approach comprises three major components, as follows:

2.1 Constructing Object Space Point Spread Function

A Point Spread Function (PSF) plots the distribution of light energy on theimage plane based on light that has emanated from a point source and haspassed through an optical system.Thus it can be used as an image space convolution kernel.

We introduce the object space point spread function (OSPSF), whichis similar to the usual image space point spread function, asdescribed above,except thatit is defined in object space and thus it varies with depth. The OSPSFis a continuous function of depth; however, wediscretize it, thereby defining a sequence of depthpoint spread functions (DPSF) at some chosen depths.

Since human blur discrimination is nonlinear in distancebut approximately linear in diopters (a unit measured in inverse meters),the depths are chosen with a constant dioptric spacing ΔDandthey range from the nearest depth of interest to the farthest. Atheoretical value of ΔD can be obtained from therelation $\Theta=p\Delta D$, where Θ is the minimum subtendedangle of resolution and p is thepupil size in meters. For a human with 20/20 visual acuity, Θis1 minute of arc; that is, Θ=2.91x10^{-4}.

The DPSFs are histograms of rays cast normal to the wavefront. To compute these functions, we firstplace a grid with constant angular spacing at eachof the chosen depths and initialize counters in each grid cell to zero.Then we iteratively choose a point on the wavefront,calculate the normal direction, and cast a ray in this direction. Asthe ray passes through each grid, the cell it intersects has its counterincremented. This entireprocess is quite fast and millions of rays may be cast in a few minutes.Finally, we normalize the histogram so that its sum is unity.

In general, wavefront aberrations are measured with the subject's eyefocused at infinity.However, it is important to be able to shift focus for vision-simulated imaging.Recent research results in optometry showedthat aberrations change significantly with accommodation.When aberrometric data is available for the eye focused at the depththat will be used in the final image,our algorithm exploits that wavefront measurement.

In the situation where such data is not available, we assumethat the aberrations are independent ofaccommodation. We can then re-index the DPSFs, which is equivalent toshifting the OSPSF in the depth dimension.Note that this may require the computation of DPSFs at negative distances.

We further assume the OSPSF is independent of the image plane location.In optics,this is called the ``isoplanatic'' assumption and is the basis for beingable to perform convolutions across the visual field. For human vision,this assumption is valid for at least several degrees aroundthe fixation direction.

2.2 Fitting a Wavefront Surface to Aberrometry Data

The output of the Shack-Hartmann device comprisesa ray orientation (normal vector)at each lenslet. Current devices yield only 50 to 200 suchvectors. To generate the millions of samples necessary to calculate theOSPSF (see Section \ref{s:OSPSF} above), we first generate a smoothmathematical surface representation of the wavefront from this sparse data.Our wavefrontsurface is a fifth degree polynomial bivariate surface defined asa height field whose domain is the pupil plane.This surface is determined by a least squares fit to the Shack-Hartmann data.

We use a particular polynomial formwhich was developed in 1934 by the Dutch mathematician and physicistFrits Zernike who was awarded the Nobel Prize in Physics 1953 for discoveringthe phase contrastphenomenon.Zernike polynomials are derived from the orthogonalization of theTaylor series. The resulting polynomial basis corresponds toorthogonal wavefront aberrations. The coefficients weightingeach polynomial have easily derived relations with meaningfulparameters in optics.

2.3 Rendering Steps

Given the input image and its associated depth map,and the OSPSF, the vision-simulated imaging algorithm comprises three steps: (1) create a set of depth images,(2) blur each depth image, and (3) composite the blurred depth imagesto form a single vision-simulated image.

Create depth images:

Using the depth information, the image isseparated into a set of disjoint images, one at each of the depths chosen in thepreceding section. Ideally, the image at depth $d$would be rendered with thenear clipping plane set to $d+\Delta D/2$ and the far clipping plane set to$d-\Delta D/2$. Unfortunately, this is not possible becausewe are using previously rendered images and depth maps.Complicated texture synthesis algorithms would be overkill here,since the results will be blurred anyway.The following technique is simple, fast, and works well in practice:For each depth, d, those pixels from the original image that are within$\Delta D/2$ diopters of d are copied to the depth image.

Blur each depth image:

Once we have the depth images, we doa pairwise convolution: Each depth image is convolvedwith its corresponding DPSF, thereby producing aset of blurred depth images.

Composite:

Finally, we composite these blurred depth images into a single, vision-simulated image.This step is performed from far to near, using alpha-blendingfollowing alpha channel compositing rules.

2.4 Elimination of Occlusion and Discretization Artifacts

Although processing in image space allows an increase in speed, the imagesmay have artifacts introduced. This can occur in two ways, which we referto as *occlusion* and*discretization*. The occlusion problemarises because there is scene geometry that is missing. This resultsfrom the finite aperture of the lens, which allowsmore of the scene to be visiblethan would be seen through an infinitesimal pinhole.Thus, without additional input, the colors from parts of the scene that arebehind objects would have to be approximately reconstructed using the bordercolors of visible objects.

The discretization problem occurs fromseparating the image by depth. At adjacent pixels in different sub-images, thecalculation of depth of field is complicated. This arises because theseadjacentpixels may or may not correspond to the same object.An artifact can beintroduced into the image when a single object straddles twosub-images and the sub-images are blurred.The artifact arises when the far pixel is averaged with neighboring colorsbehind the near pixel that do not match the far pixel's color. Theneighboring colors are often black, which is the default backgroundcolor. Consequently, a black blurred band occurs at the intersectionof the object with the separation of the sub-images that it spans.

