On the Efficacy of Correcting for Refractive Effects in Iris Recognition

Image Science and Machine Vision Group
Oak Ridge National Laboratory
Oak Ridge, TN 37831
pricejr@ornl.gov

Abstract

In this study, we aim to determine if iris recognition accuracy might be improved by correcting for the refractive effects of the human eye when the optical axes of the eye and camera are misaligned. We undertake this investigation using an anatomically-approximated, three-dimensional model of the human eye and ray-tracing. We generate synthetic iris imagery from different viewing angles using first a simple pattern of concentric rings on the iris for analysis, and then synthetic texture maps on the iris for experimentation. We estimate the distortion from the concentric-ring iris images and use the results to guide the sampling of textured iris images that are distorted by refraction. Using the well-known Gabor filter phase quantization approach, our model-based results indicate that the Hamming distances between iris signatures from different viewing angles can be significantly reduced by accounting for refraction. Over our experimental conditions comprising viewing angles from 0 to 60 degrees, we observe a median reduction in Hamming distance of 27.4% and a maximum reduction of 70.0% when we compensate for refraction. Maximum improvements are observed at viewing angles of 20°-25°.

1. Introduction and Motivation

Iris recognition is a well-known and robust biometric method [1, 2]. In traditional systems, a subject willingly presents their eye to the system for verification. Though these systems are very accurate, false rejections can occur when the optical axis of the camera and the eye are misaligned, resulting in nonlinear distortions of the imaged iris pattern due to refraction. An example of such distortion can be seen in the images of Fig. 1, acquired in our laboratory. Defining the viewing angle \( \phi_v \) to be the angle between the optical axis of the eye and the camera, the left image in Fig. 1 was acquired with \( \phi_v = 0^\circ \) and the right image with \( \phi_v = 50^\circ \). Similarly problematic images can also be found in the NIST Iris Challenge Evaluation (ICE) 2005 data (http://iris.nist.gov/ICE/). Such problems will likely become more significant as iris recognition proliferates and/or identification systems are developed that work at a distance, where the subject might even be unaware. Our goal in the work presented here is to determine if correcting for refraction in iris recognition is a worthwhile endeavor. We pursue this goal using computer-rendered imagery, which provides us with ideal experimental control so that we can approximate the upper limits on what improvements, if any, might be achieved.

We note that, to our knowledge, this problem has not been explored to date in a quantitative manner. Imaging of the iris involves several surfaces and indices of refraction; the quantitative effects of off-normal viewing are not obvious. Though it may seem intuitively obvious that refraction will cause problems, it is unclear if, and/or at what angle, such problems will be significant. As the initial step in this domain, our model-based approach is purposefully simple; significance and feasibility must be established in the most controlled and straightforward setting before embarking upon increased complexity. With these thoughts in mind, the specific contributions of this paper are as follows:

- We present a relatively simple model of the human eye,
based on real anatomical and optical properties, that can be rendered using freely available software.

- We quantify the adverse effects, under optimal conditions, of nonzero viewing angles when refraction is not considered. We do this using the well-known, Gabor filter phase quantization approach with Hamming distance scoring.

- We present experimental results on computer-generated imagery that demonstrate significant improvements are achievable by accounting for refractive distortion under nonzero viewing angles.

We conclude from these results that further research in this area is certainly warranted. Continuing work should include the acquisition of a database of real, off-normal iris imagery from human subjects with stringent experimental control. Furthermore, more complex and accurate models for the shape of the human eye surfaces should be constructed and investigated. Such models should be based upon those from the latest vision research[3, 10] and include natural variation.

The remainder of this paper is organized as follows. In Section 2, we describe the model of the eye that we employ in this study. We discuss in Section 3 how we quantify and mitigate the effects of refraction on the imaged iris. We report results in Section 4 and close in Section 5 with some summary remarks and suggested directions for further research.

