A pupil center detection algorithm based on eye color pixels differences

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Abstract - In this paper we present a new algorithm for pupil center localization. The face and eyes of the target subject are detected using the Cascade Classifier algorithm based on Haar-like features. A histogram equalization method is employed to increase image contrast. The core feature of our pupil center detection consists of an adaptive template matching procedure applied on the eye region image that integrates specific constraints related to location and color proprieties of areas surrounding the pupil in order to compute the precise pupil center. Experimental results demonstrate the efficiency of the algorithm by assessing the correctness of the pupil center detection with respect to a ground truth reference. This procedure will allow further development of a system that facilitates social interaction of impaired people by analyzing their eye movements and translating key zones of visual attention focus into sentences that alleviate their communication.

Keywords: **face detection, eye detection, pupil edge detection, pupil center, HSV space filtering.**

I. INTRODUCTION

Humans perceive a large amount of the surrounding information by means of their visual perception. In this case the eyes have an important role in everyday life. Using digital image processing techniques we can analyze particular features of eye movements and correlate them to real life factors or situations that requires focusing ones visual attention. In this regard, in [1] it is studied the pupil dilatation as a result of focusing the attention of the participants. Other study demonstrates that pupil diameter is modified by stressful or relaxing circumstances [2].

Continuous evaluation of eye movements can provide insight data about intended user actions that could be used as inputs in applications that require user interaction [3]. Perceived user actions are effectively used by applications in research areas like: psychology, human-computer interaction, or virtual reality, to decipher a various range of user inputs.

Detection of eyes and pupils is achieved by approaches based on models made employing classifiers trained with the stances of the target objects. One procedure that detects the position of both pupils computes the first pupil position with high precision and the second location is approximated by means of symmetry between the eyes [4]. Another recent algorithm [5] uses the OTSU method and the Hough transform to determine the center of the pupil. An iris description method based on the pupil location detection and limbus location estimation was used with promising results in real scenarios [6].

In the paper we propose an algorithm that is part of a larger project focused on building a system devoted to help totally immobile people to communicate by using letter selection on a screen with the help of the eyes in order to form words and sentences by means only of image processing techniques without any other additional device.

The proposed method uses color and geometric features of the eye region to achieve a high degree of accuracy for pupil center detection. The distinct features employed by our algorithm are the uniform colored areas and the central placement of the pupil area consistent in most eye region images. Small amplitude eye movements are sensed and quantified by computing the variation of position for pupil center coordinates with a confident accuracy.

The implementation uses an adaptive method to highlight features of the Region Of Interest (ROI), by adjusting parameters to obtain an enhanced image from the preprocessing step. Parameters are coerced with respect to eye image size, image brightness and ROI position. The following operations are included in the preprocessing step: histogram equalization, HSV filtering to improve color saturation of white areas, image binning and conversion from HSV to Grayscale space. Each row of the ROI is then processed in order to compute the difference between nearby pixels in order to determine if the row is a part of the pupil area or not. Multiple row intervals, which could comprise the pupil area, are found by considering that the highest discontinuities between two pixels in a row define a new possible target interval.

The final result is assured by the algorithm using a validation step that checks if the target interval is endorsed by white pixels, positioned at the beginning and at the end of the target interval. Further validation is achieved by sorting the target intervals using the amount of specific black pixels and selecting one described as the best fit for border pixels of pupil region.

II. PUPIL CENTER DETECTION ALGORITHM

The pupil center detection algorithm consists of the following steps: preprocessing, detection of the pupil border and detection of the pupil position. In the following, we

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present the mathematical expressions that showcase our algorithm and describe in detail the principle of operation.

1. Preprocessing step

In this step, an enhanced image is obtained from the original one by applying known methods for increasing image brightness and contrast. Thus, first, the ROI is established by detecting the human face and eyes position using the Cascade Classifier method along with Haar-like features.

In order to increase the image luminosity and to highlight the white area of the eye, our method modifies the parameters of the pixels in the HSV space. The image representation in HSV space is split in three channels that are used to process the original image in order to enhance the visibility of white eye areas and to highlight the pupil region.

The brightness of the image for the *H* channel is calculated using the following formula:

$$B_{RH} = \frac{100}{M*N*255} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} P_{ij} \quad (1)$$

where M and N are the number of rows and columns respectively and P_{ij} is the pixel value in HSV color space according to the i,j location determined with respect to a conventional reference.

The same equation is used to compute the brightness of the image in the *S* channel. These two values of brightness and the image size are employed to change the brightness of the image and to increase white pixel values. The expressions that characterize the pixel changes are expressed using the following formulas:

$$P_{ij\ new} = P_{ij\ old} - F_H \quad (2)$$

$$P_{ij} = P_{ij\ new} * F_{S1} - F_{S2} \quad (3)$$

P_{ij} represents the pixels of the image obtained by applying the above transformations, where F_H, F_{S1} and the F_{S2} are constants applied by the algorithm to change the pixel values in the *S* channel of the image in order to emphasize the values of the white pixels. Since our algorithm is designed to work with Grayscale images, the processed frames are converted from HSV to Grayscale color space. At the end of this step the contrast of image is increased by histogram equalization.

