Pupil Detection Algorithms for Eye Tracking Applications

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***Abstract*— In this paper two pupil detection algorithms (based on Starburst and circular Hough transform) for the eye tracking application are presented. The operation of the eye tracker device depends mainly on the infrared video camera performances, PC processing power of the video signals and the precision of the pupil detection algorithm. Both algorithms used for the eye tracker implementation have been comparatively analyzed in different conditions for a set of subjects in the field of assistive technology. The performances of the proposed system, given by algorithm running time, cursor stability on the user screen and algorithm accuracy, have been presented.**

***Keywords*— eye tracking, pupil detection, Starburst, circular Hough transform.**

I. Introduction

In this paper two pupil detection algorithms used for eye tracking application are comparatively presented.

The proposed eye tracker system based on this algorithms is used in assistive technology in order to bidirectional communicate with severe neuro-motor disabled patients.

Taken into consideration that the care of these patients is very expensive, they requiring permanent monitoring, we propose a simple communication solution between them and healthcare professionals, based on keywords technology. The proposed assistive system can be used by these patients in order to establish a simple communication with their family or caretaker and for medical investigation, too.

The software component of the system can be adapted to the patients' needs, without the help of the administrator.

II. Materials and Methods

An eye tracker is a device used to acquire real time data from the gaze direction of the human eyes and transitioning this information into cursor movement on the user screen. This type of devices can be used in assistive technology applications for communications between patients with neuro-motor disabilities and specialized healthcare professionals.

The hardware component of the eye tracking system consists of two main components: the infrared camera used to acquire the video signal and the PC that runs the pupil detection algorithms. The video camera used in our application has a 640x480 resolution, with a modified IR light emission and an IR filter. This type of device is used in order to take advantage of the dark pupil technique that allows a better discrimination of the pupil in comparison to the iris and the sclera of the eye.

The eye tracking algorithms were implemented in MATLAB and both have similar structures from the standpoint of algorithm stages (Fig. 1), which are: 1) Eye image acquisition; 2) Image filtering; 3) System calibration on the nine target points; 4) Pupil center coordinates detection in each frame provided by the IR video camera; 5) Mapping of the detected pupil center from the eye image to the cursor movement on the user screen; 6) Algorithm optimization in order to stabilize the cursor movement on the user screen using different techniques: real time filtering and spikes removal [1].

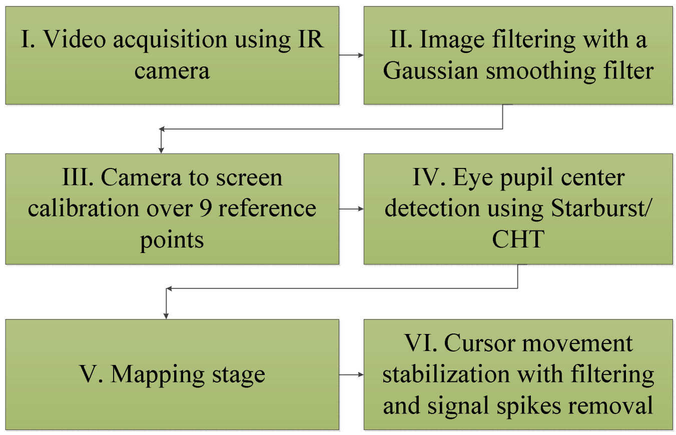

Fig. 1. Pupil detection algorithm implemented using Starburst/CHT

A. *Pupil detection algorithm*

The pupil detection algorithm (PDA) has to offer a robust, fast and adaptive process in order to be used efficiently in assistive applications, such as neuromotor patients' telemonitoring and bidirectional patient-health professional communication. The pupil detection algorithm presented in this paper was based on either circular Hough transform (CHT) or Starburst. The stages of the PDA are: 1) acquisition of the input image with a low cost IR camera of 640x480 resolution, 2) image filtering using a 3x3 mask smoothing filter, 3) eye pupil center detection algorithm.

