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NON-INTRUSIVE INFRARED-FREE EYE TRACKING METHOD

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Abstract: *In the paper a technique of eye tracking based on visible light is presented. The approach described does not require an additional hardware equipment used in the infrared eye tracking system. First, examples of existing eye tracking techniques were presented. Then, the proposed algorithm of image processing and the process of determining the eye position are described. The engineered eye tracking application was tested and the results of these tests are presented.*

1 Introduction

The development of computer technology enables an intelligent analysis of processed images delivered by camera connected to the computer screen. It may be said that machines can see. Obviously, this skill depends on the complexity and the advancement of the implemented image processing algorithms. Computer vision implies analyzing, evaluating and interpreting data. Knowing the gaze direction could provide very useful information. The technique to carry out this kind of analysis is called gaze tracking. Nevertheless, estimating where the person is looking at relies in fact on eye tracking. Typically eye tracking approaches rely upon infrared illumination.

The paper presents an eye tracking technique alternative to the infrared illumination which is based on the visible light spectrum analysis. Eye trackers working in visible light are often called infrared-free (IR-free) eye trackers.

The IR-free eye tracking system engineered at the Multimedia Systems Department of Gdansk University of Technology (GUT) was implemented on the Macintosh platform running *Mac OS X*. The application itself is not compatible with the PC-based platforms, however the proposed algorithms work on any type of computer.

There are many potential applications of the eye tracking system. Nowadays, there exist many commercial gaze tracking systems, and they achieve very high levels of accuracy. However, they are still very expensive making this technique unsuitable for many potential users. Moreover, they perform poorly outdoors due to the presence of ambient infrared light. The technique described in this paper could be regarded as an alternative, inexpensive approach to eye tracking.

2 Review of eye tracking techniques

Systems that track the gaze point in order to know where or what a person is looking at were researched already at the end of the 19th century. These first attempts were related to observing a reader and were performed by using direct observations of the reader's eye [7]. This field was continuously being explored during the 20th century. Until the beginning of the 21st century, eye tracking was recognized as an area of the scientific research rather than an issue for general public. Only some years ago, eye tracking technologies turn to be more precise, and as a result eye tracking systems were rediscovered as very good candidates to offer an affordable way to the so-called Alternative and Augmentative Communication (AAC). It is worth mentioning that disabled people (particularly, paralyzed persons) could find in this emerging technology a very simple way to enhance quality of their communication with the outside world.

As a result of the continuous research in this field, an important number of technologies and methods were discovered and applied to track eye movements and gaze point. The most important technologies are based on the infrared illumination and on visible light (IR-free).

2.1 Infrared eye trackers

The eye tracking system based on the IR illumination is often used in head mounted and hands-free interfaces.

In order to estimate the fixation point the eye is illuminated by infrared diode light which is invisible to the user and does not disturb his/her interaction with the computer. The IR sources, properly installed on the camera, produce unique reflections on the user's eye (so called 'glints'). The IR illuminating eliminates unwanted artifacts in an eye image [6]. Another advantage of using the IR light is that the strongest feature in the image is the contour of the pupil rather than the limbus. This is because both the sclera and the iris strongly reflect infrared light, while only the sclera does that with the visible light. Tracking the sharp contour of the pupil instead of the iris is a best option, since its small size makes it less likely to be occluded by the eyelid. The drawback of this technique is that daylight can interfere with the system because of the important ambient IR spectrum.

The dedicated algorithm analyzes the image captured by the camera in order to detect the IR reflections present on the eyeball and performs mathematical calculation resulting in coordinates of the point where the user is looking at [6]. Fig. 1 presents the idea of an eye tracking system equipped with four sections of IR diodes localized in the computer display corners. IR diodes form a shape of quadrangle on the cornea. The point of fixation is determined based on relation between positions of 'glints' which are static and pupil center which moves when a person changes his/her direction of looking.

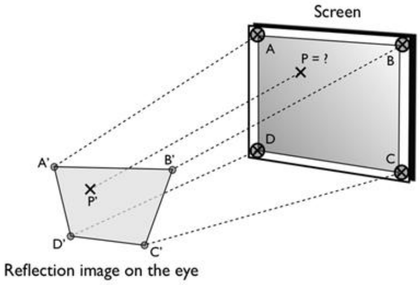


Fig. 1. Projection of the screen corners (A, B, C and D) on the user's eye (A', B', C' and D') and center of pupil P' related to the gaze point P [5].