2. Detection of the pupil border

The following description of our algorithm refers to a row of pixels belonging to the ROI. It repeats for all M rows of the ROI. For each vector of pixels, selected using a ROI from the eye image, the maximum and the minimum values are computed using the following equations:

$$P_{min} = \min(P_j) \quad (4)$$

$$P_{max} = \max(Pj) \quad (5)$$

where $j \in [0,\ N\text{-}1]$ and $P_j \in [0,\ 255]$, N is the number of pixels in a raw of the ROI. Therefore P_{min} and P_{max} are the smallest and the highest values of the pixels vector. The values of data contained by a row located in the center of the pupil and the correct pixel intervals that should be detected are shown in Fig. 1.

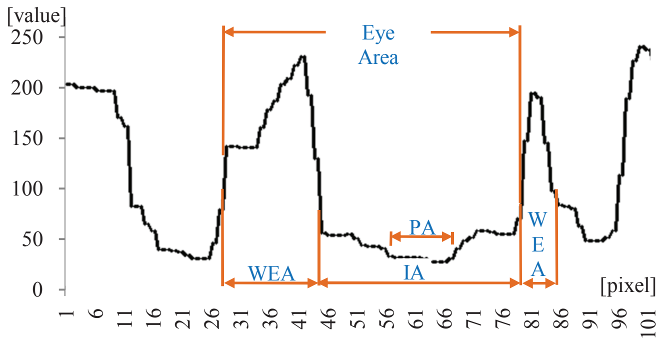

Fig. 1. The values of a row that go through the center of the iris. WEA is the white eye area, IA represents the iris area and PA is the pupil area.

The main function is to determine the longitudinal borders of the iris or pupil in case the examined eye has a light colored iris.

In a row it is possible to find more than one pixel interval bounded by two border pixels. For this shortcoming, when there are multiple intervals, it is selected only the one that has the most pixels with the lowest values, the most black pixels. This procedure may lead to good results since the pupil area has the highest amount of dark pixels in the ROI. To compute the position of the border pixel, our method uses the pixel of the current location and the one of the next location.

The border pixel is described in accordance with the highest difference between successive pixels. It is used to find the start and the end pixels of the interval, using the formula:

$$P_B = \begin{cases} P_i, P_{next} - P_{current} \geq Th \\ P_B, P_{next} - P_{current} < Th \end{cases} \quad \forall\, i \in [0, M) \quad (6)$$

P_B is the pixel location that delimitates the border whereas P_i is the new pixel location computed from each specific row of the image that describes the border. *Th* is a threshold defined by the user according to experimental trials. We found that *Th* provides best results for values around one third of P_{max}. $P_{current}$ is the pixel value from the current location and P_{next} is the value of the next pixel. Actually, for a given interval, we found a pair of borders, referred as (P_{Bmin}, P_{Bmax}).

It is possible to find more intervals bounded by pairs of pixel borders defined by the same *Th* (like shown in Fig.1). Let us denotee as St_k the k^th such interval defined as ($P_{Bmin(k)}$, $P_{Bmax(k)}$). The longest one is selected from all found intervals by employing the following expressions:

$$\begin{gathered} S_{BP} = \max_k(St_k) \\ St_k = P_{Bmax_{(k)}} - P_{Bmin_{(k)}} \end{gathered} \quad (7)$$

3. Pupil position detection

On longitudinal axis, the iris area is considered to be surrounded by white pixels. So, the black pixel interval is bounded by a few white pixels on the left and on the right of the interval. The number of successive white pixels in both cases is counted using the following formulas:

$$\begin{gathered} N_{w_{left}} = \mathrm{P}_{Bmin(k)} - \mathrm{P}_{Bmax(k-1)} \\ N_{w_{right}} = \mathrm{P}_{Bmin(k+1)} - \mathrm{P}_{Bmax(k)} \end{gathered} \quad (8)$$

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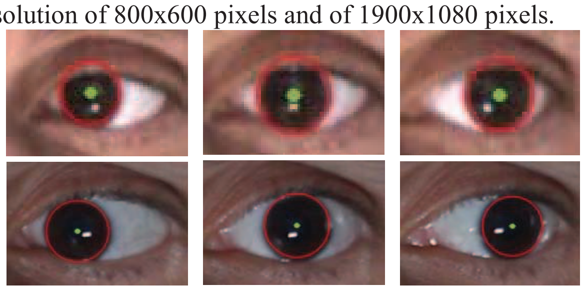
In the above equations N_{Wleft} and N_{Wright} are the amount of successive white pixels located respectively on the left and on the right of the iris. The iris and the pupil areas could contain several white pixels caused by ambient light sources that may affect the results of the pupil border detection method.