3. VALIDATION

An important area of future work is validation, and will involve the establishment of psychophysical experiments.

Nonetheless, some preliminary experiments are possible immediately, and our initial results have been positive. First, patients who haveunilateral vision problems can view our simulations of the visionin their pathological eye using their contralateral eye, thereby evaluating the fidelity of the simulation.

Second, consider patients who have vision conditions such as myopia, hyperopia, and astigmatism,that are completely corrected by spectacles or contact lenses.More precisely, in optometry terms, they might have 20/20 BSCVA (best spectacle corrected visual acuity). Such patients could validate thequality of the depiction of their vision in vision-simulated images simply by viewing them while wearing their corrective eyewear.Third, the visual anomalies present in keratoconus are different fromthose in more common conditions such as myopia, and this distinctionis indeed borne out in our example images. Specifically, keratoconuscan cause the appearance of diplopia (double-vision) whereas myopia.

4. CONCLUSION AND FUTURE WORK

We introduced the concept of *vision-simulated imaging* -- thecomputer generation of synthetic images that incorporate thecharacteristics of a particular individual's entire optical system.This paper took the first steps toward this goal, bydeveloping a method for simulating the scanned foveal image from wavefrontdata of actual human subjects, and demonstrated those methods on sample images.First, a subject's optical system is measured bya Shack-Hartmann wavefront aberrometry device. This device outputs ameasured wavefront which is sampled tocalculate an object space point spread function (OSPSF).The OSPSF isthen used to blur input images.This blurring is accomplished by creating a set of depth images,convolving them with the OSPSF, and finally compositingto form a vision-simulated image.Applications of vision-simulated imaging in computer graphics as well as in optometry and ophthalmologywere discussed.

The problem of vision-simulated imaging is by no means solved.Like early work on photo-realistic rendering, our method contains severalsimplifying assumptions and other limitations. There is muchinteresting research ahead.

The first limitationsare those stemming from the method of measurement. The Shack-Hartmanndevice, although capable of measuring a wide variety of aberrations, does nottake into account light scattering due to such conditions as cataracts.The wavefront measurements can have some error, and fitting the Zernikepolynomial surface to the wavefront data can introduce more. However,since the wavefronts from even pathological eyes tend to be continuous,smooth interpolation of the Shack-Hartmann data should not produce anysignificant errors. Consequently, any errors that are introducedshould be small and, furthermore, such small errors would imperceptiblein final images that have been discretized into pixels.

Strictly speaking, the pupil size used for vision-simulated imagingshould be the same as the pupil size when the measurements are taken.However, the error introduced in using only part of the wavefront(smaller pupil) or extrapolating the wavefront (larger pupil) shouldbe quite small. We have made use of three assumptions commonly usedin the study of human physiological optics: isoplanarity,independence of accommodation, and off-axis aberrations beingdominated by on-axis aberrations. Although we have argued that theseassumptions are reasonable and provide a good first-order approximation,a more complete model would remove at least the first two.

As discussed in Section 2.1, we have assumed"independence of accommodation" since aberrometric measurements with theeye focused at the depth is not usually available.However, this is not a limitation of our algorithm.Our algorithm can exploit wavefront data wherethe eye is focused at the depth that will be used in the final image,when such a measurement is made.

We currently do not take chromatic aberration into account, butagain that is not a limitation of our algorithm. Since the datawe acquire is from a laser, it is monochromatic. However, someresearch optometric colleagues have acquired polychromatic dataand will be sharing it with us. It is again interesting thatrecent research in optometry by Marcos [3] showed that except for the low orderaberrations, most aberrations are fairly constant over a range ofwavelengths.

We only compute the aberrations for one point in the fovea,and not for other points in the visual field. However, itis important to note that forcomputer graphics, the on-axis aberrations are criticallyimportant because viewers move their eyes around when viewing ascene. If we had actually included the off-axis aberrations ofthe eye, then the off-axis parts of the scene would have beenimproperly blurred for a person who is scanning the scene. Theoff-axis aberrations are of minor concern even without eyemovements since the retinal sampling of cones is sparse inperipheral vision. The image that we are simulating is formedby viewing the entire scene using the on-axis aberrations becausewe assume that the viewer is scanning the scene.

However, since peripheral vision does makes important contributions to visualappearance, viewers are affected by optical distortions of peripheral vision.Thus, it is of interest to extend this method to properly address theoff-axis effects.

REFERENCES

[1] Brian A. Barsky, Adam W. Bargteil, Daniel D. Garcia and Stanley A. Klein, "Introducing Vision-Realistic Rendering", Eurographics 2002 Poster Proceedings, Pisa, Italy, 26-28 June 2002, pp. 1-7.

[2] Brian A. Barsky, "Vision-Realistic Rendering: Simulation of the Scanned Foveal Image from Wavefront Data of Human Subjects",First Symposium on Applied Perception in Graphics and Visualization, co-located with ACM SIGGRAPH. Los Angeles, August 7-8 2004, pp. 73-81.

[3] Susana Marcos, Stephen A. Burns, Esther Moreno-Barriuso and Rafael Navarro, "A New Approach to the Study of Ocular Chromatic Aberrations", *Vision Research*, 1999, Vol. 39, pp. 4309-4323.

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