Plausible Iris Caustics and Limbal Arc Rendering

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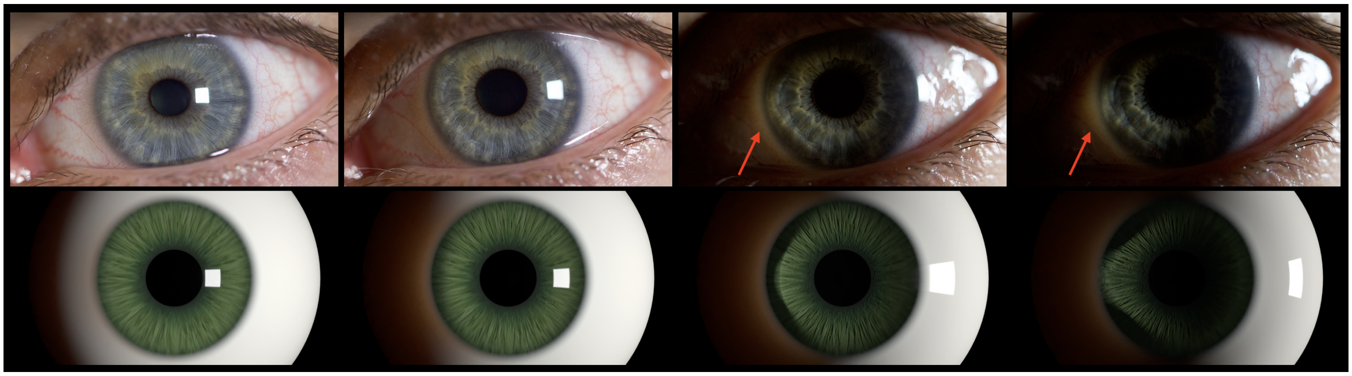

Figure 1: The distinct characteristics of the iris caustics and the limbal arc (red arrow) are captured in our renders, which agree well with the photo reference under varying illumination.

ABSTRACT

In this paper, we apply anterior segment tomography measurements from contact lens research to photorealistic eye rendering. We improve on existing analytic rendering models by including a conical extension to the usual ellipsoidal corneal surface and we demonstrate the advantage of using a more accurate iris depth. We also introduce a practical method for automatically rendering the limbal arc as an intrinsic part of sclerotic scattering.

CCS CONCEPTS

• **Computing methodologies** → **Rendering**; **Reflectance modeling**;

KEYWORDS

eye shading, caustics, sclerotic scatter

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1 INTRODUCTION

Plausible human eye rendering is equally critical for photorealistic visual effects and art-directed animation and typically includes such effects as corneal refraction, iris caustics, and sclerotic scattering. Increasingly, physically-based methods such as path tracing have been used to reduce artist effort. Achieving plausible rendering of iris caustics however requires sufficiently accurate anterior eye geometry as illustrated in Figure 2. An additional optical effect resulting from sclerotic scattering is the *limbal arc* which is often observed on the shadowed side of a partially lit limbus, providing a subtle yet distinct feature of human eyes as shown in Figure 1. Such limbal arc illumination has been well-studied in the medical field [Denion et al. 2016] but has typically been ignored in rendering eyes.

In our work, we demonstrate the beneficial effect of using a more accurate cornea shape and iris depth for producing iris caustics. We describe how we preserve caustic plausibility in the presence of eyeball deformation that typically occurs in animated films. We also introduce what we believe to be the first physically motivated model for rendering the limbal arc and demonstrate that it improves the realism of our results.

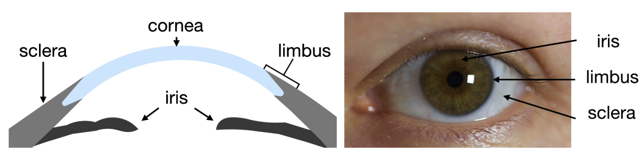

Figure 2: Schematic cross-section and photo illustrating key anterior segment components of the human eye.

2 IRIS CAUSTICS

Geometric model. The shape of the cornea is commonly modeled as an ellipsoid following medical literature [Francois et al. 2009]. However, based on the measurement from contact lens community [Kojima et al. 2013], the iris intersects the cornea at a depth beyond the point where the ellipsoid model is a good fit. Kojima et al. [2013] used optical coherence tomography (OCT) to profile the anterior segment of 55 normal eyes. The researchers concluded that

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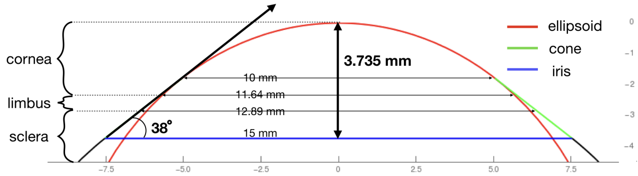