2.2 Infrared-free eye trackers

Most of the existing eye tracking systems and algorithms take advantage of the IR illumination, since it heavily increases the achieved accuracy. However, some eye tracking algorithms do not rely upon IR light. This kind of eye tracking systems is able to work correctly even with a typical webcam [9].

Blink detection

The blink movement is used as a reference to locate the eyes in the image. This approach is based on the fact that duration of an involuntary eye blink is very short and therefore the frames during this lapse will likely be equal except in the region of the eyelids. It is assumed that the user cannot avoid this involuntary blinking. Exploiting these facts, Chau et al. proposed a system to detect the blink and to track eyes achieving up to 95.3% accuracy at 30fps with a cheap UBS webcam [4]. Li and Parkhurst developed a similar system, which become an open-source software package. The camera in their system is mounted on the extended arm of a chin rest [9].

Bhaskar et al. describe blink detection using frame differencing combined with the flow computation [1]. Firstly, possible motion regions are determined by obtaining the difference image of the consecutive frames. If movement is detected, the optical flow is computed within these regions. The flow computation is a technique that permits to determinate the direction of moving, unsteady features in an image. Fig. 2 shows two sample images illustrating the system introduced by Bhaskar et al.

a)  b) 

Fig. 2. Blink detection algorithm: a) movement detected with frame differencing; b) performance of the optical flow computation [1].

One-circle algorithm

Wang et al. presented an algorithm for estimating the gaze point from a single image of one eye. The system did not need the IR illumination, but it could be combined with an IR tracker to increase the accuracy of the system.

The principle of this algorithm is based on the observation that although the contour of the iris can be approximated into a circle in 3D, the 2D perspective view of the limbus captured by the camera becomes an ellipse. The ellipse can then be projected into the original circle and its orientation can be calculated. The gaze, defined as the normal to the iris circle, can be estimated from this correspondence.

An ellipse can be back-projected into space on two circles of different orientations. However, the correct solution can be disambiguated using an anthropometric property of the eye. Relying on a simplified eye model, Wang et al. observed an obvious fact that the distance between one eye corner and the center of the eyeball is the same as the distance between the other eye corner and the center of the eyeball. The algorithm of the above described approach is presented in Fig. 3. First, from the image of the eye the approximating ellipse fitting the iris is calculated. This ellipse can be interpreted by two different ways as the 2D projection of a 3D circle. Each circle, representing a potential pupil, has a corresponding sphere normal to its surface, representing the eyeball, according to the eye model. The distances between the eye corners A and B and the center of the sphere are compared. Knowing that both distances must be equal, the correct solution can be disambiguated, and the gaze direction is taken as the optical axis of the eye (the line passing through the center of the eyeball and the center of the iris) [12].

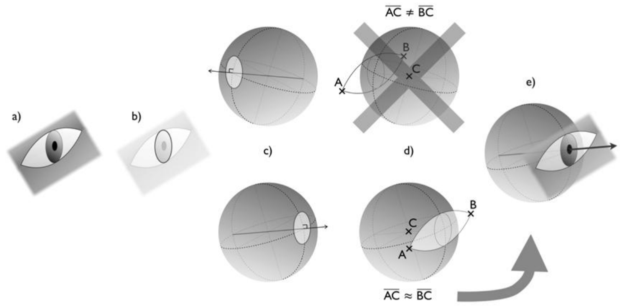


Fig. 3. One-circle algorithm [11].

3 Eyes and characteristic points tracking

In this Section the main algorithm steps underlying the developed IR-free eye tracker were presented. They are as follows: localization of the eye region, exact determination of the limbus (the contour between the iris and the sclera) [12] and finally the localization of the eye corners.

3.1 Localization of the eye regions

The first step of detection of the gaze is to locate the eye regions, in order to extract the necessary features. By investigating various approaches how to achieve this task, it was decided to employ Haar cascade object detector.

Haar cascade was trained with eye images to directly locate the eyes. Freely available eye detectors were used – for the right and left eyes – trained by Castrillon-Santana - each with 7000 positive samples [3].

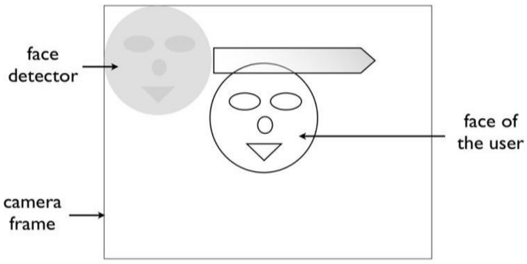


Fig. 4. Face detection with Haar cascade.