B. Circular Hough Transform

The first method used to detect the pupil center is implemented using the CHT which is an algorithm that identifies the three parameters of a circle: the center coordinates x_c and y_c and the circle radius r, represented in the following parametric equations for the circle contour [2].

$$x = x_c + r \times \cos(\theta) \tag{1}$$

$$y = y_c + r \times \sin(\theta) \tag{2}$$

The CHT is considered a two dimensional type of algorithm when the circle radius is known because in this case we only have to determine the center coordinates x_c and y_c. When using this algorithm for eye pupil detection however, the circle radius is unknown or varies over time, so it is necessary to implement the CHT for an unknown who translates into a three dimensional problem in which we have to determine the center coordinates and the circle radius [3].

The principle of the CHT relies on the property of the edge points to describe circles with optimal radius r that intersect in the same point that is the center of the circle we want to detect, as presented in Fig. 2.

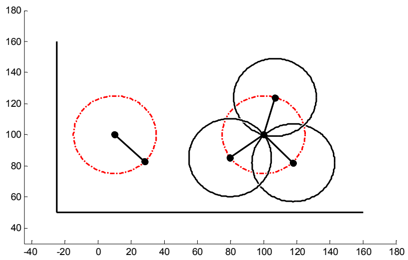

Fig. 2. CHT principle

C. Starburst algorithm

The second method used relies on the Starburst pupil detection algorithm which is a combined model and feature based approach algorithm which works on the premise of optimal balance between running time and detection accuracy. The stages and the work flow of the Starburst algorithm are presented in Fig. 3.

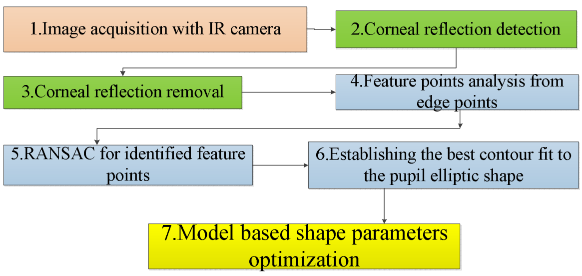

Fig. 3. Starburst algorithm stages

The first stage, image acquisition with an IR camera is required because of the dark pupil technique which relies on the light reflection of the iris, making the pupil more discernable.

The second and third stages of the algorithm are implemented in order to remove noise that is introduced by the corneal reflection, which is the brightest spot on the IR image. Due to its nature, corneal reflection can be identified and removed by applying an adaptive detection threshold specific to each frame. Because the corneal reflection usually is found in the area delimited by the pupil edge we apply the detection and removal threshold on a square area of h=150 pixels. Initially, the threshold is set to the highest value in order to obtain a binary image. The identified areas correspond to the corneal reflection or other bright areas such as the eyelids' joint. The ratio between the largest area and the medium value of all the identified areas is determined and used as a threshold which is lower than the initial maximal threshold. The lower threshold allows us to identify pixels with intensity on the gray scale that is lower than the maximum threshold value 1. This allows us to extend the identified corneal reflection area in order to better approximate its real size [4]. The optimal ratio is considered the highest value that has the largest corneal reflection area with the lowest number of false detections. Thus the corneal reflection location is given by the geometric center $[x_{cr};y_{cr}]$ of the largest area identified using an adaptive threshold. The area localized is approximated with a circle fit and in order to determine the actual corneal reflection, which is larger than the localized area, we apply a bivariant Gaussian distribution to determine the radius r_{cr} with the highest drop of the Gaussian distribution, also known as the standard deviation radius. The extended corneal reflection area has the radius $2.5 \cdot r_{cr}$ and should cover approximately 99% of the actual corneal reflection area [5]. The initial value of r_{cr} is given by:

$$r_{cr} = \sqrt{Area / \pi} \tag{3}$$

The forth to sixth stages refer to the actual pupil contour detection. We begin by establishing the most likely position of the pupil center. For the first frame pupil center is determined by selecting the center of the image as the origin point. For the following frames, the most likely pupil center is the pupil center determined for the previous frame. We then evaluate derivatives (Δ) of N number of radii from the initial point by analyzing each pixel, until the threshold value φ is surpassed. Due to the use of the dark pupil technique, only the positive derivatives (increased intensity on the respective radius) are taken into consideration as possible candidate points for the pupil contour. If the threshold isn't surpassed, and the radius reaches the image border, on that radius there is no point to be considered as a possible candidate [6].

