CAMERA BASED EYE-TRACKING SYSTEM FOR MEDICAL PURPOSES

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Abstract: Cortical blindness patients suffer from losses in their visual field. A therapy is possible by stimulating the borders of their field of view by signals represented on a therapy display. During the training the patient has to follow the viewing instructions precisely. Any movements of the eyes lead to a stimulation of wrong regions in the patients field of view, which causes the therapy to fail. To increase the training efficiency, it is necessary to register and compensate changes of the line of gaze by adjusting the stimulus position. Another intention of the new method is to reduce the need for medical supervision, so that the treatment can be performed at the patient's home. For such a telemedical use a low cost robust Eye-Tracking system has been developed.

Introduction

In this paper we present an optical Eye-Tracking system. Compared to commercially available systems, low cost standard components are used. The system is developed to optimize the therapy of cortical blindness [1] where the patient's line of gaze has to be tracked to adjust the stimulus position. The system concept also enable usage in a range of different applications.

Tracking Concept

The therapy takes place in a dark room with a display to stimulate the patient's eye. Thus the use of the visible spectrum for tracking purposes is not possible. In order not to disturb the patient during the therapy, an infrared sensitive camera and IR LED lighting is used (Figure 1). The LED positioning will be explained below. An image processing algorithm computes the coordinates and properties of relevant image objects. The recognition is based on the principle of the *Pupil and Corneal Reflection* [2]. With such a procedure the different reflection characteristics of pupil and cornea are used. The pupil appears as a dark ellipse in the camera image. The surface of the cornea reflects IR light to the camera. Changes in the viewing direction cause a change in the distance between the pupil and the corneal reflections. Thus the relation between them is used for gaze estimation.

As shown in Figure 2, a centred viewing angle results in a corneal reflection positioning close to the pupil. Changes in the viewing direction leads to an offset between the pupil's centre and the position of the corneal reflection depending on the viewing direction. Here two light sources are used to guarantee a tracking with a wide area of operation. Otherwise, the reflection point would be outside the iris. In this case the contrast would not be enough for a reliable detection. According to this, at least one reflection point is available for gaze point estimation. The calculation depends on the geometrical eye characteristics which will be discussed in the next section.

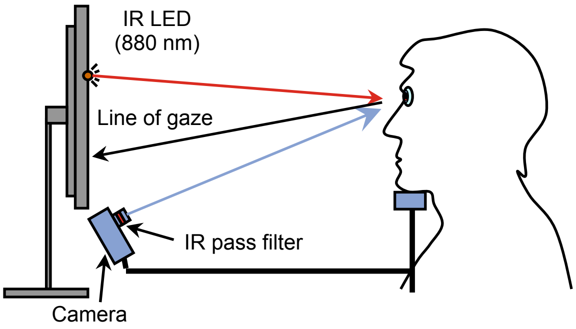

Figure 1: Eye-Tracking system

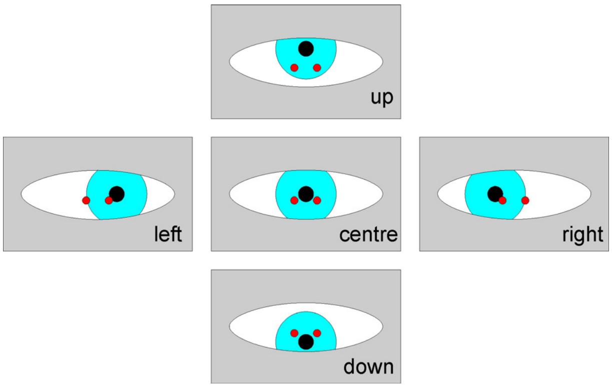

Figure 2: Relation between pupil and corneal reflection with different viewing directions

System Modelling

Geometrical Eye Characteristics:

Using the different reflections of the pupil and the cornea makes it necessary to analyse the geometrical structure of the eye and the eye movement characteristics. In the following paragraphs the used eye model is discussed.

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In the first approximation the eye could be described by a sphere. This model is easy to analyse but contains too many simplifications. Referring to medical literature [6], [8] the curvature of the frontal eye surface (cornea) differs from the eyeball curvature. Neglecting these differences would result in measurement inaccuracy and finally to errors in the gaze point estimation.

