Pupil Diameter Estimation in Visible Light

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Abstract— Pupil size is a valuable source of information since it can reveal the emotional state, fatigue and ageing process. A lot of research has been carried out in this area with clinical and even psychiatric validity, since the fluctuations in the size of the pupil are closely linked to the autonomic nervous system. The pupil size analysis of oscillations due to contraction and dilation could be a useful instrument for diagnosis of disorders related to their own control mechanisms and an index of neurological disease affecting other nerve centres. Pupillography is the pupil size clinical examination which involves the use of infrared light, which allows performing an optical analysis of the pupil, varying the light conditions and measuring the pupillary diameter in different luminance levels. The aim of the proposed work is to exploit video processing techniques in visible light to calculate the pupil diameter and analyse the pupil diameter changing as a result of the lighting conditions variation.

I. INTRODUCTION

Many unobtrusive and contactless studies are focused on the monitoring of the pupil diameter measurement over time, performed with infrared (IR) light cameras or in the visible spectrum. The pupil measurement methods are often based on the detection of the gaze tracking [1], the estimation of emotions [2], the evaluation of the autonomic nervous system (ANS) [3], [4] and detection of the right and left pupils on a PC screen [5]. Clinical validity methods are based on pupillometry, a well-established laboratory technique used in different areas of medicine and science, including neuroscience [6], psychiatry [7], psychology [8] and even computer science. Pupillometry involves measuring the pupil size in IR light and the relative changes in brain function. In a study about pupillography [9], the parameters calculated by the dilation or contraction of the pupil can identify subjects with sleep deprivation. The authors, using an IR video camera and acquiring pupil in the dark for 10 minutes in healthy subjects, stated that, during fatigue, the average pupillary diameter decreases while the pupillary diameter standard deviation increases. In different studies with clinical validity, the transient pupillary light reflex (PLR) [10]–[12] referred to the variations in pupil size in response to a transient light stimulus under constant illumination. Soltany et al. proposed a detection method of the pupil region from the image of the eye taken from a visible light camera [13]. The authors employed a method based on grey projection and circular Hough transform [14] without colour space conversion. They stated that the accuracy of their approach is equivalent to using the clinical method in which an IR camera is used.

However, this method is only effective for people whose iris colour is blue or green. Recently, methods based on automatic iris segmentation and recognition [15], [16] have been proposed by exploiting the iris images acquired with visible light cameras. The study [15] relies on dual-purpose RGB and Near IR (NIR) front facing camera for smartphones by segmenting iris and pupil at distances of 15-20 cm from the camera and using a sensor resolution of almost 13-16 Megapixels. Methods based on iris recognition need to detect the pupil region from images of the eye. Yu et al. proposed a detection method of the pupil region from images of the eye acquired by a camera under visible light conditions [17].They applied contour extraction algorithms by removing the light spot interference inside the pupil region. A normalisation to remove light reflections is done in a study [18] in which the authors found the correlation between respiration, Heart Rate Variability (HRV) and fluctuations in pupil diameter by analysing the Power Spectral Density (PSD). In this study the authors made the pupil darker than the iris, enabling the segmentation process of the pupil and iris boundaries under controlled different lighting conditions. They used as a ground-truth a commercial heart rate monitor and an integro-differential operator to calculate the pupil radius, obtaining robust system performance. An iris segmentation method [19] accurately extracted iris regions from non-ideal quality iris images. This method use AdaBoost eye detection to compensate for the iris detection error caused by circular edge detection operations, colour segmentation technique for detecting obstructions due to ghosting and reflections of the visible light. To extract the pupil diameter measurement, the authors in [20] observed that diameter value depends also on the distance between subject and device. To resolve this issue, the reference taken is the ratio of pupil diameter to iris diameter. In 2013, Petridis et. al [21] investigated an unobtrusive method to extract pupil size measurement by using web cameras. They proposed a pupil size estimation by applying different approaches: a face detection for images with a frame rate greater than $50 fps$, a selection for eyes area and finally an iris and pupil detection by exploiting a variation in saturation. In 2010, Whitelam et. al. [22] investigated three different bands, i.e., the visible ($400nm - 700nm$), multispectral ($400nm - 1000nm$), and short wave IR (SWIR, $950nm - 1700nm$) to estimate the pupil diameter. They performed Sobel edge detection to extract the pupil contour, manually cropped the eyes, estimated the pupil diameter by creating an accuracy circle at the pupil centre and calculated the Euclidean distance to measure the correct pixel distance. The authors presented promising results with respect to commercial software. In a recent study [23] the centre position

of the pupil and pupil diameter was estimated by using a visible light camera. The authors used as ground-truth the true value of pupil centre position and pupil diameter by fitting the circle to the pupil region manually. The ground-truth value is compared with the pupil measurement obtained thanks to Canny filter [24], for edge detection, and Hough transform [13] methods.

