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Fast ray-tracing of human eye optics on Graphics Processing Units

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ABSTRACT

We present a new technique for simulating retinal image formation by tracing a large number of rays from objects in three dimensions as they pass through the optic apparatus of the eye to objects. Simulating human optics is useful for understanding basic questions of vision science and for studying vision defects and their corrections. Because of the complexity of computing such simulations accurately, most previous efforts used simplified analytical models of the normal eye. This makes them less effective in modeling vision disorders associated with abnormal shapes of the ocular structures which are hard to be precisely represented by analytical surfaces. We have developed a computer simulator that can simulate ocular structures of arbitrary shapes, for instance represented by polygon meshes. Topographic and geometric measurements of the cornea, lens, and retina from keratometer or medical imaging data can be integrated for individualized examination. We utilize parallel processing using modern Graphics Processing Units (GPUs) to efficiently compute retinal images by tracing millions of rays. A stable retinal image can be generated within minutes. We simulated depth-of-field, accommodation, chromatic aberrations, as well as astigmatism and correction. We also show application of the technique in patient specific vision correction by incorporating geometric models of the orbit reconstructed from clinical medical images.

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1. Introduction

Modeling and simulating human eye optics has been an active field of research with wide applications in various fields. In vision science research, the focus of these efforts is on understanding human vision and the functional significance of different ocular structures. In ophthalmology, modeling retinal image formation serves as a tool to capture defects of the eye and simulate vision corrections to provide better treatment. However, simulating realistic light refraction through ocular structures in three dimensions (3D) is challenging due to the inherent complexity of human optics. In general, it is computationally intensive to trace millions of rays that form the retinal image. Fink and Micol report that it takes more than 300 min to simulate one still image [1], urging for the need of a more efficient simulator.

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Human eye optics simulation has been performed primarily on analytical models. The finite element ray tracing method proposed by Richerzhagen applied discretization on the spatial refractive index but not on the orbit geometry [2]. Most widely used schematic eye models are based on simplified spherical surfaces to conveniently obtain the surface curvatures [3]. Higher order representations have also been proposed: Zernike polynomials were used to characterize cornea and lens surfaces [1], and quantitatively study optical aberrations of human eyes [4]. The lens was represented by biconic surfaces in [5]. These approximation surfaces have inherent limitations as they globally optimize the shape and lack the flexibility to model local geometric variation. The geometric shapes of ocular structures involved in visual processing play a crucial role in image formation. In particular, realistic 3D representations are important for studying vision disorders, many of which are associated with abnormalities in the shape of an ocular structure. For instance, one common cause of astigmatism is the asymmetry of cornea [3]. There has also been evidence on the positive correlation between myopia (hyperopia) and the eyeball axial length [6].

In this paper, we present a novel 3D human eye optics simulator that simulates retinal image formed on the retinal surface by computationally propagating millions of light rays. Our proposed approach improves existing retinal image simulation by modeling ocular structures by polygon meshes. Compared to an analytical model, a polygonal mesh can more precisely represent the geometry of an anatomical structure of arbitrary shape. Many biomedical applications such as patient-specific treatment prediction require modeling the anatomical abnormality of an individual, which makes polygon representation preferable. Polygon models can be built from patients' data such as medical images using standard image reconstruction algorithms. With these models, we simulated retinal images by applying ray tracing to calculate refractions of light rays through the multiple layers of lens and cornea.

Our simulator is sufficiently general to incorporate spherical, aspheric, and even arbitrarily shaped ocular structures including cornea, lens, and retina. The contributions of our new technique are:

- Optical structures were modeled as polygon meshes which can model arbitrary shapes more accurately. With this representation, surface intersection and curvature as well as refractive rays can be computed efficiently.
- The powerful parallel computing architecture of commodity Graphics Processing Units (GPUs) was utilized to accelerate optics ray tracing. Half a million light rays propagating through multiple optical surfaces can be simulated in one second.
- Topographic and geometric measurements of the retina, cornea, and lens from keratometer or medical imaging data can be easily integrated to provide subject-specific simulation.
- Various settings of the 3D environment related to depth, color, shape, and motion are programmable in the virtual model, potentially useful for studying visual perception problems.

2. Methods

Human eye is a complex organ. Light enters the eye from the anterior cornea, propagates through the cornea, anterior chamber, pupil, lens, and vitreous humour and forms the retinal image on the retinal surface. Light ray is refracted at the interface of two different structures as it propagates. While the eye is treated as a physical optical system that is computationally tractable, the most prominent structures to consider are cornea, lens, and retina.

Considering what occurs in optics of the human eye, numerous light rays coming from different sources arrive at the same spot on the retina and contribute to the sensed image. However, such optical process is impossible to model computationally. The practical approach to simulate how an image is formed on the retina is to trace the light rays in the backward direction from the retina. That is, millions of points are first sampled randomly on the retinal surfaces, representing the destinations of the light rays on the retina. Then the source of each light ray reaching that particular point is traced backwards, which determines the color contributing to the retinal image.

Our problem is analogous to ray tracing, a fundamental computer graphics technique to render images of three-dimensional scenes as seen from a camera from a particular view. Intersections of light rays originating from the camera with the objects in the external world are first computed. Illuminations of light sources at these positions are then determined, as well as other realistic effects such as refractions, reflections, and shadows. In addition to numerous other applications in graphics, ray tracing has been applied to simulate optical effects [7–9]. However, because their main objective is to produce a visually pleasing rendering, the optics models included are not necessarily physically realistic.

Our proposed approach on computing retinal image is to use distributed ray tracing [10] augmented with a realistic optics model. The idea is to apply stochastic sampling to take into account the fact that numerous light rays reach the same spot on the retina. In our optics simulation, to calculate the color of each pixel on the retinal image, hundreds of light rays were generated which pass through randomly distributed locations on the posterior lens surface. Although computationally more expensive, combining multiple rays is necessary to realistically simulate vision effects such as depth of field and motion blur.

Fig. 1 shows the diagram of how retinal images are calculated in our simulator described above, which includes an optics model with arbitrarily shaped ocular structures.

We represented each surface of the retina, lens, and cornea as a polygon mesh (specifically, a triangle mesh), an efficient and flexible shape primitive common in computer graphics. A triangle mesh consists of a list of connected faces, each of which is defined by three vertices. Previously, ocular structure surfaces have been modeled as analytical (parametric) geometries, such as spheres, quadric surfaces [11], or

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