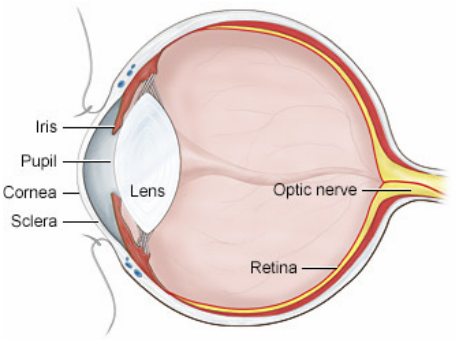

Figure 3: Anatomy of the Eye [8]

A new eye model based on the different curvatures of eyeball and cornea is used in our calculations. As shown in Figure 4 the eye can be modelled with two spheres. The first one is the eyeball with a radius of r_b (~11-12 mm). Its centre is positioned in the origin (x/y/z) of the eye coordinate system (ECS). The second sphere describes the corneal curvature. Its centre has an offset k to the axis origin. The offset differs from one person to the other and is around 5-6 mm. The corneal globe radius r_c is around 6.5-7 mm. Looking to different directions results in a moving of the corneal globe centre $\vec{x}_c$ in the ECS. To describe the position depending on the viewing direction, it is necessary to analyse the eye movement first.

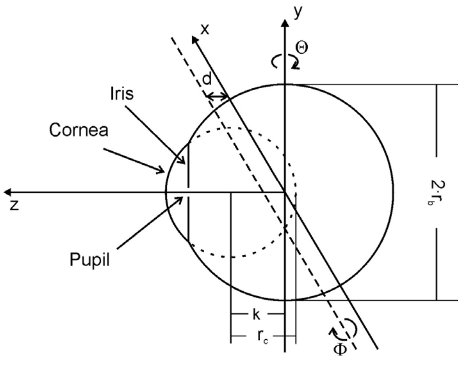

Figure 4: Model of the eye

Muscles of the Eye:

The eyeball is moved by six extrinsic muscles, four recti muscles and two oblique muscles which are responsible for the eyeball rotation [9]. The muscles of the eye are shown in Figure 5. The lateral rectus muscles abduct the eye (away from the nose) and the medial rectus muscles adduct the eye (towards the nose). The lateral and medial muscles move the eye only in the horizontal plane. The vertical motion is a little more complex. Four muscles (superior rectus, inferior rectus, superior oblique and inferior oblique) control the vertical motion.

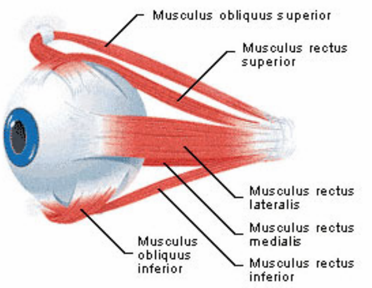

Figure 5: Muscles of the eye [10]

The easiest way to explain the action of these muscles is to isolate the superior/inferior rectus from the superior/inferior oblique. When the right eye is fully abducted (away from the nose), only the superior and inferior rectus muscles can elevate and depress the eye. This is purely a mechanical property due to the axis of the eye lining up perpendicular to the superior/inferior muscles.

When the right eye is fully adducted (towards the nose), only the inferior and superior oblique muscles can elevate and depress the eye. This is again due to mechanical properties of the attachment of these muscles. From Figure 5 it can be derived how the superior oblique muscle will depress the eye when the eye is looking at the nose. The inferior oblique will elevate the eye.

All four of these contribute to the vertical motion depending on the position of the eye. If the eye is looking straight forward, about 50% of vertical motion is due to the inferior/superior oblique muscle combination and 50% is due to the superior/inferior rectus muscle combination.

Eye Rotation Axis:

The easiest way of model implementation would be if the eye had one centre of rotation for its vertical and horizontal rotation. Since 1825 many investigations were made [7]. Early results had only one rotation centre for both directions. Recent studies, using more precise techniques, have established that a fixed centre of rotation is just an approximation. It moves rarely greater than 1 mm. Furthermore certain subjects have a centre of rotation for vertical movements, situated about 2 mm further forward than for horizontal movements. On the other hand, the variations of the opening of the eyelids and raising and lowering the eyes cause notable translations.