With respect to the previous works here introduced, in this paper, we estimate the pupil diameter in visible spectrum and in two conditions: static, by comparing two images at different light controlled conditions, and dynamic, by analysing the variation of pupil size with time. In both cases the pupil measurements are obtained by applying four fundamental approaches: a conversion from RGB in a grey scale, a binarization with normalisation, an edge detection with Canny approach and a radius extraction through Hough transform. The precision of the proposed method is calculated using the ground truth measurements [25] as a comparison. The rest of this paper is organised as follows: Section 2 describes in detail the techniques used in each step to extract the pupil diameter. Section 3 describes the experiments performed and discusses our results. Finally, conclusion are made in Section 4.

II. SETUP AND METHODS

The images and videos of 17 volunteer subjects, 10 men and 7 women, aged between 15 and 74 years, with different eye colour, have been acquired using the GoPro Hero 6 device to analyse the pupil diameter in two different light intensity conditions (low and high relative light intensity, this last realised with a flashlight in subjects' eye). Two studies are focused on static conditions, by analysing the frames one at a time, and dynamic conditions, by capturing an RGB video of the pupil with a duration of $20s$. The experiments have been conducted in the university lab and at home by capturing subjects' face at a resolution of 1920x1080 px using GoPro Hero 6 camera with a frame rate of $30fps$ and MATLAB® is the programming environment used. The GoPro device is chosen in order to optimise the performance of the camera by regularly downloading the latest software updates and also because it allows setting the frame rate of test acquisitions from 30 fps to 240 fps. Before processing the pupil, the Viola and Jones automatic algorithm [26] is used to crop the eye image from the starting images, in order to have a width of about 300 px for all conducted tests.

The main steps of the algorithm are shown in the flow chart in Figure 1. This proposed work is developed on the basis of Viola and Jones [26] face detection algorithm, of Canny [24] edge detection and finally of Hough transform for extraction of the pupil diameter measurement [13]. The face detection algorithm is used to automatically detect the eye from an image containing the entire face of the subject under test. Canny edge detection is exploited for the first raw pupil border extraction. This algorithm relies on different filters to identify the horizontal, vertical and diagonal contours of the image. A gradient map provides the light intensity level for each pixel of the image, where a strong intensity
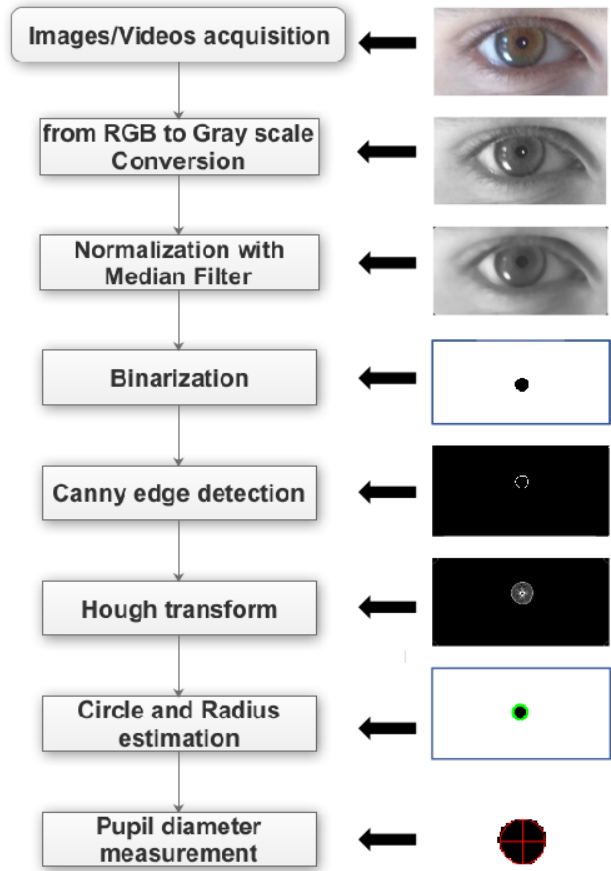

Fig. 1: Flow chart highlighting the main steps of the algorithm.

indicates a high probability of finding a contour. In the last phase the edge is extracted from the gradient map by applying a process called "hysteresis thresholding". The Hough transform is finally used to calculate the diameter measurement. This is a widespread extraction technique in digital image processing. The Hough transform exploits in particular two properties, the first of which states that each point of the Image Space (IS) is related to a hypersurface (generalised surface) of the Parameter Space (PS). The latter is based on property that n points in the IS, belonging to the same curve, generate n surfaces that intersect at the same point in PS.

In our work two approaches with the aim to extract pupil diameter from visible light are developed: static and dynamic methods.

