A Single-Camera Remote Eye Tracker

André Meyer, Martin Böhme, Thomas Martinetz, and Erhardt Barth

Institute for Neuro- and Bioinformatics, University of Lübeck
Ratzeburger Allee 160, D-23538 Lübeck, Germany
{meyera, boehme, martinetz, barth}@inb.uni-luebeck.de
http://www.inb.uni-luebeck.de

1 Introduction

Many eye-tracking systems either require the user to keep their head still or involve cameras or other equipment mounted on the user's head. While acceptable for research applications, these limitations make the systems unsatisfactory for prolonged use in interactive applications. Since the goal of our work is to use eye trackers for improved visual communication through gaze guidance [1, 2] and for Augmentative and Alternative Communication (AAC) [3], we are interested in less invasive eye tracking techniques.

In recent years, a number of so-called "remote" eye-tracking systems have been described in the literature (see e.g. [4] for a review). These systems do not require any equipment to be mounted on the user and allow the user to move their head freely within certain limits. The most accurate remote eye tracking systems that have been described in the literature to date use multiple cameras and achieve an accuracy of 0.5 to 1.0 degrees [5–9]. We need this level of accuracy for our applications but would ideally like to achieve it using a single fixed wide-field-of-view camera for reasons of cost and complexity. That single-camera systems can achieve an accuracy in the range of 0.5 to 1.0 degrees is demonstrated by a commercial system [10], but no implementation details have been published, and we are not aware of any similar system being described in the literature.

In this paper, we will describe a single-camera remote eye tracking system we are working on that is designed to achieve an accuracy in the range of 0.5 to 1.0 degrees.

The hardware of the eye tracker consists of the following components: (i) A single calibrated high-resolution camera (1280x1024 pixels), (ii) two infrared light-emitting diodes (LEDs) to either side of the camera that illuminate the face and generate corneal reflexes (CRs) on the surface of the cornea, and (iii) a display located above the camera and the LEDs (see Fig. 1).

The eye tracking software consists of two main components: The image processing algorithms that are used to extract the location of the pupils and corneal reflexes from the image and the gaze estimation algorithm that is used to calculate the position the user is fixating on the screen.

These two components were developed independently and have recently been integrated into a running system, which will be shown at the workshop. No accuracy measurements have been made yet on the complete system, but tests

Fig. 1. Physical setup of the eye tracking hardware, consisting of a single high-resolution camera below the display and two infrared LEDs to either side of the camera.

on simulated data show the gaze estimation algorithm can achieve an accuracy of one degree or better.

2 Algorithms

Due to space constraints, we can only give a brief outline of the image processing and gaze estimation algorithms but will demonstrate the functionality of the system at the workshop.

The algorithm used to extract the locations of the pupils and CRs from the camera image is based on the Starburst algorithm [11], which was modified to fit the needs of the remote eye tracking setting. An open source implementation of this algorithm is available under the name "openEyes", but we chose to reimplement the algorithm for better integration within our existing computer vision and eye tracking framework.

In general terms, the pupil and CR location extraction algorithm proceeds as follows: The locations of the CRs are extracted by applying a difference of Gaussians and searching for maxima; the approximate pupil centre is determined as the darkest pixel in the vicinity of the CRs; contour points are identified on rays shot from the centre of the pupil as well as on secondary rays shot from these primary contour points; and an ellipse is fitted to the these contour points.

The gaze estimation algorithm is based on a physical model of the eye. Figure 2 shows the eye model, which models the following components of the eye:

- The surface of the cornea. This is modelled as a spherical surface with a centre of curvature CC and a curvature radius of r_{cornea}. The corneal surface plays a role in two effects that are relevant for eye tracking: First, the corneal reflexes are generated by reflections of the infrared LEDs at the corneal surface; and second, the image of the pupil that we observe through the cornea is distorted by refraction at the corneal surface.

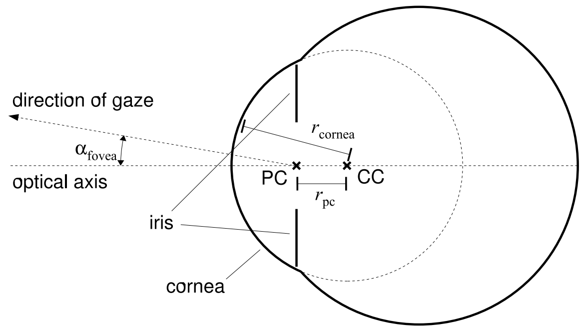

Fig. 2. Eye model used for gaze estimation. PC: Pupil centre. CC: Cornea centre. The model contains three user-dependent parameters α_{fovea}, r_{cornea} and r_{pc} (see text for an explanation).