In consideration of the investigation results the model has two independent rotation centres as depicted in Figure 4. The horizontal rotation centre is placed in the ECS origin. The vertical rotation centre is situated by d on the positive z-axis. The translation by raising or lowering the eye will be neglected.

Model Integration

Currently a 5-point calibration is used. After an initial calibration the calculated parameters are saved to be available for further training sessions. With a linear approximation the view point is calculated from the distance between the pupil's centre and the corneal reflection. With a fixed head position on a chinrest reliable results are obtained. Changes in the head positioning leads to estimation inaccuracies. The developed model will be used in further steps instead of the approximation for the view point calculation. The first advantage of the model is a precise description of the movement and behaviour of the eye which enables the calculation of the position of the pupil's centre and the corneal reflection in the 3D space depending on the current viewing direction. The second advantage results from the use of two light sources. The distance between the left and right reflection point depends on the distances between the eye, the camera and the IR LED arrangement as well as the viewing direction. The centre of the corneal curvature, on which the IR light gets reflected, moves by changing the viewing angle. By known or calibrated model parameters the distance can be calculated and used for the gaze point estimation on the monitor.

IR Lighting

As shown above, the arrangement of the IR lighting has strong impact on the reliable separation between pupil and iris as well as the detection of reflection points. An unfavourable positioning of the IR LED array can result in reflection point obstruction under some circumstances. Investigations were made concerning the dependencies of the eye-reflection from the illumination angle, the pupil reflection behaviour and the covered field of view. During the investigations IR sources were positioned in the monitor edges. The test persons had to follow marks on the screen. For each light source the limits of a detectable corneal reflection were registered. The positioning angles of the light sources are listed in Table 1.

Table 1: IR LED measuring position

Light source		Illumination angle	
		hor.	ver.
Upper left	(ul)	-24.5°	35°
Upper right	(ur)	34.5°	35°
Bottom left	(bl)	-24.5°	-19°
Bottom right	(br)	34.5°	-19°

Figure 6 shows the detection limits using the illumination from the lower monitor edges. The field is limited in the worst case to +10° vertically and 12.5/22.5° to the left/right side. Combining both, left and right illuminations results in the expansion of the detectable field to the whole monitor width.

A similar behaviour can be concluded from Figure 7. Combining both, left and right upper illuminations the whole width can be detected. The vertical range is limited to -10° viewing angel. With greater viewing angles the corneal reflection is covered by the upper eye lid and can not be used for gaze point estimation. Using the upper left and right light source together would make the detection possible over the whole monitor width but is still limited vertically.

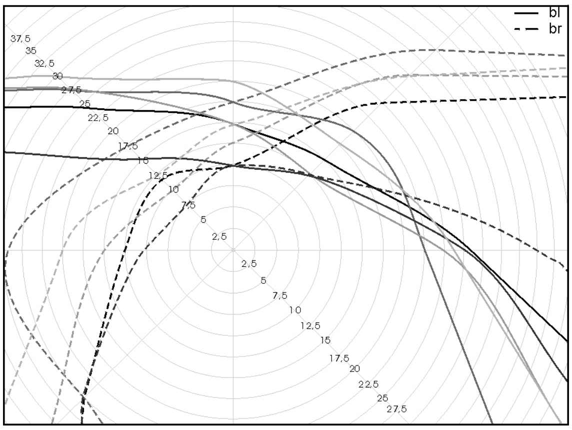

Figure 6: Detection limits with bottom left/right illumination

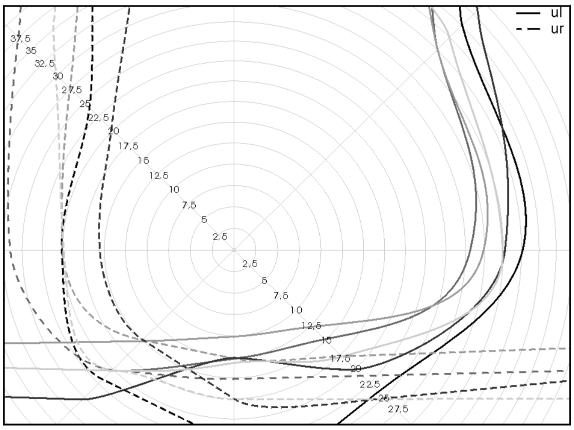

Figure 7: Detection limits with upper left/right illumination

Moving the upper IR LEDs down would move the detection limit towards the lower monitor margin. A similar behaviour can be noticed by moving the lower IR LEDs up. Combining the results leads to vertically centred positioning of the IR light sources. In this case two light sources would be enough to extend the detectable range to the whole monitor range. In the current system two sources were attached to the left and right monitor margin.