## 2. A Simple Model of the Human Eye

The anatomy and optical properties of the average human eye are still subjects of active research [3, 10]; a completely accurate model of the human optical system is quite complex. In this work, we employ a simpler model under the premise that significant measurable benefits must be realizable with the simple model before we embark upon the considerable effort that would be required with a much more elaborate model. We develop an anatomically-approximated model of the human eye in the POV-Ray environment (http://www.povray.org). We use the geometric and optical parameters from [5] and summarized in Table 1 for our model. To construct the model, we employ simple geometric primitives, similar to [6], and constructive solid geometry as follows. Referring to Fig. 2, the cornea is formed as the difference of an anterior sphere (radius 7.8mm) and a posterior sphere (radius 6.5mm) displaced from one another according to the cornea thickness of 0.55mm. According to [5], we set the cornea index of refraction to 1.37 for near infrared wavelengths (NIR), which is the domain of most iris imaging systems [2]. The aqueous humor is constructed using a sphere identical in size and placement to the posterior cornea sphere, but with index of refraction 1.33. The pupil (lens) is formed by subtracting from the aqueous humor sphere a black sphere of radius 10.2mm, positioned to preserve the anterior cornea-to-lens distance of 3.6mm. Similarly, the iris is formed by subtracting from the aqueous humor sphere a (textured or pigmented) cone with outer diameter 12.0mm and inner diameter set to the desired pupil diameter, which is varied according to the desired dilation. We construct the sclera as the difference of two white spheres of radius 11.5mm that are positioned to align with the limbus. For all subsequent renderings shown and/or reported upon, we employ a pinhole camera model positioned 60mm from the apex of the cornea with a 40° field of view. Furthermore, all scenes are illuminated with three white light sources arranged in an equilateral triangle of 500mm sides in a plane 500mm from and perpendicular to the normal of the cornea apex.

### Table 1. Quantities used to construct our simple eye model. Other parameters needed for constructing the model described in Section 2 can be computed from these quantities using basic geometry.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cornea, anterior radius of curvature</td>
<td>7.8mm</td>
</tr>
<tr>
<td>Cornea, posterior radius of curvature</td>
<td>6.5mm</td>
</tr>
<tr>
<td>Cornea, thickness</td>
<td>0.55mm</td>
</tr>
<tr>
<td>Cornea, index of refraction in NIR</td>
<td>1.37</td>
</tr>
<tr>
<td>Aqueous humor, index of refraction in NIR</td>
<td>1.33</td>
</tr>
<tr>
<td>Lens (pupil), radius of curvature</td>
<td>10.2mm</td>
</tr>
<tr>
<td>Cornea anterior to lens distance</td>
<td>3.6mm</td>
</tr>
<tr>
<td>Iris diameter</td>
<td>12.0mm</td>
</tr>
<tr>
<td>Pupil diameter</td>
<td>≈ 2 - 8mm</td>
</tr>
</tbody>
</table>

![Simple schematic and example rendering of our eye model where, for visualization purposes, the cornea and aqueous humor have been shaded and set to be non-refractive.](image)

**Figure 2.** Simple schematic and example rendering of our eye model where, for visualization purposes, the cornea and aqueous humor have been shaded and set to be non-refractive.

## 3. Refraction

As we begin to consider the effects of refraction, we first briefly review the (currently very common) approach that we employ for encoding the iris pattern, following the presentation in [1]. First, points on the pupil-iris and iris-sclera boundaries are identified (as are any interfering eyelids) using image segmentation techniques. Next, the iris image is
Figure 3. An illustration of the effects of refraction. On the left, a rendered iris acquired at $\phi_v = 0^\circ$ is shown with its unwrapped iris pattern below it. (Note that the top of the unwrapped images represents the pupil-iris boundary). On the right, the same artificial iris is shown acquired at $\phi_v = 50^\circ$. Below it are the unwrapped image we generate by correcting for refraction as described in Section 3.

sampled in a polar-like grid at angles equally spaced about the pupil center and along radial arcs emanating from the pupil-iris boundary to the iris-sclera boundary; the result is an “unwrapped” rectangular representation, sampled on a polar grid, of the iris region. In Fig. 3, we illustrate this unwrapping process (with rendered imagery) for $\phi_v = 0^\circ$ and $\phi_v = 50^\circ$, where the iris has been textured with a few concentric rings; the refractive distortion is readily apparent in the unwrapped image for $\phi_v = 50^\circ$.

Using the geometric model described in Section 2 above, we render a series of 13 images with $\phi_v \in \{0^\circ, 5^\circ, \ldots, 55^\circ, 60^\circ\}$. We use the minimum pupil diameter (i.e., approximately 2mm or 0.167 times the iris diameter) and texture the iris surface with a series of 44 equally-spaced concentric rings. We analyze these images to quantify distortion, along the radial direction only, as a function of three variables: the viewing angle $\phi_v$, the angle in the iris-centric coordinate system (which we call the iris angle, $\theta_i$), and the relative distance from the pupil-iris boundary to the iris-sclera boundary, which we shall call $\alpha$, where $\alpha \in [0, 1]$. With this notation, the coordinates in an unwrapped image are given by $(\theta_i, \alpha)$ pairs. We define $\theta_i$ relative to the short axis of the (approximately) elliptical pupil. To simplify analysis at this point, we currently ignore distortion along the angular direction $\theta_i$. Though we did observe angular distortion in our experiments, the effects are not as significant as radial distortion. Furthermore, the results we report in Section 4 below demonstrate the potential of the technique without requiring further complexity at this early stage.

