Realistic Simulation of Peripheral Vision Using An Aspherical Eye Model

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Abstract

A novel method is proposed to accurately simulate the peripheral vision under different visual perception. An accurate aspherical schematic eye model is firstly introduced to reasonably predict the anatomical and optical properties of the human eye. This eye model is composed of the Navarro schematic eye model with aspherical surfaces as a basic model, and a corresponding accommodation model, and both these models are combined to simulate the varying refractive power of the human eye. Finally, distributed ray tracing techniques is combined with this eye model to produce a variety of visual results.

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

1. Introduction

Accurate simulation of the human vision by computerized techniques need to fall back upon the rendering techniques in computer graphics [MKL97]. However, camera lens models in computer graphics, such as pin-hole, thin lens, thick lens and geometric lens [WZH*10], are abstract and general, and just suitable for general image synthesis. For special image synthesis to simulate the human vision, current lens models do not incorporate the anatomical and optical characteristics of the human eye and cannot consequently produce accurate visual results consistent with that the human eye really observes. Fortunately, a number of schematic eye models, devised by optical modeling community of the human eye, are good candidates for modeling the complicated properties of the human eye. Human vision simulation can find its potential value in many applications, such as refractive surgery planning and evaluation, new lens combination, contact lens design, spectacles design, and so on.

In virtue of research work from both the human eye modeling and computer graphics, we propose a new method to more accurately simulate the peripheral visual perception of the human eye under different conditions. At first, we adopt an accurate schematic eye model with aspherical surfaces as the basic model, and then introduce a compatible accommodation model to simulate the adaptive refractive capability of the human eye at different distances. In the end, distributed ray tracing technique is combined with both models to produce synthesized images for simulating the visual perception.

2. Related work

So far, a few papers have been devoted to simulate the visual perception of the human eye. Mostafawy et al. [MKL97] introduced a thick lens model to approximate the human eye and simulated refractive surgery effects using distributed ray tracing technique. Loos et al. [LSS98] used wavefront tracing technique to evaluate the human eye accommodation process and employed distributed ray tracing technique to visualize refractive correction effects by progressive lenses. Both of the above exploit distributed ray tracing to improve the accuracy of the results, but adopt simple thin or thick lens models. Barsky et al. [Bar04] coined the concept of vision realistic rendering and introduced an image-based depth-of-field rendering technique. They simulated the retinal images incorporating the characteristics of a particular individual's entire optical system, but used a pin-hole model. Kakimoto et al. [KTMN07] used a thin toric lens to simulate the human eyesight syndrome and the corrected vision by spectacle lenses. These lens models used above are abstract and gener-

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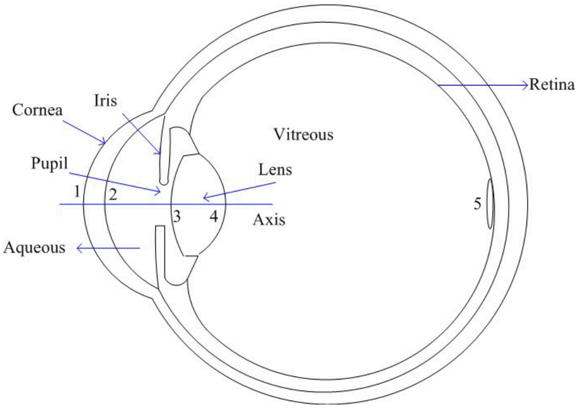


Figure 1: *The anatomical structure of the human eye.*

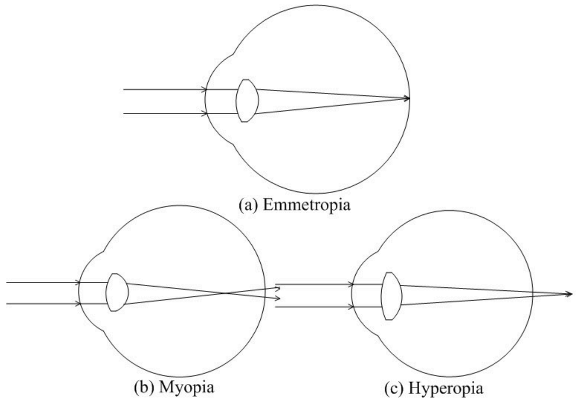


Figure 2: *The optical principles of the visual defects for the human eye.*

al in computer graphics for mapping the 3D scene to the 2D image surface, and do not consider the optical characteristics specific to the human eye, and hence none produce accurate results consistent with visual performance of the human eye.