Image Processing

The real-time object recognition is realised with a multi-step image processing algorithm [3] [4]. The algorithm detects the position of the pupil and the reflection points in the camera image. After a dynamical thresholding an edge detection is applied. Connected edge elements are grouped to contours. An ellipse fitting algorithm [3] validates the pupil's shape and size and calculates the pupil's centre (Figure 8.1). To speed up the computation the search region is limited to a small region of interest around the estimated pupil. It is necessary to detect both, left and right, reflection points (Figure 8.2). Depending on the reflection size and its distance and angular range to the pupil's centre wrong reflection candidates are eliminated.

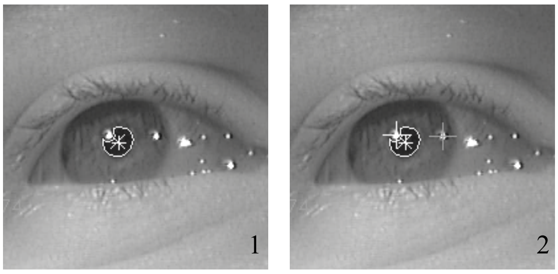

Figure 8: Detection of pupil and corneal reflection

Because of the use of two IR light sources independent calibration parameters are calculated for each one. Special calibration methods are needed to estimate the viewing direction from a calculated relation between the pupil centre and the reflection points. During the calibration procedure eye and system parameters are calculated. With a successful calibration the viewing direction can be estimated. A pincushion correction compensates geometrical errors. In further steps alternative calibration methods will be analyzed and compared to increase the reliability of the patient's focus point calculation on the screen.

Discussion and Conclusion

The current Eye-Tracking system allows the tracing of the patients line of gaze. The system offers benefit for a telemedical treatment of cortical blindness. Thus, the therapy costs can be reduced and the reliability can be increased. In addition to the medical treatment this Eye-Tracking system could be used in a multitude of other applications like Human-Machine-Interaction, marketing research purposes or in driver supervision systems in automotives.

References

[1] WIDDIG W., PLEGER B., ROMMEL O., MALIN J.-P., TEGENTHOFF M. (2003): 'Repetitive visual stimulation: A neuropsychological approach to the treatment of cortical blindness', NeuroRehabilitation 18, pp. 227-237, IOS Press

[2] OHNO T., MUKAWA N. (2002): 'A Free-head, Simple Calibration, Gaze Tracking System That Enables Gaze-Based Interaction', Proceedings of the symposium on ETRA 2002: Eye Tracking Research & Application Symposium, pp. 125-132

[3] AL NAHLAOUI M. Y., JOSTSCHULTE K., KAYS R., SCHMITZ J. (2005): 'Kostengünstiges Eye-Trackingverfahren für die ambulante Sehtherapie', 6. Würzburger Medizintechnik Kongress, Fachverband Biomedizinische Technik e.V., Wetzlar

[4] AL NAHLAOUI M. Y., JOSTSCHULTE K., KAYS R., SCHMITZ J. (2005): 'A Cost-efficient Eye-Tracking System for Ophtalmologic Home Therapy', 39th Annual Congress of the German Society for Biomedical Engineering, Nürnberg

[5] FITZGIBBON A. W., PILU M., FISCHER R.B. (1999): 'Direct Least Squares Fitting of Ellipses', IEEE Transactions on Pattern Analysis and Machine Intelligence 21, no. 5, pp. 476-480

[6] FARKAS L.G. (1994): 'Anthropometry of the Head and Face', New York, Raven Press

[7] LE GRAND Y., EL HAGE S.G. (1980): 'Physiological Optics', Springer-Verlag Berlin Heidelberg New York

[8] Lions Eye Health Program, Internet site address: http://www.lehp.org

[9] UC Davis, School of Medicine, Internet site address: http://cim.ucdavis.edu

[10] Dres. Curschmann, Fachärzte für Augenheilkunde, Internet site address: http://www.curschmann-lasik.de