

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 and animations that demonstrate specific defects in how a person sees. Such images of simulated vision could be shown to an individual's eye care clinician to convey the specific visual anomalies of the patient. Doctors and patients could be educated about particular vision disorders by viewing images that are generated using the optics of various ophthalmic conditions such as keratoconus and monocular diplopia.

One of the most compelling applications is in the context of vision correction using laser corneal refractive eye surgeries such as PRK (photorefractive keratectomy) and LASIK (laser in-situ keratomileusis). Currently, in the United States alone, a million people per year choose to undergo this elective surgery. By measuring subjects pre-operatively and post-operatively, our technique could be used to convey to doctors what the vision of a patient is like before and after surgery. In addition, accurate and revealing medical visualizations of predicted visual acuity and of simulated vision could be provided by using modeled or adjusted wavefront measurements. Potential candidates for such surgery could view these images to enable them to make more educated decisions regarding the procedure. Still another application would be to show such candidates some of the possible visual anomalies that could arise from the surgery, such as glare at night. With the increasing popularity of these surgeries, perhaps the current procedure which has 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 animation of simulated vision showing 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 the image plane based on light that has emanated from a point source and has passed through an optical system. Thus it can be used as an image space convolution kernel.

We introduce the object space point spread function (OSPSF), which is similar to the usual image space point spread function, as described above, except that it is defined in object space and thus it varies with depth. The OPSF is a continuous function of depth; however, we discretize it, thereby defining a sequence of depth point spread functions (DPSF) at some chosen depths.

Since human blur discrimination is nonlinear in distance but approximately linear in diopters (a unit measured in inverse meters), the depths are chosen with a constant dioptric spacing ΔD and they range from the nearest depth of interest to the farthest. A theoretical value of ΔD can be obtained from the relation $\theta = p \Delta D$, where θ is the minimum subtended angle of resolution and p is the pupil size in meters. For a human with 20/20 visual acuity, θ is 1 minute of arc; that is, $\theta = 2.91 \times 10^{-4}$.

The DPSFs are histograms of rays cast normal to the wavefront. To compute these functions, we first place a grid with constant angular spacing at each of 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. As the ray passes through each grid, the cell it intersects has its counter incremented. This entire process 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 eye focused at infinity. However, it is important to be able to shift focus for vision-simulated imaging. Recent research results in optometry showed that aberrations change significantly with accommodation. When aberrometric data is available for the eye focused at the depth that will be used in the final image, our algorithm exploits that wavefront measurement.

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

We further assume the OPSF is independent of the image plane location. In optics, this is called the "isoplanatic" assumption and is the basis for being able to perform convolutions across the visual field. For human vision, this assumption is valid for at least several degrees around the fixation direction.

2.2 Fitting a Wavefront Surface to Aberrometry Data

The output of the Shack-Hartmann device comprises a ray orientation (normal vector) at each lenslet. Current devices yield only 50 to 200 such vectors. To generate the millions of samples necessary to calculate the OPSF (see Section \ref{s:OSPSF} above), we first generate a smooth mathematical surface representation of the wavefront from this sparse data. Our

wavefront surface is a fifth degree polynomial bivariate surface defined as a 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 form which was developed in 1934 by the Dutch mathematician and physicist Frits Zernike who was awarded the Nobel Prize in Physics 1953 for discovering the phase contrast phenomenon. Zernike polynomials are derived from the orthogonalization of the Taylor series. The resulting polynomial basis corresponds to orthogonal wavefront aberrations. The coefficients weighting each polynomial have easily derived relations with meaningful parameters in optics.

2.3 Rendering Steps

Given the input image and its associated depth map, and the OPSF, 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 images to form a single vision-simulated image.

Create depth images:

Using the depth information, the image is separated into a set of disjoint images, one at each of the depths chosen in the preceding section. Ideally, the image at depth d would be rendered with the near clipping plane set to $d + \Delta D/2$ and the far clipping plane set to $d - \Delta D/2$. Unfortunately, this is not possible because we 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 do a pairwise convolution: Each depth image is convolved with its corresponding DPSF, thereby producing a set 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-blending following alpha channel compositing rules.

2.4 Elimination of Occlusion and Discretization Artifacts

Although processing in image space allows an increase in speed, the images may have artifacts introduced. This can occur in two ways, which we refer to as *occlusion* and *discretization*. The occlusion problem arises because there is scene geometry that is missing. This results from the finite aperture of the lens, which allows more of the scene to be visible than would be seen through an infinitesimal pinhole. Thus, without additional input, the colors from parts of the scene that are behind objects would have to be approximately reconstructed using the border colors of visible objects.

The discretization problem occurs from separating the image by depth. At adjacent pixels in different sub-images, the calculation of depth of field is complicated. This arises because these adjacent pixels may or may not correspond to the same object. An artifact can be introduced into the image when a single object straddles two sub-images and the sub-images are blurred. The artifact arises when the far pixel is averaged with neighboring colors behind the near pixel that do not match the far pixel's color. The neighboring colors are often black, which is the default background color. Consequently, a black blurred band occurs at the intersection of 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 have unilateral vision problems can view our simulations of the vision in 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 the quality 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 from those in more common conditions such as myopia, and this distinction is indeed borne out in our example images. Specifically, keratoconus can cause the appearance of diplopia (double-vision) whereas myopia.

4. CONCLUSION AND FUTURE WORK

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

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

The first limitations are those stemming from the method of measurement. The Shack-Hartmann device, although capable of measuring a wide variety of aberrations, does not take into account light scattering due to such conditions as cataracts. The wavefront measurements can have some error, and fitting the Zernike polynomial 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 any significant errors. Consequently, any errors that are introduced should be small and, furthermore, such small errors would be imperceptible in final images that have been discretized into pixels.

Strictly speaking, the pupil size used for vision-simulated imaging should 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) should be quite small. We have made use of three assumptions commonly used in the study of human physiological optics: isoplanarity, independence of accommodation, and off-axis aberrations being dominated by on-axis aberrations. Although we have argued that these assumptions 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 the eye focused at the depth is not usually available. However, this is not a limitation of our algorithm. Our algorithm can exploit wavefront data where the 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, but again that is not a limitation of our algorithm. Since the data we acquire is from a laser, it is monochromatic. However, some research optometric colleagues have acquired polychromatic data and will be sharing it with us. It is again interesting that recent research in optometry by Marcos [3] showed that except for the low order aberrations, most aberrations are fairly constant over a range of wavelengths.

We only compute the aberrations for one point in the fovea, and not for other points in the visual field. However, it is important to note that for computer graphics, the on-axis aberrations are critically important because viewers move their eyes around when viewing a scene. If we had actually included the off-axis aberrations of the eye, then the off-axis parts of the scene would have been improperly blurred for a person who is scanning the scene. The off-axis aberrations are of minor concern even without eye movements since the retinal sampling of cones is sparse in peripheral vision. The image that we are simulating is formed by viewing the entire scene using the on-axis aberrations because we assume that the viewer is scanning the scene.

However, since peripheral vision does make important contributions to visual appearance, viewers are affected by optical distortions of peripheral vision. Thus, it is of interest to extend this method to properly address the off-axis effects.

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