To ensure a correct detection of pupil center, we have developed a method to select only the rows that are a part of the iris area and intersect the pupil region. To validate the rows that compose the iris and the pupil area, the largest amount of black pixels found on each row was taken into account. This procedure determines the valid rows of the pupil area.

Validated rows are further processed by considering the position of the pixels found at the beginning and at the end of a pupil row to compute the best fit of pupil bounds. After this step, only the boundaries of the validated rows are taken into consideration to determine the best circle fit that links the detected edge points to describe the pupil area limits.

Pupil regions are characterized by this final step using the coordinates of the circle center and the values of circle radius. Data related to the placements and dimensions of the two circles that identify the corresponding left and right pupil regions of eyes could be used to obtain information about the directionality of the visual attention. Continuous measurements related to the directionality of the visual attention could be achieved by analyzing the evolution of pupil centers with respect to a robust reference, for example the inner corners of the eyes or the location of the eyebrows.

Fig. 2 presents the results of the pupil position detection algorithm that was applied on two sets of images having resolution of 800x600 pixels and of 1900x1080 pixels.



a)

b)

Fig. 2. Detection results of pupil center in various positions: a) images with a resolution of 90x90 pixels and b) images with a resolution of 250x250 pixels.

The images describe a human subject with a fixed head position and different orientations of the visual attention, corresponding to various positions of pupils. In these images the circle that describes the pupil region is represented with a red color and the positions of the pupil center is noticeable by a green marker.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The pupil center detection algorithm is tested using 900 images with a resolution of 1900x1080 pixels and 900 images with a resolution of 800x600 pixels that comprise the eye movements of four human subjects. During the experimental trials the subject's head and the video camera are situated at the same height, about 90 cm. The distance between subject and camera is about 80 cm (±1%) in case of the images with a resolution of 1900x1080 pixels and about 60 cm (±1%) for the images with a resolution of 800x600 pixels. The luminosity of the surrounding environment is maintained the same for all acquired images at about 1400 lx. During the experiment, only the eyes have been moved, the head remaining fixed, so that we could record different stances of the human subject visual attention.

During the experimental trials, the subjects were asked to focus their gaze for about five seconds at nine different points presented on a plane surface. The points of interest on the surface were marked as: top left (*TL*), top middle (*TM*), top right (*TR*), center left (*CL*), center middle (*CM*), center right (*CR*), bottom left (*BL*), bottom middle (*BM*) and bottom right (*BR*). The known placement of the points of interest in the video camera field of view was used as a reference to compare the algorithm results and to assess the accuracy of our approach. The points of interest were placed in a matrix configuration, across the plane surface at a distance of 30 cm. The preliminary eye detection algorithm found that the eye areas belonging to the first series of images had a resolution of around 250x250 pixels and the eye areas on the second series of images had a resolution of around 90x90 pixels.

Table I contains the coordinate points of the detected pupil centers from images that have a resolution of 250x250 pixels. The *X* and *Y* coordinates describe the position of the detected pupil center point in the eye images.

TABLE I
COMPARISON BETWEEN PUPIL CENTER MEASUREMENTS MADE BY THE ALGORITHM AND THE PUPIL CENTER REFERENCE FOR 250X250 RESOLUTION IMAGES

Nr. Crt.	Measured Pupil Center in eye image		Reference Pupil Center in eye image		Brightness of the eye image	Original image		Started point of face image		Started point of eye image		Measured Center In Original Image		Reference Center In Original Image		Mean Of The Measured Center		Mean Of The Reference Center	
	X	Y	X	Y	%	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
Right eye																			
1	138.9	129	141	132	33.17	1920	1088	517	118	658	291	796.9	420	799	423				
2	145.5	124.8	148	127	33.68	1920	1088	517	118	651	295	796.5	419.8	799	422				
3	145	132	148	135	33.8	1920	1088	517	118	651	286	796	418	799	421	796.68	419.16	799.4	421.8
4	149	131	152	133	33.8	1920	1088	517	118	648	287	797	418	800	420				
5	137	123	140	126	33	1920	1088	517	118	660	297	797	420	800	423				
Left eye																			
1	123	114	123	113	29.82	1920	1088	498	105	1029	309	1152	423	1152	422				
2	116	108	116	111	31.2	1920	1088	498	107	1035	314	1151	422	1151	425				
3	125	115	126	112	30	1920	1088	508	116	1026	307	1151	422	1152	419	1151.4	422	1152	423.2
4	120	110	121	111	30	1920	1088	508	116	1031	312	1151	422	1152	423				
5	113	108	114	114	29.25	1920	1088	516	137	1039	313	1152	421	1153	427				

