A Precise Eye-Gaze Detection and Tracking System

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ABSTRACT

This paper describes a real-time contact-free eye-gaze tracking system that bases its accuracy in a very precise estimation of the pupil centre. The eye camera follows the head movements maintaining the pupil centred in the image. When a tracking error is produced, the image from a camera with a wider field of view is used to locate the eye and quickly recover the tracking process. Four infrared light sources, synchronised with the shutter of the eye camera, are used to produce corneal glints. Its special shape has been exploited to allow the optimisation of the image processing algorithms developed for this system. Special care has been taken in limiting the illumination power and working way below the dangerous levels. After a calibration procedure, the line of gaze is determined by using the pupil-glint vector. The glints are validated using the iris outline with the purpose of avoiding the glint distortion due to the changes in the curvature on the ocular globe. The proposed algorithms determine the pupil centre with sub-pixel resolution, minimising the measurement error in the pupil-glint vector.

Keywords

Pattern recognition, image processing, eye-tracking, gaze-tracking.

1. INTRODUCTION

The line of gaze determination has been the subject of a great number of studies, with applications in very different fields including medical research for oculography determination, car drivers behaviour characterisation, and even to build computer interfaces for handicapped people [Kim99].

Systems based on different technologies have been implemented, in many cases with some devices mounted on the person head. Also, non-intrusive systems have been developed [Mor00] and are being used in many applications [Tal99].

The system described in this paper approach the problem of gaze detection by considering an application for tracking the gaze of a person driving a car, though it can be used for many applications. In this case, a non-intrusive system is the most suitable one in order to maintain the conditions for the usual behaviour [Pap98] in such a way that the driving process is not disturbed during the experiment.

The main objective of this work has been building a non-intrusive eye-gaze tracking system based on the images taken by conventional video cameras and performing real-time tracking and analysis [Beb00].

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2. GENERAL SYSTEM OVERVIEW

The system analyses an image of the eye and determines the gaze direction by computing the vector defined by the pupil centre and a set of glints generated in the eye by an infrared illuminator. To optimise the resolution, the vector has to be as large as possible, therefore a very narrow field of view (NFV) is needed in the eye camera. In this situation, to centre the eye in the image, the camera has to be moved to follow the eye and compensate for the head movements. When, due to a sudden head movement, the eye gets out of the NFV camera image, the eye is quickly located using another camera, this one with a wide field of view (WFV) [Sin99].

The change in the curvature between iris and sclera, can provoke distortions of the glint complicate the determination of its co-ordinates and its geometrical characteristics. The glint can also disappear for strong torsions of the eye.

The use of two illuminators to guarantee at least one valid glint [Ebi94] is not enough, therefore a configuration with four illuminators has been chosen for this system. In case of having more than one valid glint, they have to be identified. The specific shape of the illuminators allows the optimisation of the identification algorithm. With this approach, the centre and radius of the iris has to be determined to reject the glints found outside the iris area.

Another problem is the influence of external illumination variations in the quality of the image [Smi00]. To minimise it, the shutter of the NFV camera is set to 1/2000s and a powerful infrared illumination is used. Special care has been taken in limiting the amount of illumination power applied to the eye in order to avoid the risk of hurting it, following the ophthalmologic recommendations and working way below the dangerous levels.

Each illuminator consists of 20 high intensity infrared LED with aperture angle of 6º and located at an average of 75 cm from the eyes. That enables enough face illumination and the generation of the glints. This illumination is synchronised with the electronic shutter of the NFV camera to generate 500 microseconds long flashes every 20 milliseconds.

Figure 1 shows a general view of the system with the four illuminators, the NFV video camera mounted on a pan-tilt unit to centre the eye in the image and the WFV camera for taking images of the face.

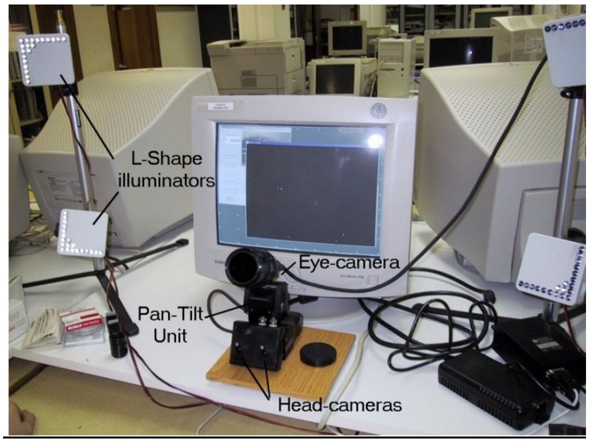


Fig. 1. General view of the system at the lab.