3. Modeling of the human eye

3.1. Anatomy of the human eye

The human eye (Figure 1) is a slightly ovoid organ for perceiving color and depth, about 24 mm from front to back (length) and 23 mm from left to right (diameter). Its focal length in air is about 16.7 mm or about 60 diopters for its refractive power. The primary refractive elements of the human eye are the cornea and crystalline lens. Any abnormality of size, distance, or shape of these elements leads to visual defects such as myopia (near sightedness), hyperopia (far sightedness), presbyopia or astigmatism.

The human eye has the capability of changing its refractive power to maintain a clear image of an object as the object distance varies, and this special capability is called accommodation. When the accommodation of the human eye can not work well, some visual defects mentioned above will occur.

An emmetropic eye is always able to focus the incident rays on the retina by proper accommodation efforts, shown in Figure 2 (a). For myopia, the relaxed eye refracts rays too strongly, so the focal point is located in front of the retina, illustrated in Figure 2 (b). This causes those rays to diverge when they reach the retina, and creates a circle of confusion on the retinal image. Hyperopia, on the other hand, is caused when an eye has insufficient refractive power, so that even when fully accommodated, nearby objects are focused behind the retina, consequently creating a similar circle of confusion, shown in Figure 2 (c). Presbyopia describes another kind of visual defect where the eye exhibits a progressively diminishing ability to focus on near objects with age.

Table 1: *Optical data of the Navarro eye under the unaccommodated condition. Cornea and lens have two rows, which mean two surfaces, anterior and posterior.* Pos *represents the distance from the current surface to the first one,* Rad *radius of the current surface at the eye axis and* Index *the refractive index of the medium after current surface. The unit for position and radius is millimeters.*

		Pos	Rad	Index	Conic
Cornea	1	0.0	7.72	1.367	-0.26
	2	0.55	6.5	1.3374	0.0
Lens	3	3.6	10.2	1.42	-3.1316
	4	7.6	-6.0	1.336	-1.0
Retina	5	24.4			

3.2. Eye modeling

Schematic eye models are especially valuable for reproducing optical properties of the human eye from anatomy. A great variety of schematic eye models have been developed, and their representatives are introduced by Gullstrand [Gul09], Le Grand [LGEH80], Kooijman [Koo83] and Navarro [NSB85], respectively. Gullstrand and Le Grand models consist of only spherical surfaces and consequently exhibit substantially higher aberrations than normal eyes. For Kooijman and Navarro models, aspherical surfaces are introduced for eliminating or reducing the extra aberrations incurred by spherical surfaces. Both models predict similar optical properties, but Navarro model is more suited for being adapted to model the accommodation process of the human eye. Therefore, we decide to adopt Navarro's schematic eye model as the basis to simulate visual perception of the human eye, whose detailed optical parameters under the fully relaxed (unaccommodated) state are listed in Table 1. It is a four-optical-surface model using aspherical surfaces for the front surface of the cornea and both surfaces of the lens.