Our goal in correcting for refraction can be described as follows: Given a point $(\theta_i, \alpha)$ in the reference iris $(\phi_v = 0^\circ)$, what are the coordinates of that point, $(\theta_i, \hat{\alpha})$, in an iris image acquired at some nonzero $\phi_v$? We approximate the answer to this question by tracking the positions of the concentric rings in our 13 rendered images and generating a 3D look-up-table (LUT) whose three dimensions correspond to $\theta_i$, $\alpha$, and $\phi_v$. The values in this LUT are then the $\hat{\alpha}$ and effectively tell us how to space our sample locations along the radial lines when computing the unwrapped images for a given $\theta_i$ and $\phi_v$. To help make this idea more clear, we consider for some $\theta_i$ a point on the pupil-iris boundary, $x$, and its corresponding point on the iris-sclera boundary, $y$. In generating the unwrapped image, we sample the line connecting $x$ and $y$ at $N$ points. For $\phi_v = 0^\circ$, these sample points are equally spaced and given by $(1 - \alpha_n)x + (\alpha_n)y$ where $\alpha_n = n/(N - 1)$ for $n = 0, 1, \ldots, N - 1$. For nonzero $\phi_v$, we consult the LUT to find $\hat{\alpha}_n$ for the equally spaced $\alpha_n$ and then sample the iris image at $(1 - \hat{\alpha}_n)x_v + (\hat{\alpha}_n)y_v$, where $x_v$ and $y_v$ represent the locations of $x$ and $y$ in the nonzero $\phi_v$ image. As an example, we plot in Fig. 4 $\hat{\alpha}$ vs. $\alpha$ for $\theta_i = 0^\circ$ and $\phi_v = 50^\circ$. Note from the figure that points corresponding approximately to $\alpha \geq 0.85$ are effectively lost in the refracted image, since they are all mapped to the same $\hat{\alpha} \approx 1.0$; we account for this by zeroing these pixels in the unwrapped image and masking them in the Hamming distance comparisons (this masking is evident in the bottom corners of the corrected unwrapped image shown in Fig. 3.).
Figure 5. Top plot shows the ratio of the short-to-long diameters of an elliptical fit to the pupil vs. viewing angle. The solid line is a quadratic fit to the observed data points. The bottom plot shows the ratio of the pupil-to-iris diameters (both long and short) using elliptical fits vs. the pupil dilation factor $p$. The solid line is a linear fit to the data (correlation coefficient of 0.9993).

Referring to Fig. 4, recall that $\alpha = 0.0$ (the horizontal axis) corresponds to the minimum pupil dilation, which we shall call $p_{\text{min}}$ (equal to 0.167 relative to the iris at 1.0). If the image under consideration has a pupil dilation $p > p_{\text{min}}$, we simply compute $N$ values of $\alpha$ equally spaced between $\alpha_p = (p - p_{\text{min}})/(1 - p_{\text{min}})$ and 1.0 and find the corresponding $\hat{\alpha}$ from the LUT. We then rescale these $\hat{\alpha} \in [\hat{\alpha}_p, 1.0]$ to $[0.0, 1.0]$.

It should be evident from the discussion above that we must be able to estimate the viewing angle $\phi_v$ and the pupil dilation to apply the refraction correction. In Fig. 5, we plot some relationships related to elliptical fits of the pupil and iris boundaries under different conditions. From these plots, it can be seen that it is straightforward to determine the viewing angle and the dilation in our model. For real-world iris imagery, such relationships will obviously be more difficult to measure and more complex; this is a topic of future research and beyond the scope of this paper. In Fig. 6, we show a simple block diagram illustrating the steps of the proposed approach.

Finally, it may be apparent that the methods described above effectively implement constrained, non-rigid image registration through the use of a lookup-table (LUT). We note that unconstrained, non-rigid image registration is not quantitative and could potentially match irises that should not be matched. We should allow only physically real deformations as determined by corneal shape and viewing angle. Using a model-based approach with the LUT, the image sampling (warping) can be done easily in real-time with the appropriate constraints.