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TABLE II

COMPARISON BETWEEN PUPIL CENTER MEASUREMENTS MADE BY THE ALGORITHM AND THE PUPIL CENTER REFERENCE FOR 90X90 RESOLUTION IMAGES

Nr. Crt.	Pupil center measured in eye image		Reference pupil center in eye image		Brightness of the eye image	Original image		Started point of face image		Started point of eye image		Pupil center measured in the original image		Reference pupil center in original image		Mean of the measured center		Mean of the reference center	
	X	Y	X	Y	%	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
Right eye																			
1	49.5	47.5	51	48	39.9	800	600	215	65	273	164	322.5	211.5	324	212				
2	53.3	50.1	52	51	40.1	800	600	216	67	270	160	323.3	210.1	322	211				
3	51.4	48.2	52	48	39.8	800	600	215	66	271	161	322.4	209.2	323	209	322.74	210.4	323	211
4	56.5	54.6	56	55	39.76	800	600	220	70	266	157	322.5	211.6	322	212				
5	55	53.6	56	55	39.84	800	600	218	69	268	156	323	209.6	324	211				
Left eye																			
1	47.2	43.71	49	42	36	800	600	213	64	429	171	476.2	214.71	478	213				
2	44.5	41.8	45	43	40.32	800	600	211	63	430	172	474.5	213.8	475	215				
3	48.9	46.2	54	45	41.05	800	600	215	67	427	170	475.9	216.2	481	215	475.52	215.302	476.6	215
4	53.6	50.5	51	52	37.6	800	600	214	65	423	167	476.6	217.5	474	219				
5	52.4	49.3	53	48	39.24	800	600	218	70	422	165	474.4	214.3	475	213				

The data computed by our pupil center detection algorithm was compared with the known center pupil data, which was taken as reference. Table II contains the coordinate points of the detected pupil centers from images that have a resolution of 90x90 pixels in which the human subject was looking right at the camera. Analyzing data presented in the above tables one can observe that although the images were acquired when the human subject focuses his visual attention on specific points of interest, the eye position detected from these images exhibits some small differences between them. We explain these small variations of position by the micro saccadic movements of the eyes required to maintain the subject visual attention.

From Table I we can calculate the highest deviation from the known reference point of about 1%, with respect to the computed diameter of the pupil of about 30 pixels. From Table II we calculate a deviation of about 0.4%, when the pupil diameter is approximately 10 pixels. The detection error D_E, employed to describe the accuracy of our pupil center detection algorithm is computed using the following formula:

$$D_E eye = \frac{\max\left(\|P_{Lr} - P_{Lm}\|, \|P_{Rr} - P_{Rm}\|\right)}{\|P_{Lr} - P_{Rr}\|} \quad (9)$$

Pupil center detection results are synthesized in Fig. 3, considering the points of interest and the resolution of target images by indicating the detection error and detection rate.

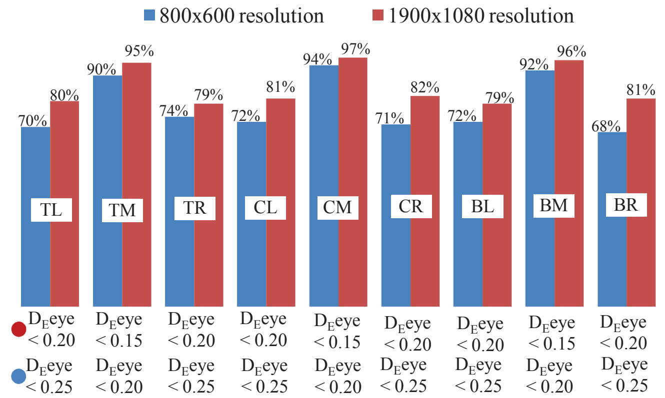

Fig. 3. Performances of the pupil center detection algorithm are indicated by detection errors and detection rates with respect to the points of interest.

Analyzing the performance indicators presented in Fig. 3, one can observe that the detection rate presents higher values in images with high resolution in comparison with the low resolution ones. This occurs because the eye regions have relatively small dimensions in low resolution images.

IV. CONCLUSIONS

In this paper we proposed an algorithm to detect the center of the pupil with high degree of accuracy. We have used a Cascade Classifier algorithm based on Haar-like features to detect the face and eye regions of a human subject. Our algorithm is comprised of the next steps: image enhancement, detection of pupil edges and pupil position detection. The performance analysis indicates robust results when high resolution images are used and when the visual attention of the human subject is focused in the center region of the gaze field. When the user is looking in peripheral field of view directions the detection results are more prone to errors. We plan to integrate a refined implementation of our method into a gaze based interaction interface that will facilitate interaction and communication of physically impaired people.

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