3.3. Accommodation modeling

It is well known that the change in the anterior radius of the lens is the major factor in the increment of refracting power of the lens with accommodation, while the posterior radius and the thickness play a secondary role. This continuous change of the anterior radius can be represented by a mathematical function. We adopt Navarro's accommodation model [NSB85], which builds on Navarro schematic eye under the unaccommodated state. The varying functions of radius, thickness, asphericity and refractive indices of the components of the human eye are displayed as follows,

$$\begin{aligned} R_a(D) &= 10.2 - 1.75\ln(D+1.0), \\ R_p(D) &= -6.0 + 0.2294\ln(D+1.0), \\ T_a(D) &= 3.05 - 0.05\ln(D+1.0), \\ T_l(D) &= 4.0 + 0.1\ln(D+1.0), \\ Q_a(D) &= -3.1316 - 0.34\ln(D+1.0), \\ Q_p(D) &= -1.0 - 0.125\ln(D+1.0), \\ n_l(D) &= 1.42 + 9.0\times 10^{-5}\ln(D+1.0), \end{aligned} \tag{1}$$

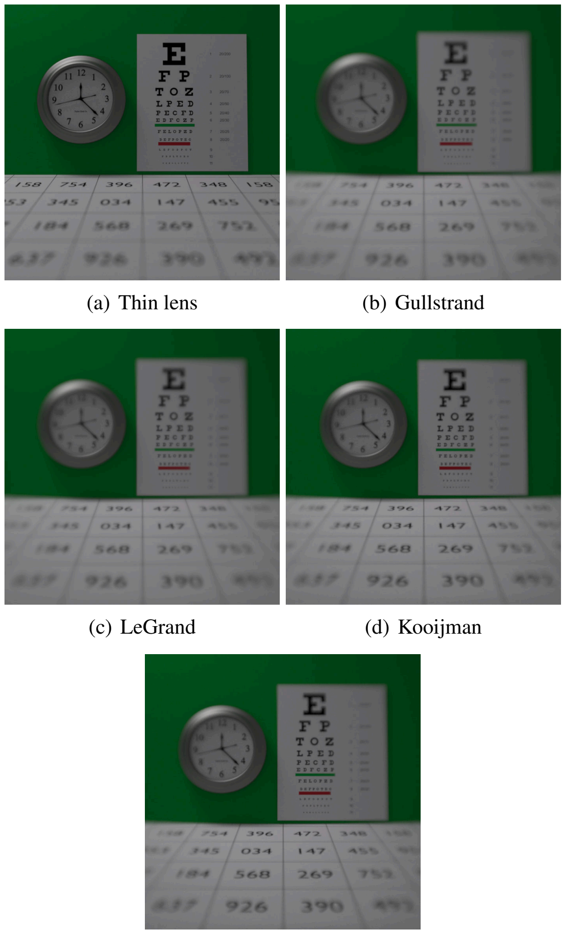
where D represents the amount of accommodation (diopters), R_a the anterior lens radius, R_p the posterior lens radius, T_a the aqueous thickness, T_l the lens thickness, Q_a the anterior lens asphericity, Q_p the posterior lens asphericity, and n_l the lens refractive indices. Here, asphericity (conic) coefficient is relevant with eccentricity by $Q = -e^2$.

4. Simulation of the human vision

In order to simulate accurate human vision, it is necessary to view our eye model as a special geometric lens model and integrate it into a general ray tracer. We extend a recently developed geometric lens model [WZH*10] to support aspherical surfaces and then transform the optical data of Navarro model into a format that the geometric lens model can recognize. In addition, the pupil plays the role of the aperture stop, and therefore its images in object space and image space, called entrance pupil and exit pupil in applied optic terminology, need to be calculated to accelerate the rendering of visual perception. We use distributed ray tracing technique to synthesize the retinal images of the human eye, and integration of geometric lens model and distributed ray tracing have been elaborated in [WZH*10].

5. Results and discussion

In order to verify accuracy of the Navarro eye model, we chose a frequently used thin lens model in computer graphics, and three other representative schematic eye models in optical modeling field of the human eye, namely Gullstrand, Le Grand and Kooijman, and then simulated the peripheral visual images of these models under the unaccommodated condition. Figure 3 displays the simulation results of different eye models, and the diameter of the pupil is set to 5 mm. It is noticed that the thin lens model incurs blurring only in depth, which is characteristic of depth of field of the human eye. However, it fails to create horizontally or vertically gradual blurring, which is caused by optical aberrations by the human eye. In contrast, these schematic eye models are designed to attempt to accurately predict the aberrations inherent in the human eye, and therefore able to produce deep, horizontal and vertical blurring effects. However, it is seen that the results produced by Gullstrand and LeGrand models are much blurrier than Kooijman and Navarro models because spherical surfaces introduce additional aberrations and aspherical surfaces can decrease these additional aberrations. The result produced by Kooijman model is nearly the same as that by Navarro model, but the accommodation model is introduced based on Navarro model. Therefore, Navarro model are adopted to simulate visual perception under different accommodation states.



