Peripheral Retinal Image Simulation Based on Retina Shapes

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Abstract

We present a method to render the image of a scene reaching the retina, the retinal image, taking into account human off-axis optical aberrations. To this end, we consider realistic wide-angle eye models that offer an anatomical description of the refractive structures of the eye as a set of lenses and accurately reproduce the optical aberrations in the periphery. We then combine these with representative retinal shapes and with distributed ray tracing. Due to the interplay between the eye model and the curved retina, we obtain a realistic simulation of the retinal image, not only foveally but also in the periphery.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—

1. Introduction

Human visual properties are not homogeneous over the entire field of view. Central vision is characterised by higher visual acuity and it is crucial in tasks that require awareness of details, such as reading and driving. On other hand, peripheral vision is preferred, for example, in night vision and motion detection.

The comparison between the human eye and a camera is an intuitive analogy. The cornea and the crystalline lens are the eye's refractive structures and the pupil plays the role of the aperture stop. Eye models are theoretical representations of the eye that address these similarities to a camera. The development of anatomically based eye models began in the 19th century and intended to characterise human central vision. Eye models that describe vision in the periphery appeared in the seventies of the last century. These models focus not only on the features of the refractive structures of the eye but also on the retinal shape, because the latter plays a major role in the calculation of the off-axis optical aberrations of the eye.

Many camera model techniques in computer graphics, such as pinhole camera, thin lens approximation, and thick lens approximation are not suitable to simulate vision because they fail to reproduce the human eye's optical aberrations [BHK*03a]. In 1995, Kolb et al. developed a rendering technique based on the description of cameras by a system of lenses that overcomes this problem [KMH95].

Wu et al. proposed a method to simulate peripheral vision [WZHX11] that combines the work of Kolb with the wide-angle eye model introduced by Navarro [NSB85]. However, they only considered a flat retina. This simplification allows a good description of the central but not of the peripheral vision. As a consequence, they do not fully benefit from the realistic description of the peripheral optical aberrations that Navarro's eye model provides.

Image-based approaches in computer graphics often suffer from artifacts, such as lack of blur quality and occlusion problems [BHK*03b, BK08]. Barsky developed an image-based technique to simulate human vision, in which the blur introduced to an image is based on the wavefront measurement of an eye [Bar04]. This is an individualised technique but it is only accurate locally, because a wavefront measurement is only precise for a specific point on the retina.

The non-uniformity of human vision is shaped by different factors. It depends on the optics of the eye, on the distribution of the different photoreceptor types across the retina and on the neuronal processing of visual information. Thus, to simulate vision one must not disregard the neuronal contributions to it. Still, reproducing the image reaching the periphery of the retina is the first step to model peripheral vision.

We consider the description of the eye as set of lenses by taking into account anatomically based eye models. Additionally, we associate this representation with a realistic depiction of the retinal shape, in order to obtain an accurate reproduction of the human optical aberrations over a wide field of view. Finally, we combine them with distributed ray tracing to simulate the peripheral retinal image.

DOI: 10.2312/egsh.20161015

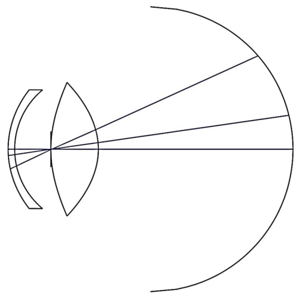


Figure 1: Schematic representation of Navarro's eye model.

Surface	n	R [mm]	Q	d [mm]
Cornea 1	1.376	7.72	-0.26	0.55
Cornea 2	1.3374	6.5	0	3.05
Lens 1	1.42	10.2	-3.1316	4.00
Lens 2	1.3360	-6.0	-1.0	16.40398
Retina		-12.0	0	

Table 1: Navarro's eye model description. n is the refractive index of the next medium in direction to the retina. R is the radius of curvature and Q is the asphericity coefficient of the surface. d is the axial distance to the next surface.

2. Wide-angle eye models

The earliest eye models addressed the cornea and the crystalline lens using spherical surfaces and assumed the retina to be flat [AS00]. However, in order to describe peripheral vision and accurately calculate the off-axis aberrations, the use of a more realistic description of the retinal shape is needed. Moreover, considering spherical surfaces to model the eye's refractive structures induces too much spherical aberration when compared with human eyes. Navarro's and Lotmar's wide-angle eye models use aspherical surfaces and spherical retinas [NSB85, Lot71]. Kooijman's model considers, in addition to the aspherical refractive structures, an aspherical retina [Koo83]. Alternatively, other models also consider a crystalline lens with a varying refractive index, such as the Liou and Brennan model [LB97].

For consistency, the retinal images presented in this article are rendered using Navarro's eye model, since it provides a good description of the off-axis optical aberrations of the human eye [ESN99, BEPH08] (see Table 1 and Figure 1). In addition, we use a 3 mm diameter pupil and either a flat or a spherical retina.