Once the face is correctly detected, the eye detector is applied. It is not necessary to apply it on the whole face, to avoid unnecessary amount of computation time. Observing general features of the face composition, it is possible to assume that eyes are always situated within the same region: when a face is divided in four horizontal stripes of the equal height, eyes are likely to be found in the second stripe from the top.

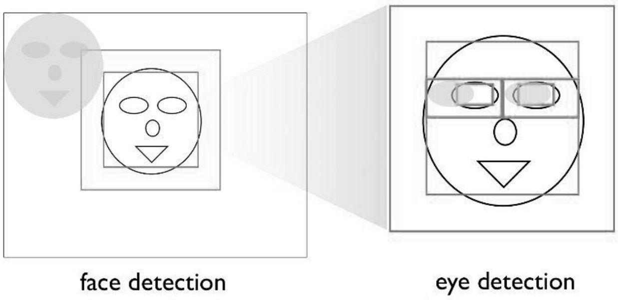


Fig. 5. Face and eye detection.

Going a step further, this horizontal strip should be divided to equal parts, corresponding to the right and left eye. Finally, one can apply right and left eye detectors to these two well-defined eye regions.

3.2 Iris detection

Once the eye regions have been localized, the eye features can be detected. The next step of the algorithm is then to determine the center and the radius of the contour between the iris and the sclera assuming that it has a perfect circular form. This assumption is in fact very accurate, particularly when the face of the user is directly in front of the camera. However when the eye is not exactly in front of the camera, the image of the limbus becomes an ellipse because of the projection of the 3D circular shape into the 2D image. Although this effect is of a little importance for the assumed purposes, it could in fact be the goal for the future improvement of the system. Furthermore, some eye trackers, try specifically to take advantage of this observation to estimate the gaze direction.

Preprocessing of the eye image

First of all, an equalization of the histogram of the eye image should be performed. This operation influences the increasing contrast of the image. Furthermore, the histogram equalization makes the system unaffected by light conditions and therefore its accuracy better. The next operation (filter) sets thresholds and binarizes the image. It generates a new image in which pixels are white when the corresponding pixel in the original image had the brightness smaller than the threshold value. In the experiments a value of 50 was used. This threshold was found empirically. One further advantage of the histogram equalization is that there is no need to change the threshold value dynamically. The next step of the preprocessing eye image is an opening operation which removes artifacts. In the last step, the edges are retrieved with the Canny filter. The scheme shown in Fig. 6 presents the whole process.

Fig. 6. Steps of preprocessing procedure: (1) original image; (2) equalizing the histogram; (3) setting a threshold; (4) artifacts removal; (5) edge map (Canny filter).

After obtaining the edge map, the circular Hough transform can be calculated. Estimating the range of radii relies on the information stored from the previous camera frame analyzed. If in a frame an iris had a radius of R, the circular Hough transform can be iterated to the radius range from R−2 to R+2. If this information is not available, the value of the radius is set between 1/5 and 1/9 of the eye region width. These values were found empirically.

Circular Hough transform (CHT)

The CHT algorithm was implemented to detect the limbus. There are many examples in the literature showing this method as very suitable for this purpose [8][10].

The edge map and circles with several radii are needed in order to find a limbus. It is assumed that the center of the circle belongs to each pixel of the contour determined by Canny filter. The locus of points sharing this property is a circle of the radius R and the center at the given pixel. The process of marking these points could be thought out as a “vote” by the pixel (x,y) for a series of circles. A high number of votes indicate the center position of the searched circle. The main principles of this method are shown in Fig. 7.

If the value of radius is not known, the value which ensure the maximum value of the center of the iris can be used. Fig. 8 presents a process of looking for an optimal value of the radius.

Fig. 9 shows the detected iris tagged by the contour. The best fitting circle in this case confirms a circle of 19 pixels. The visualization of the CHT for this case is presented in Fig. 8c.