- The pupil centre, referred to as PC. This is the point located at the centre of the pupil disc (we make the idealized assumption that the pupil is perfectly circular). The pupil centre PC is a certain distance from the centre of corneal curvature CC, and we call this distance r_{pc}.
- The angular offset between the optical axis of the eye and the direction of gaze (referred to as α_{fovea}), which is caused by the fact that the fovea does not lie on the optical axis but is offset temporally and slightly upwards (at the moment, we only model the horizontal component of this offset).

Given the position and orientation of an eye relative to the camera, the eye model predicts where the pupil and the CRs should be observed in the camera image. The inverse problem can also be solved, allowing us to determine the direction of gaze from the pupil and CR position. The values of the model parameters for a particular user are determined by asking the user to fixate a series of calibration points and finding the set of parameter values that best explain the observations.

3 Results

The gaze estimation component was tested individually on simulated test data. To mimic the effects of camera noise, a certain amount of random error was added to the measurements of pupil centre and CR position.

Table 1 shows the eye model parameters that were estimated for varying amounts of camera error, along with the resulting gaze estimation error. Assuming a maximum measurement error of half a pixel, which we believe our image processing algorithms can achieve, we obtain a gaze estimation error of about one degree.

To date, no accuracy measurements have been made on the complete system; we plan to present these results at the workshop.

Table 1. Results of testing gaze estimation algorithm on simulated data.

camera error	r_{cornea}	r_{pc}	α_{fovea}	mean gaze error
0.0 px	7.93 mm	4.52 mm	5.98 °	0.22 °
0.1 px	7.53 mm	4.28 mm	6.16 °	0.22 °
0.3 px	7.53 mm	4.26 mm	6.15 °	0.59 °
0.5 px	7.34 mm	4.12 mm	6.20 °	1.04 °
1.0 px	6.94 mm	3.84 mm	6.36 °	2.22 °
2.0 px	6.04 mm	3.24 mm	7.07 °	5.03 °
ground truth	7.98 mm	4.44 mm	6.00 °	

Acknowledgments

Research was supported by the German Ministry of Education and Research (BMBF) under grant number 01IBC01 with acronym *ModKog*.

References

1. Itap: Information technology for active perception website (2002) http://www.inb.uni-luebeck.de/Itap/.
2. Barth, E., Dorr, M., Böhme, M., Gegenfurtner, K.R., Martinetz, T.: Guiding eye movements for better communication and augmented vision. (same volume)
3. COGAIN: (Network of excellence on communication by gaze interaction) http://www.cogain.org.
4. Morimoto, C.H., Mimica, M.R.M.: Eye gaze tracking techniques for interactive applications. Computer Vision and Image Understanding **98** (2005) 4–24
5. Yoo, D.H., Chung, M.J.: A novel non-instrusive eye gaze estimation using cross-ratio under large head motion. Computer Vision and Image Understanding **98** (2005) 25–51
6. Shih, S.W., Wu, Y.T., Liu, J.: A calibration-free gaze tracking technique. In: Proceedings of the 15th International Conference on Pattern Recognition. (2000) 201–204
7. Ohno, T., Mukawa, N.: A free-head, simple calibration, gaze tracking system that enables gaze-based interaction. In: Eye Tracking Research and Applications (ETRA). (2004) 115–122
8. Brolly, X.L.C., Mulligan, J.B.: Implicit calibration of a remote gaze tracker. In: Proceedings of the 2004 Conference on Computer Vision and Pattern Recognition Workshop (CVPRW '04). Volume 8. (2004) 134
9. Beymer, D., Flickner, M.: Eye gaze tracking using an active stereo head. In: Proceedings of Computer Vision and Pattern Recognition (CVPR). Volume 2. (2003) 451–458
10. Tobii: (Tobii 1750 eye tracker, Tobii Technology AB, Stockholm, Sweden) http://www.tobii.se.
11. Li, D., Winfield, D., Parkhurst, D.J.: Starburst: A hybrid algorithm for video-based eye tracking combining feature-based and model-based approaches. In: Proceedings of the IEEE Vision for Human-Computer Interaction Workshop at CVPR. (2005) 1–8