The NFV camera has a 1/2” infrared sensitive CCD with minimum illumination of 0.1 lux. A focal length of 150 mm is obtained with a 75-mm lens and a 2× extender. The F-stop has to be set over 5.6 to allow for enough depth of field. The WFV camera has a 1/3” infrared sensitive CCD with a minimum illumination of 0.5 lux.

The system is able to process in real time 25 frames per second for images of 768×576 pixels. It permits gaze tracking for vision angles over ±45º.

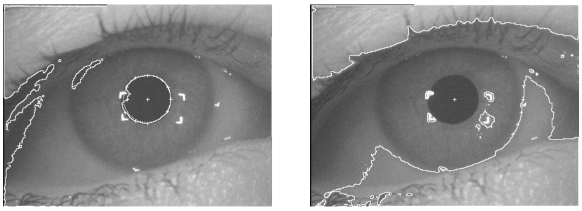
3. PUPIL AND IRIS CENTRES AND RADIUS DETERMINATION

The pupil-glint vector is used to determine the gaze direction, so the positions of the pupil centre and the glint have to be determined. The iris radius has to be computed to validate the glints.

The final precision achieved in the point of gaze is directly dependent on the vector resolution. Therefore, the proposed algorithm determines the pupil centre with sub-pixel resolution, minimising the measurement error in the pupil-glint distance. This algorithm has the following phases:

Estimation of the pupil centre. All the pixels under a given threshold (close to black) are selected in the original image and its mass centre is computed. This process is then repeated using the pixels in an area around the previously obtained centre to remove far stains or noisy areas not relevant in this analysis. This iterative process ends when the co-ordinates of the centre are stabilised.

Searching of the pupil contour. Once the pupil centre has been estimated, its contour is determined. For saving computation time the image is clipped to include only a small area around the iris. By filtering the image, a noise reduction is performed and all pixels above the pupil threshold are inverted. Then, a border detection algorithm based on the Laplacian operator is applied (Fig.2a).



a) b)

Fig. 2. a) Pupil contour and centre determination
b) Iris radius determination

Determination of the pupil centre and radius. The detected pupil has to be validated to avoid further propagation errors. Moreover, its centre has to be computed accurately. The pupil contour must have a circular shape so, if this shape is not confirmed, an error is returned indicating to the rest of the system that the pupil has not been found. With this purpose a new algorithm has been developed. It is based on a searching procedure that starts from the previously estimated centre, applied to *n* diagonals crossing the pupil contour at specific points. If all the intersection points are equidistant to the centre, its shape is confirmed, and the pupil radius is determined. Out of distance points are suppressed and the radius is recomputed.

The same diagonals are used for accurately computing the pupil centre, obtaining it with sub-pixel resolution (Fig.2a). Firstly, both very long and very short diagonals are rejected. Centres of the remaining diagonals are used to compute the pupil centre. The wrong centre values are discarded by voting.

Searching of the iris contour. The goal of this phase is to validate the glints located inside the iris. First, the image is filtered, a noise reduction is performed and all pixels above the threshold of the iris are inverted. A binary image is obtained, with the pupil, iris and eyelashes in black, while the skin and sclera are white coloured. A Laplacian operator is applied on this image for edge detection. Finally, a new binarization will give the iris outline in white over a black background.

Determination of the iris radius. By identifying the iris centre with the pupil centre, the search for the iris contour is made following radial lines. Out of distance points are rejected, and the radius is computed with the rest of the points (Fig.2b).

4. GLINTS DETECTION

An algorithm that uses blob analysis has been developed for identifying the glints on the eye image (Fig.3). The parameters of each of the original image blob are computed and labelled. The algorithm is carried out in two phases: 1) Blob analysis, to isolate all the regions fulfilling some restrictions. 2) Identification of the actual glints among all the isolated blobs.

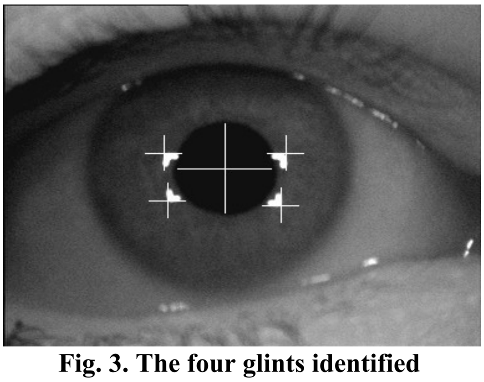


Fig. 3. The four glints identified

After binarizing the image, it is scanned looking for the origin of a new blob, initiating a propagation process that will visit all the neighbours with connectivity 8, using recursive calls to the same procedure. Labelling of each pixel is performed, and the central moments and the limits of the blob are computed in an accumulative way.