Figure 3: Geometric model based on tomography data.

between the 10mm and 15mm chords, the corneal-scleral transition is conical rather then ellipsoidal, subtending an angle of 38 degrees. They also observed that the 15mm chord (indicative of iris depth) sits a depth of 3.735 mm beneath the corneal apex. The geometric model can therefore be described (in Cartesian coordinates and units of millimeters) as

$$F(x, y, z) = \begin{cases} 0.75z^2 + 15.6z + r^2 = 0 & 0 \leq 2r < 10.02 \\ z - r \tan 38^\circ = 0 & 10.02 \leq 2r < 15.08 \end{cases}$$

where $r = \sqrt{x^2 + y^2}$ and $2r$ is the chord length. The corneal apex sits at the origin and eye gaze direction faces along the z-axis. An illustration of our geometric model is shown in Figure 3. We demonstrate in Figure 1 that our geometric model can be effectively used to generate path-traced caustics that strongly resemble photo reference.

Optical properties. The limbus is the transition zone between the transparent cornea and translucent sclera and its location dictates the proper blending of these two visibly distinct regions. Iskander et al. [2006] proposed an image-based approach to measure the visible outer and inner edges of the limbus. We allow artist placement of the limbus within a plausible range and use the reported values (11.64 mm and 12.89 mm) as an initial default as shown in Figure 3. They are exposed to the artists as ratios over the iris diameter.

Implementation. To further simplify the geometric model, we find that a paraboloid $14.5z + r^2 = 0$ is a practical, continuous approximation as demonstrated in Figure 4. To efficiently sample light for the iris across the refractive corneal portion of the geometry, we use manifold next event estimation [Hanika et al. 2015], which works with implicitly defined surfaces like ours and only requires a two-dimensional Newton solver for our case. Animated films typically exaggerate eye proportions and perform arbitrary deformations of eye geometry which result in implausible corneal refraction and iris caustics. To restore plausibility, we re-project ray hits from the animated eye surface to our eye geometric model, using an artist-controlled iris projection [Pritchett and Lancaster 2006], so that plausible iris caustics can be achieved by path tracing against our implicit geometric model regardless of how the explicit eye surface is animated or deformed.

3 LIMBAL ARC

Limbal arc is an often ignored optical effect where light entering the limbus travels through multiple total internal reflections across the cornea illuminating a portion of the limbus on the opposite side as illustrated in Figure 5 (left). To simulate the cornea's fiber-optic behavior, we define a virtual *teleportation cylinder*, embedded inside the eyeball, with its axis aligned with the eye gaze direction (i.e. the z-axis) and with diameter equal to the edge of the limbus. During path-traced subsurface sclerotic scattering, any ray intersecting

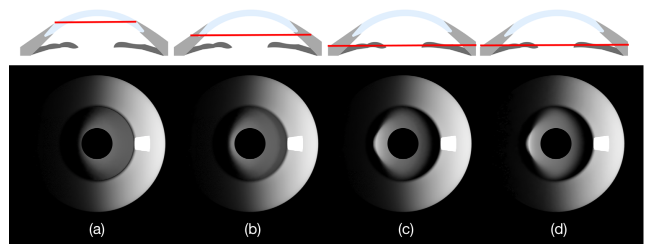

Figure 4: Impact of iris depth on caustic shape: An eye modeled with the ellipsoid–cone anterior shape rendered with its iris aligned with the beginning (a) and the end (b) of the limbus, compared to the anatomically correct depth (c). Top row shows the schematic eye cross-section illustrating the respective iris depth used. The rendered result using our paraboloid approximation (d) agrees with the ellipsoid–cone model result (c).

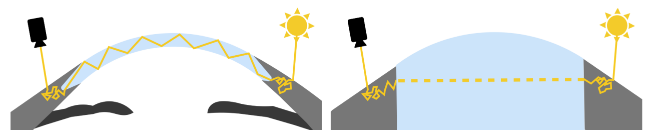

Figure 5: Left: Schematic cross-section of a human eye illustrating the cause of limbal arc. Right: Simulating limbal arc.

with the cylinder is teleported to a point directly opposite on the cylinder, as illustrated in Figure 5 (right), with the ray's scattering direction projected onto the plane perpendicular to the cylinder axis (i.e. the xy-plane). With this approach the limbal arc appears naturally as a by-product of sclerotic scattering without requiring any additional parameters, and adding no additional energy. Figure 1 shows how we are able to match the photo reference.

4 CONCLUSION

We presented an analytic model for the human eye anterior segment surface with improved accuracy, and demonstrated the importance of accurate modeling of iris depth. We introduced a novel approach for rendering the limbal arc as an intrinsic effect of path-traced sclerotic scattering. And we described implementation details, including a practical continuous approximation for the anterior segment surface, and described how plausible results can be obtained with deformed geometry as occurs in animated films.

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