4. Experimental Results

Here we report on experimental results obtained using our eye model and the seven different artificial iris textures illustrated in Fig. 7. For each of these textures, we generated 13 images corresponding to $\phi_v \in \{0^\circ, 5^\circ, \ldots, 60^\circ\}$. The original rendered images were of size 2048 × 1536 pixels, where the iris diameter in the $\phi_v = 0^\circ$ image was approximately 560 pixels. From each of the rendered images, we took square subregions of 706 × 706 pixels that covered the complete iris region. To test against differing image resolutions, we downsampled the square (Cartesian) iris images to both 512 × 512 and 256 × 256 pixels and, for each of those two resolutions, we generated unwrapped (polar) iris images of 360 × 50 and 180 × 25 pixels. To generate iris codes for comparison, the unwrapped images were filtered with complex Gabor wavelet filters and the phase images of the results were quantized into two bits per pixel. For this task, we used the baseline code provided to NIST ICE 2005 participants; this code was originally developed by Masek [8] and is freely available online at http://www.csse.uwa.edu.au/~pk/studentprojects/libor/.
To quantify the effects of refraction on Hamming distance (HD), we compare each synthetic iris image at each viewing angle to the same iris rendered at all of the other viewing angles. This provides for viewing angle differences ranging from $5^\circ$ to $60^\circ$. The HD results for the four different combinations of image resolution, averaged over all data, are shown in the top curves (red) of Figs. 8-11. In all cases, the HD is significant when the difference in viewing angle is greater than about $10^\circ$. In the images sampled on a polar grid of $360 \times 50$ – Fig. 8 and Fig. 10 – we see that the HD exceeds the EER from [1] when the viewing angle difference exceeds about $30^\circ$. In the images sampled on a polar grid of $180 \times 25$ – Fig. 9 and Fig. 11 – the HD between the same iris at imaged at different viewing angles exceeds the EER from [1] when difference exceeds about $40^\circ - 45^\circ$.

We repeated the above measurements after using the refraction compensation methods described in Section 3. The results are shown by the bottom curves (blue) of Figs. 8-11 and the improvements (reduction in HD) are quite significant. Note in Fig. 9 and Fig. 11, for example, that the HD after correcting for refraction remains below the EER out.
to the maximum difference in viewing angle. We show in Fig. 12 the average percent improvements in HD vs. viewing angle difference for all four image resolution combinations.

![Graph](image)

Figure 12. Percent improvement in HD vs. difference in viewing angle for the four different image resolution combinations shown in Figs. 8-11. The plotted symbols here correspond to the symbols used in those previous figures.

We summarize additional data of interest below:

- For the 512 × 512 Cartesian, 360 × 50 unwrapped images the median decrease in HD was 23.5%. The maximum decrease was 54.7%, from 0.2407 to 0.1090, at a viewing angle difference of 20°.

- For the 512 × 512 Cartesian, 180 × 25 unwrapped images the median decrease in HD was 29.9%. The maximum decrease was 56.5%, from 0.2453 to 0.1067, at a viewing angle difference of 25°.

- For the 256 × 256 Cartesian, 360 × 50 unwrapped images the median decrease in HD was 21.9%. The maximum decrease was 54.5%, from 0.2300 to 0.1047, at a viewing angle difference of 20°.

- For the 256 × 256 Cartesian, 180 × 25 unwrapped images the median decrease in HD was 32.8%. The maximum decrease was 70.0%, from 0.2268 to 0.0885, at a viewing angle difference of 25°.

5. Conclusions and Future Work

The goal of this study was to determine if iris recognition accuracy might be improved by correcting for the refractive effects of the human eye when the iris is imaged with a nonzero viewing angle. We approached this problem using a simple yet anatomically approximate model of the human eye and ray-tracing software. This method provided ideal experimental control so that we could focus purely on the effects of refraction. Our results indicate that refractive distortion can cause significant errors in iris recognition and, furthermore, that by compensating for refraction, such errors can be significantly reduced. We conclude, therefore, that further research into this area is indeed a worthwhile pursuit.

Future work should include the acquisition of a database of real, off-normal iris imagery from human subjects with stringent experimental control. Furthermore, more complex and accurate models for the shape of the human eye surfaces should be constructed and investigated. For example, the pupil can be offset nasally relative to the iris center. Also, the shape of the anterior and posterior cornea surface for the average human can be represented more accurately, though with significantly more complex functions [4, 7, 9] than the simple spheres we used in this work. Models in this future work should also incorporate natural variation. Finally, in rendering a reasonable set of well-controlled test data, one might consider using more realistic iris textures [11].

References