In *Proceedings of the 2006 Symposium on Eye Tracking Research and Applications* (ETRA), ACM, New York, p. 51.

Optical Eye Models for Gaze Tracking

Jeffrey B. Mulligan*
NASA Ames Research Center

The traditional "bottom-up" approach to video gaze tracking consists of measuring image features, such as the position of the pupil, corneal reflex, limbus, etc. These measurements are mapped to gaze angles using coefficients obtained from calibration data, collected as a cooperative subject voluntarily fixates a series of known targets. This may be contrasted with a "top-down" approach in which the pose parameters of a model of the eye are adjusted in conjunction with a camera model to obtain a match to image data. One advantage of the model-based approach is provided by robustness to changes in geometry, in particular the disambiguation of translation and rotation. A second advantage is that the pose estimates obtained are in absolute angular units (e.g., degrees); traditional calibration serves only to determine the relation between the visual and optical axes, and provide a check for the model. While traditional grid calibration methods may not need to be applied, a set of views of the eye in a variety of poses is needed to determine the model parameters for an individual. When relative motion between the head and the camera is eliminated (as with a head-mounted camera), the model parameters can be determined from as few as two images. A single point calibration is required to determine the angular offset between the line-of-sight and the observed optical axis.

Two recent applications of the top-down or model-based approach [Ohno et al. 2002] [Beymer and Flickner 2003] have utilized measurements of the pupil location and shape, and the positions of one or more glints. In addition to modeling the pupil and glints, we also model the outer margin of the iris, or *limbus*. The limbus is an attractive feature for several reasons. First, unlike the pupil, it is viewed directly, without refraction by the cornea. Thus we can estimate parameters such as its size without regard to the estimation of corneal shape. Secondly, and again in contrast to the pupil, the limbus does not fluctuate in size, and so once we know its size we can make good pose estimates even when only one side of the limbus is visible, particularly when head movement is not a concern. Finally, the limbus is a strong, high-contrast feature, which may be the only measurable feature. in bad lighting or for extreme gaze angles.

Simulated data describing the position and shape of the pupil and limbus were computed using an optical simulation program. The image of the pupil was computed by exploiting Fermat's principle of least action, finding the point on the cornea for which the path from the pupil point to the camera projection center had minimal optical distance. This method provided a significant computational savings over conventional ray-tracing, because only the rays of interest were computed. The orientation of the model was parameterized with respect to the line joining the center of the model eye with the center of projection of the camera. When the model and the camera point directly toward one another, the pupil and limbus appear as concentric circles. The slant angle θ (between the camera and model axes) is the primary variable of interest.

The data describing the positions of the pupil and limbus (as a function of slant) are approximately sinusoidal, as seen in figure 1. Deviations from a perfect sinusoid arise from the effects of perspective projection and refraction by the cornea. A good fit to the position data is obtained using the following formula:

$$f(\theta) = \alpha h_L \sin(\beta\theta), \tag{1}$$

where h_L is the elevation of the plane of the limbus relative to the eye's center of rotation, and the parameters α and β are stretching factors in the vertical and horizontal dimensions, respectively. Results were computed using different radii of curvature of the model cornea. The best-fitting values of the descriptive parameters are shown in figure 2. These data may be used to estimate the optical parameters of an arbitrary eye without explicit optical simulation.

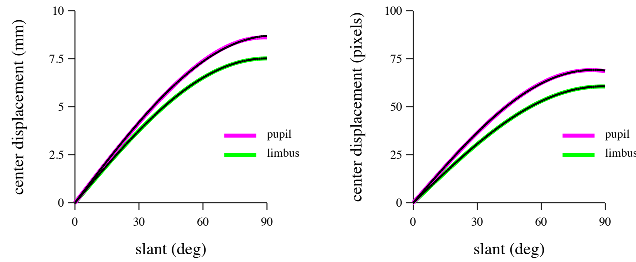

Figure 1: Center position of an elliptical fit to simulated images of the pupil and limbus. The left hand panel shows results for orthographic projection, and the results are expressed in the units of the eye model. The right hand panel shows results for a perspective camera located 75 mm from the center of the model eye, assuming an 8 mm lens and a 0.25 inch sensor with a linear resolution of 512 pixels. Corneal refraction causes the pupil to be displaced more than the limbus.

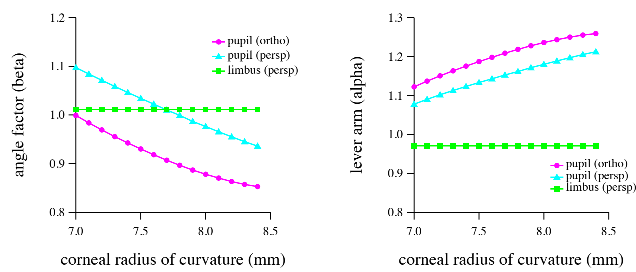

Figure 2: Parameter values for descriptive model fits to simulation data, such as that shown in figure 1.

*e-mail: jmulligan@mail.arc.nasa.gov

References

BEYMER, D., AND FLICKNER, M. 2003. Eye gaze gracking using an active stereo head. In *Proc. IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR)*, vol. 2, IEEE, 451–458.

OHNO, T., MUKAWA, N., AND YOSHIKAWA, A. 2002. Freegaze: a gaze tracking system for everyday gaze interaction. In *ACM Eye Tracking Research and Applications*, ACM, 125–132.