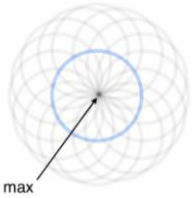
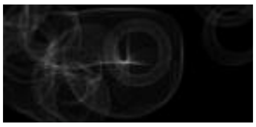
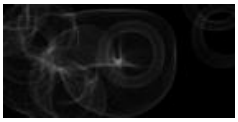


Fig. 7. The main principles of the circular Hough Transform.

a)  b) 

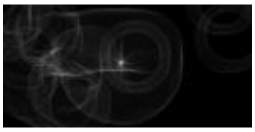
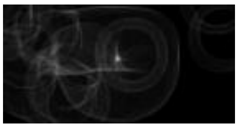
c)  d) 

Fig. 8. Iteration of the CHT within a range of several possible radii: a) 17, b) 18, c) 19 and d) 20 pixels.

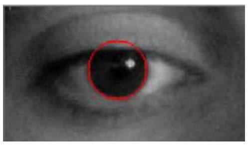
a)  b) 

Fig. 9. Iris detection: a) edge map; b) iris contour found in the eye image.

3.3 Eye corners localization

Eye tracking based on video image processing requires detecting some reference points. In IR eye tracking systems reflections of IR light on the cornea are constant theoretically, therefore they are regarded as the reference points. In the color images without the characteristic IR reflections other points should be used as reference. It was assumed that eye corners detected in the image can fulfill this role. Although there exist some literature sources on this subject, this still remains a difficult task to perform [11]. One of the reasons is the fact that the eye corners can be defined less accurately than other features like e. g. the center of the iris. The main principle used in the research is shown in Fig. 10. The region of interest (ROI) of the eye is the area determined in the earlier step.

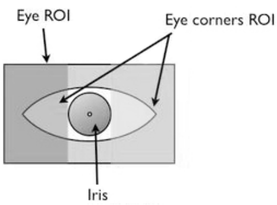


Fig. 10. Regions of interest of eye corners

The eye corners are supposed to be found in two regions of the eye ROI. The left and right parts of the eye ROI should be selected, starting from both ends of the iris contour and covering until the limits of the eye ROI. These ROIs are showed in Fig. 10. It was observed that the variance of the brightness of the pixels in both eye corner ROIs is of a great importance. Vertical scanning the pixels in these regions on the grayscale image allows to observe that close to the iris the variance tends to be very high, since it covers regions of skin (middle pixels), eyelashes (dark pixels) and sclera (light pixels). Scanning the pixels close to the outer limit of the eye ROI results in very low variances of brightness, because the pixels of the skin are more or less equal middle grey.

However it is necessary to know at every moment which eye (right or left one) is analyzed. This is because the left or right eye corners are inner or outer corners depending on the eye. The principle of eye corners detection is presented in Fig. 11.

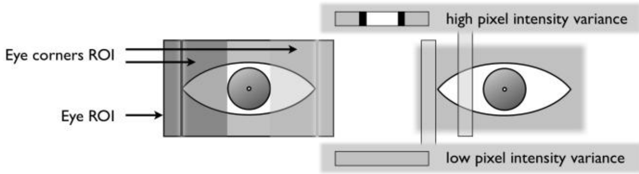


Fig. 11. Eye corners detection principle.

It occurred in experiments that the method based on variances returns good results for the outer eye corners, but not for the inner ones. Some examples of the complete detection performed by the developed eye tracker are shown in Fig. 12. In Fig. 12b it can be observed that inner eye corners are detected incorrectly.

a) 

b) 

Fig.12. Examples of detection results: a) part of the frame with found irises; b) part of the frame with detected eye corners.

5 Concluding remarks

The most important feature of the system engineered was the fact of using a simple laptop with no added hardware. The eye tracking systems existing in the market are very complex from the hardware point of view, making the systems expensive and unsuitable for potential users.

Another important point was the fact that the eye tracker was able to work without requiring the user to keep the head localized in the middle of the screen. In fact, the eye tracking system allows for the user's movements across the field of the view of the camera.

The application engineered enables a very reliable localization of the eye regions and relatively accurate detection of the iris contour. Although the eye corners were detected correctly, the method still needs an improvement, especially for the inner corner detection. Nevertheless, the goal of the implementation of IR-free eye tracker was achieved because it shows that it is possible to develop the eye tracking system without utilizing the infrared diodes.

It seems that the approach presented, namely the detection of the eye corners deserves a closer attention in order to obtain a reliable reference point for the system. Therefore, the research in this field should continue in this direction, focusing on the accuracy and at the same time on the simplicity of the system.

Acknowledgements

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