For each candidate point found, we repeat the previous process, with radii situated in the interval $\gamma = \pm 50$ degrees around the radius used to determine the candidate point. This step is similar to the radii drawn from the initial point, meaning that each candidate point will create a new set of candidate points that follow the same rule of the derivative higher than the threshold value φ. This allows determining the points situated on the ellipse contour of the pupil, however there is also the possibility to generate additional points that are not situated on the pupil contour. The number of radii generated by candidate points is variable, depending on the ratio $5\Delta/\varphi$, where Δ is the derivative value of the candidate point analyzed.

Fig. 4. Ellipse pupil contour detection stages using Starburst algorithm

Based on this ratio, the minimum value of radii generated by a candidate point is 5 because $\Delta \geq \varphi$. The radii that are determined from each candidate point situated on the pupil contour will converge in the point situated in the center of the pupil, as presented in Fig. 4.

The two stages of the actual pupil contour estimation (stages forth to sixth of the Starburst algorithm) are used in order to improve detection in cases with badly selected initial point (the center of the image). This type of implementation also improves detection for a situation where the eye movement is too fast of the video device has a low frame rate. A pupil contour could be established only by taking into consideration the situation presented in Fig. 4a), where all the candidate points are determined by drawing radii from the initial point, but if the initial point is not the center of the pupil, the ellipse contour in this case will have a very high offset. Thus, the algorithm runs a series of iterations from the candidate points, as presented in Fig. 4b). The location of the determined candidate points will be the starting location for the following iteration. If the center of the image corresponds to the pupil center, only one iteration will be necessary, an unlikely event due to camera position and the physiological traits of the subjects [7]. For other situations, the algorithm will run a series of iterations until the radii from candidate points intersect into one point which is the pupil center.

The best fitting of the ellipse contour is realized using the Random Sample Consensus (RANSAC) algorithm for model based fitting. This type of algorithm is used for the case of candidate points situated in other zone than the pupil contour, also known as outliers. These points are the source of inaccurate contour fitting. The points situated on the pupil contour and are used in the process of ellipse fitting are known as inliers. The RANSAC algorithm is essentially an iterative process that utilizes only a subset of random candidate points for model fitting and selects from all the subsets the one that has the best fit. This is advantageous in pupil detection, because in some cases the number of outliers can be high, due to various factors that decrease the quality of the image used to detect the pupil contour [8].

Inliers are characterized by the value of the distance to the ellipse contour lower than a threshold value. This threshold is determined as a probabilistic model of the expected error. Inliers points are all situated on the pupil ellipse contour.

III. Experimental Results

The operation and performances of the eye tracker device implemented on the base of both algorithms have been tested for specific situations of assistive technology. The communication with neuromotor disabled people is done with an eye tracking system by using keywords technology. The user screen is divided into four equal quadrants that display various ideograms, as Fig. 5 shows. During the tests, the users move their gaze between the centers of these quadrants with equal pauses between them, in the order 1-2-3-4, shown in Fig. 5.

The cursor movement tracking on the user screen and cursor coordinates on the X and Y axes for both pupil detection algorithms based on circular Hough transform (a) and Starburst (b) are presented. The eye tracker tests confirm that the system based on Starburst algorithm shows a more increased precision than the one based on the circular Hough transform, but it is noisy, which leads to a worse cursor stability on the user screen.

The tests for both algorithms have shown that we have to reach a trade-off between the algorithm running time and the precision. When using the CHT algorithm, the running time is influenced by the number of radii we have to test in order to obtain a better detection of the pupil center coordinates. When using the Starburst algorithm the running time is influenced by image quality and the number of bright areas on the image (other than the corneal reflection). Also, the RANSAC process induces noise due to the fact that the pupil shape will modify every iteration of the algorithm. This means that the pupil center position will vary with each frame. We implemented a real time filtering process in order to improve the precision of the algorithm and the stability of the cursor on the user's screen [9]. The optimal compromise for an eye tracking application is established at a frame rate of 10-15 fps. Test have also shown that the running time for both algorithms is dependent on the CPU processing power [10].

IV. Conclusions

We implemented and compared two pupil detection algorithms: a parameter based algorithm in the CHT and a model and feature based algorithm in Starburst.