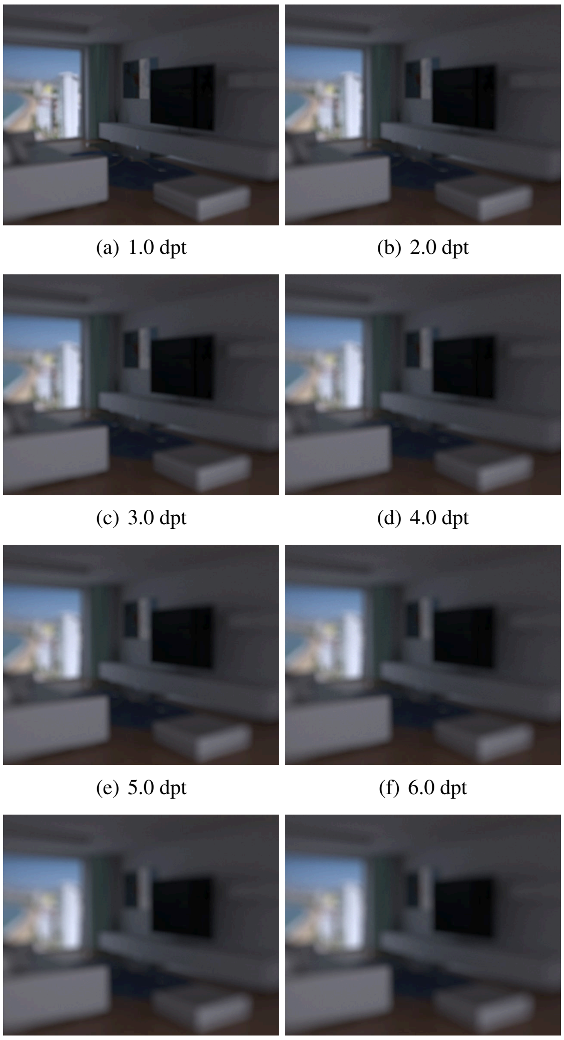
(a) Thin lens (b) Gullstrand

(c) LeGrand (d) Kooijman

(e) Navarro

Figure 3: *Peripheral visual perception of different eye models under the unaccommodated (fully relaxed) state.*

Based on Navarro eye model and corresponding accom-



(a) 1.0 dpt (b) 2.0 dpt (c) 3.0 dpt (d) 4.0 dpt (e) 5.0 dpt (f) 6.0 dpt (g) 7.0 dpt (h) 8.0 dpt

Figure 4: *Visual perception of Navarro's eye model under different accommodation power (measured in diopter, dpt).*

modation model, the visual perception under varying accommodation power was simulated, shown in Figure 4. It is observed that the produced visual images become gradually blurrier as the amount of the accommodation gradually increases. When the accommodation power of the human eye arrives at some value but can not return to the relaxed state, myopia will occur. Therefore, Figure 4 depicts a gradual process that myopia becomes more and more severe and the vision become much blurrier.

6. Conclusion

We have proposed a more accurate method to simulate the peripheral visual perception of the human eye under different conditions, and the key parts are the introduction of the Navarro eye model and corresponding accommodation model from the human eye modeling field, and employment of distributed ray tracing rendering technique in computer graphics. Our method can be applied to many applications demanding the visualization of the optical properties of the human eye, for instance, refractive surgery planning and evaluation, new lens combination, contact lens design, spectacles design. However, our eye model is still limited to modeling of the optical performance of the human eye. In the future, we plan to model multiple optical characteristics of the human eye, such as wide-angle, non-symmetry, polychromatic and iris dynamics.

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