3. Methods

3.1. Eye model

We use PBRT [PH10], a physically based rendering software that relies on a 3D model of a scene and on distributed ray tracing. Furthermore, we developed a plug-in that renders the retinal image of a scene, shaped by schematic eye models. The software admits any eye model with constant refractive indices and with refractive structures consisting of surfaces with conicoidal shape, rotationally symmetric around the z axis. These surfaces are described by

$$x^2 + y^2 + (1+Q)z^2 - 2Rz = 0, \quad (1)$$

where Q and R represent, respectively, the asphericity coefficient and the radius of curvature of the surface.

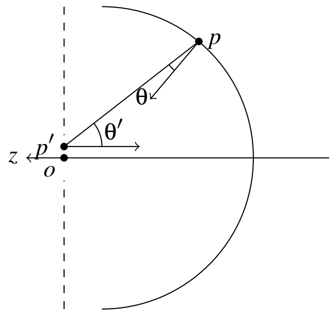


Figure 2: Geometry for computing the irradiance at a point of the retina (sagittal view).

3.2. Retinal surface

The retina can be represented either by a plane or a conicoid. The irradiance $E(p)$ at any point p on the retina can be calculated taking into account the radiance at p, $L(p', p)$, and the shape of the retina

$$E(p) = \int_{p' \in D} L(p', p) \frac{\cos\theta \cos\theta'}{\|p - p'\|^2} dA', \quad (2)$$

where θ is the angle between the vector $\vec{pp'}$ and vector normal to the retinal surface at p. θ' is the angle between the vector $\vec{p'p}$ and the vector normal to the exit pupil (see Figure 2).

Inspired by Kolb [KMH95] we assumed θ and θ' constant, because the exit pupil subtends a small angle from p. Let o be the centre of the exit pupil and A its area. θ' is considered equal to the angle between $\vec{op}$ and the optical axis. θ is assumed equal to the angle between $\vec{po}$ and the vector normal to the surface at p. R is defined as $\|p - o\|$. These premises allow us to simplify equation (2) to

$$E(p) \approx L(o, p) A \frac{\cos(\theta)\cos(\theta')}{R^2}. \quad (3)$$

3.3. Projection of the retinal surface

In the case of a curved retina, it is used an orthographic projection from the surface onto a plane to display a flat retinal image (see Figure 3).

In order to compare the optical quality between different eccentricities at the retina in Section 5, we use images that are projections of the retinal surface with different centres of projection, for the sake of avoiding additional distortions. Thus, the centres of the chosen projections coincide with the points that we want to compare (see Figure 4).

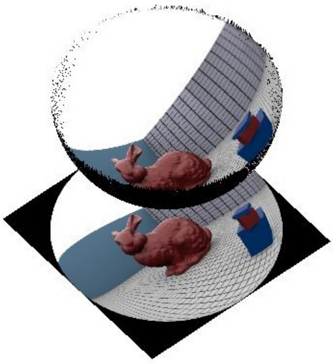


Figure 3: Orthographic projection of the retinal image rendered considering a spherical retina.

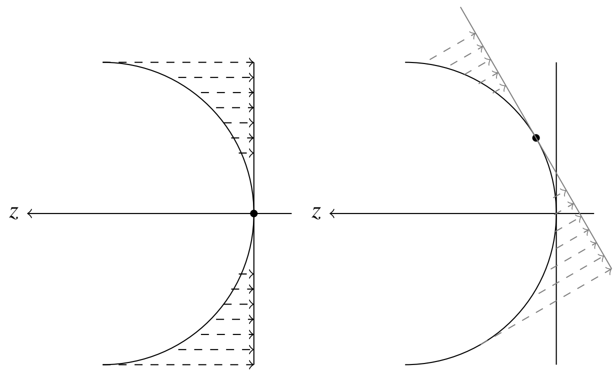


Figure 4: Schematic representation of orthographic projections of the retinal surface, centered at different retinal positions (sagittal view).

4. Flat and spherical retinas comparison

It is discussable if the perception of the world would change if the human retina were flat. The visual cortex apparently deals easily with any kind of distortions, given that even cortical maps are distorted. So, it seems reasonable to assume that the brain would adapt to the constraints imposed by the geometry of the retina in order to offer a similar perception. Nevertheless, flat retinas are not found in vertebrate eyes and this assumption implies a different neuronal processing from the one that humans have. It is thus useful to look into the particularities of the images that the brain has to deal with as a consequence of the retinal shape.

Considering the same dimensions, curved retinas allow a much wider field of view than flat retinas (see Figures 5 and 7). Also, flat retinas induce a decrease in the image quality in the periphery of retinal images, due to the decay of irradiance with eccentricity (see Figures 6 and 7). In addition, the distance between the exit pupil and a point on a flat retina increases with eccentricity, exceeding the focal length. Hence, the image reaching the periphery of flat retinas is defocused and magnified (see Figure 5).

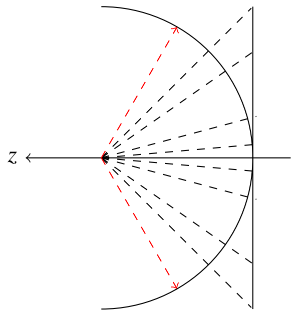


Figure 5: Comparison between a spherical and a flat retinal surface, with similar dimensions. A flat retina cannot account for very eccentric rays and induces a stronger magnification in the periphery when compared with a curved retina.