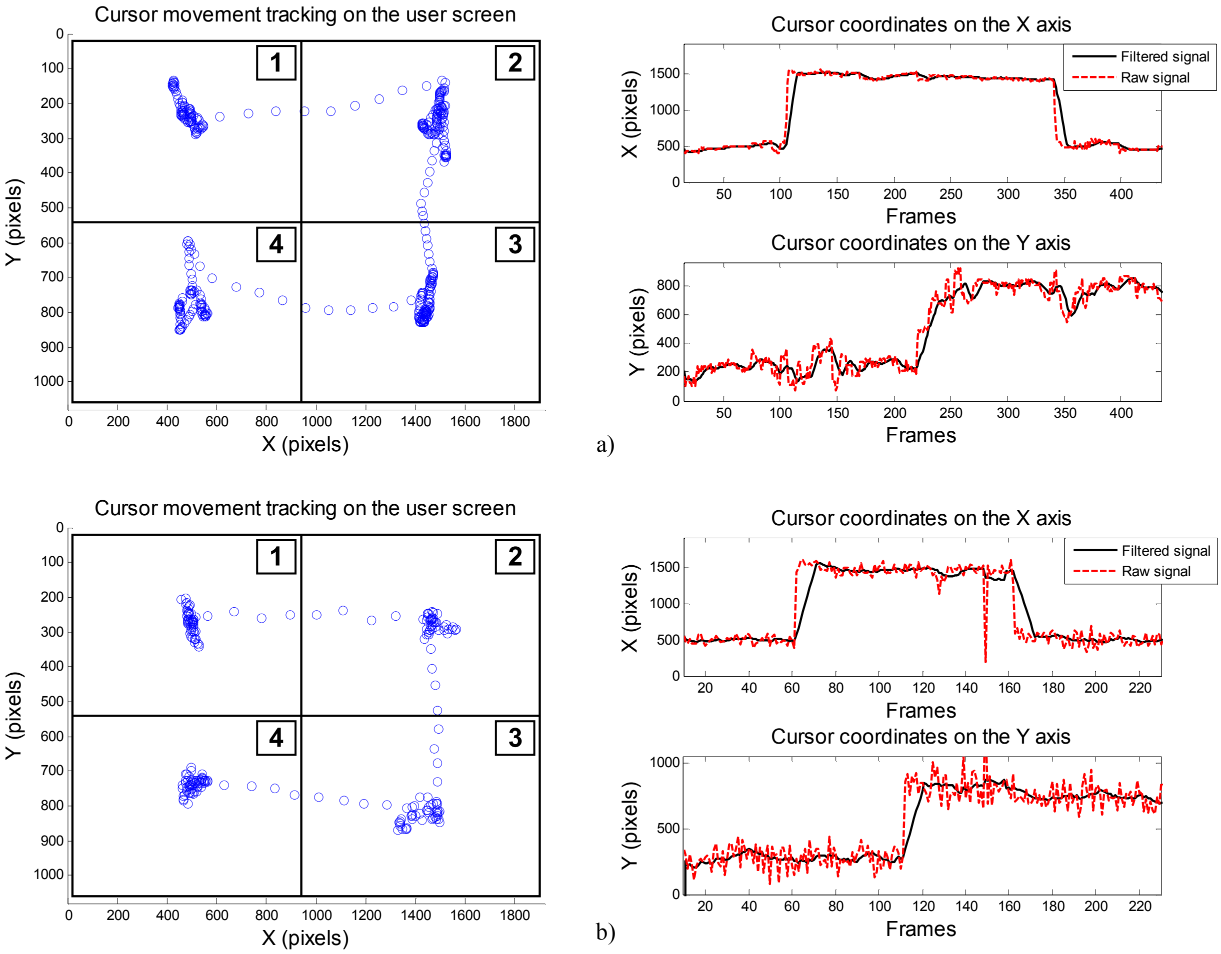

Fig. 5. Cursor movement tracking on the user screen and cursor coordinates on the X and Y axes for both pupil detection algorithms: a) circular Hough transform; b) Starburst

We compared the two algorithms, integrated in the proposed eye tracking application for neuromotor disabled patients, by means of algorithm running time, precision of pupil center detection and cursor stability on the user screen.

The determined eye pupil center coordinates were real time filtered in order to improve cursor stability, with a Gaussian smoothing filter and spikes removal technique has been used.

Both the algorithms had good performances for the desired application, but the Starburst algorithm offers better accuracy in cursor movement with higher noise levels due to the high disparity of the pupil center position from frame to frame.

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