Undesired blobs are rejected before starting the last identification of the glints. Two techniques are used: 1) Rejecting out of size blobs and 2) Rejecting the blobs outside the iris.

Once the wrong blobs have been rejected, the identification phase based in the L shape of the glints is carried out. An index from zero to three is assigned for each glint, starting from the higher left corner and going clockwise.

The described algorithm includes the computation of the absolute co-ordinates of the corner of each valid glint. When more than one glint can be identified, redundant information about the point of gaze is obtained.

5. CALIBRATION METHOD

To correlate the co-ordinates of the point of gaze (X_G, Y_G), and the components of the pupil-glint vector (dx,dy), a previous calibration is needed. This relationship depends on the eye geometry and its relative position to the glint and to the point of gaze. The calibration is performed using the data gathered with the user fixing the gaze on several points.

An analytic study of the problem indicates that a quadratic function of (dx,dy) is a good approximation for (X_G, Y_G). The analytic relationship between dy and Y_G can be expressed as:

$$\frac{y_G - a}{\sqrt{y_G^2 - 2ay_G + b^2}} = K_1(dy) + K_2$$

Where a, b, K_1 and K_2 are constants that depend on the geometry of the problem.

In this quadratic function, the co-ordinates of X and Y can be considered independent, or else can have a possible inter-relation in the form:

$$x_G=C_0+C_1(dx)+C_2(dy)+C_3(dx)(dy)+C_4(dx)^2+C_5(dy)^2$$

$$y_G=K_0+K_1(dx)+K_2(dy)+K_3(dx)(dy)+K_4(dx)^2+K_5(dy)^2$$

The determination of the values for C_i and K_i is done by polynomial regression, by means of a function that generates the regression matrix R (using the data obtained during the calibration phase) and apply an algorithm for generating the coefficients:

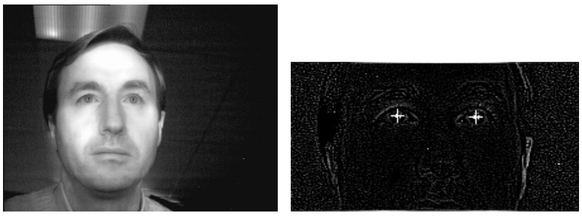
$$C = (R^tR)^{-1}R^tX$$

$$K = (R^tR)^{-1}R^tY$$

The calibration process presents two critical aspects: 1) A very accurate determination of the pupil centre is needed, and 2) Training is needed in the gaze fixation, because measurement dispersion can be observed if looking several times at the same point.

6. FACE AND EYE DETECTION

Face analysis algorithms are used in different fields and applications [Mar00] and many of them are based on the search of the skin colour in the gathered image [Bak99]. Face detection is used in this system to locate the eye when, due to a sudden head movement, its image gets out of the NFV camera field of view. Although this kind of movements are not very frequent, they are wide enough for the system to loose track of the eye. The monochrome images generated by a WFV camera are appropriate to make an accurate determination of the eye position.



a) b)

Fig. 4. a) Original image. b) Eye location

First, the unwanted reflections (fig. 4a) that would hinder the detection of the face contour are eliminated by the application of a contour detection algorithm based on the Laplacian operator.

The algorithm to determine the face contour applies an image filter and a blob detection to isolate the face area, obtaining an image that only includes the face contour in which the eyes and other features like mouth or eyebrows can be distinguished. Applying antropometric considerations the image is clipped in such a way that only an area around the eyes is included. Finally, to locate the eyes, again blob detection is applied (fig. 4b). Results are validated using antropometric distances.

These algorithms have been integrated with the rest, providing an efficient system to track and determine the point of gaze of a user, which is especially robust for the usual head movements.

7. CONCLUSIONS

A real-time contact-free eye-gaze tracking system prototype has been developed. The system processes in real time 25 frames per second for images with 768×576 pixels taken by the eye camera. It allows gaze tracking for vision angles over ± 45º.

The system uses sub-pixel determination of the pupil centre to improve the accuracy and four specially shaped infrared illuminators to allow eye gaze determination, even with high eye or head torsion. The illuminators are synchronised with the camera shutter to provide immunity to changes in the external illumination, but avoiding hurting the eye by controlling the illumination power.

By processing the image of a wider field of view camera and determining the absolute eye position, the system quickly recovers from tracking errors due to sudden head movements or slow blinking.

The prototype has been tested for various subjects and lighting conditions and it is a robust system with high potential to be used in different applications.

8. ACKNOWLEDGMENTS

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