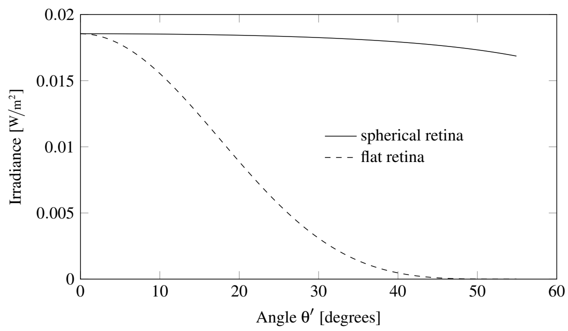
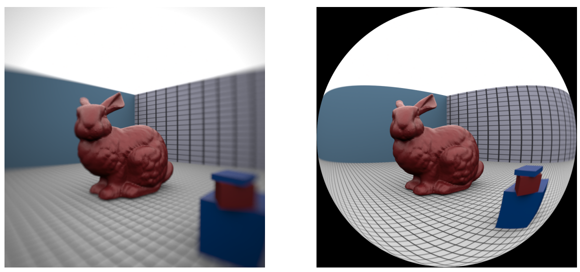


Figure 6: Irradiance distribution on a flat and on a spherical retinas resulting from an uniform unit radiance field imaged through Navarro's eye model. θ' represents the angle between the vector $\vec{op}$ from the centre of the exit pupil to a point p on the retina and the optical axis.

5. Central and peripheral visual acuity

Standard methods to subjectively measure visual acuity consist of asking a patient to read optotypes, such as letters or numbers, printed on an eye chart that is located at 5 or 6 metres away from the person. In order to assess the central visual acuity and check



(a) Flat retina (b) Spherical retina

Figure 7: Retinal images using different retinal shapes. The spherical retina allows a wider angle of view and presents a better image quality in the periphery.

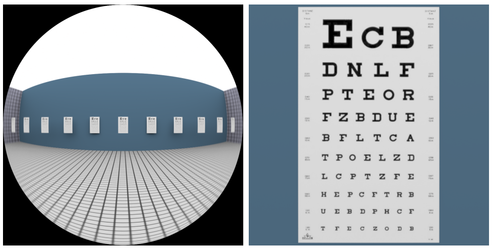


Figure 8: Retinal image, centred at the image of the eye chart at 0 degrees and a close up view of the central eye chart.

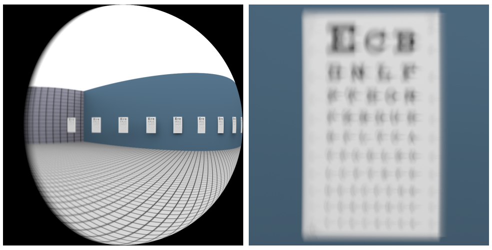


Figure 9: Retinal image, centred at the image of the eye chart at 30 degrees and a close up view of the central eye chart.

its degradation in the periphery, we created a scene that mimics the subjective refraction situation. Eye charts were placed tangentially to a circle with 5 metres radius, centred in the eye. The distance between the eye charts was 10 degrees, covering a field of view from -50 to 50 degrees. At the considered distance, the size of the letters in the charts allows the assessment of an eye's visual acuity ranging from 0.125 to 1.0 in decimal scale.

Figures 8 and 9 illustrate the central visual acuity and the visual acuity at 30 degrees eccentricity, respectively. We find that centrally all the letters in the eye chart can be easily identified. Hence, the eye model has an acuity of at least 1.0 in decimal scale. This result is in agreement with the visual acuity of emmetropic human eyes, i.e. with no need of glasses. However, at 30 degrees eccentricity the acuity decreases drastically. Only the first line of the eye chart can, eventually, be considered to be seen, corresponding to a maximum visual acuity of 0.165. Therefore, the optics of the eye contribute strongly to the decrease of visual acuity in the periphery.

6. Discussion and future work

We propose an alternative method to simulate retinal images, considering the peripheral properties of the human eye. The method has the advantage of allowing the simulation of a wide angle of view without compromising the realistic description of the peripheral optical aberrations and the image quality.

With these features, we aim to study the extent to which peripheral visual acuity is limited by the optical quality degradation. Centrally, the optics of the eye limit visual acuity, because the fovea is densely packed with cones and in addition, there is a one to one correspondence between the photoreceptors and the ganglion cells. In the periphery, the eye has a poorer optics due to the increase in aberrations and, besides that, each ganglion cell receives inputs from many photoreceptors.

To extend the current model to a vision model, we intend to include neuronal features, such as the distribution of cones in the retina. Deeper insight will be obtained from the comparison of the model's performance with human visual performance regarding, for example, visual acuity, colour perception or crowding effect.

The simulation of peripheral vision has potential applications on, for instance, the development of progressive additional lens designs that minimise peripheral distortions. It can also be advantageous in predicting how changes in any ocular structures, due to cataract or refractive surgeries, affect ocular aberrations and vision quality.

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