A. Static Method

Figure 2 shows the scheme of the static approach developed. In the first study, two photos of the subject's eye are taken in two different light intensity conditions. In the first condition, an image of the subject in a visible light and in a "normal" light state, where normal stands for no application of artificial high level light, is captured. In the second
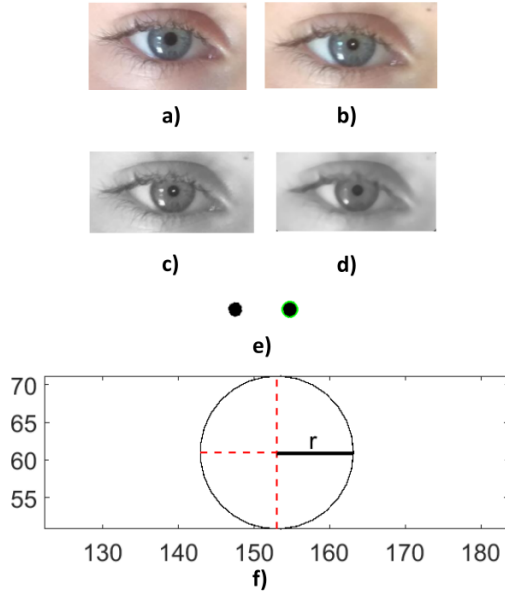
Fig. 2: General scheme of the proposed static method: **a)** eye in normal light condition; **b)** eye with light intensity increased; **c)** greyscale; **d)** normalisation; **e)** binarization, Canny edge detection and Hugh transform; **f)** circle and radius extraction.

approach, however, we put a flashlight in front of the subject. In fact, with a greater intensity of light, the pupil tends to constrict and decrease in size. On the other hand, with the decrease of light intensity, the pupil tends to dilate. An ad hoc function has been developed in order to load the image of the subject's eye and re-size it to obtain a new image with a width of 300 pixels. After the face detection, the image is converted from RGB to a greyscale normalised image and the binarization is performed. The images are binarized to highlight and extract only the pupil (dark part of the eye) and then filtered by using a median filter. As shown in Figure 2 c) shows the normalisation process implies filling the pupil (with the lower index, towards the black, 0), avoiding the noise caused by light reflections that implies values with high contrast (towards white, 255). For this purpose, a median filter represented an appropriate preprocessing step for noise-cancelling. In particular, the median filter is chosen with a kernel of 7-by-7 as pixel neighbourhood size, in order to preserve edges in the input image but to sufficiently filter the reflections. At this point the Canny algorithm and the Hough transform are applied to identify the pupil edge and measure its radius expressed in pixels.

In order to calculate the pupil diameter expressed in millimeters, it is necessary to set a scale factor (SF) relative to the distance between the subject's eye and the camera, and a Calibration Factor (CF) depending on the width of the examined subject's eye. The CF is set as the ratio between the diameter Real Value (RV) measured by a calibrated ruler in millimeters with respect to the Width (W) in pixel of the image, taken by fitting the pupil to the diameter manually
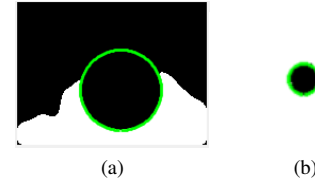

Fig. 3: The decrease in light intensity determines a changing in binarization level; **a)** the Hough transform take the wrongly iris as circle; **b)** binarization level dynamic correction.

via software; in formulas

$$CF = \frac{RV}{W} \tag{1}$$

Considering that the image W is scaled for all the subjects to 300 pixel, W is a constant in (1).

The comparison between pixel and millimeters in a first frame was applied for all the subsequent frames composing the sequence. The SF that takes into account the distance between the camera and the subject under test, is experimentally set to 1.5. The diameter is calculated as follows

$$D_{mm} = (2 \cdot r) \cdot SF \cdot CF \tag{2}$$

where r is the radius calculated with Hough transform and expressed in pixel value.

B. Dynamic Method

The dynamic study relies on a 20-second video to analyse the pupil size variation during the time. The video is acquired with a frame rate of 30 fps and the first step is to detect the subject's eye with the Viola and Jones algorithm [26]. The algorithm that extracts the pupil diameter is developed with the same steps of the static approach. Firstly, a conversion from RGB space colour to greyscale is implemented, then binarization and normalisation are performed, and finally the Canny algorithm detects the pupil edge and the Hough transform is applied to calculate the diameter during the time. The pupil diameter value is calculated during the entire sequence and is expressed both in millimeters and pixels. The experiments are conducted by varying the light intensity and the variation over time is compared with the diameter average value, to better analyse the offset between them in the different light conditions during the time.

At the transition from normal light to the high light intensity, the binarization level (BL) must be changed to better extract the pupil. We implemented empirically a dynamic control for the BL floating exchange considering that the radius of the circle that approximates the pupil decreases with a factor of at least 1.5 and inversely, the radius increases 1.5 times at least when the light returns to normal values. Figure 3 is explanatory of this change in BL when the light comes back in normal condition from the high intensity level.

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III. RESULTS

In the static study, the pupil size value in a normal light condition and then under an intensified illumination is evaluated. The static analysis of the pupil was the preliminary study that has allowed us to better perform the dynamic process. Taking into consideration two individual subjects' eye images, the first in standard lighting conditions and the latter in strong lighting conditions, our goal was to mark the pupil diameters differences in the two cases. When the eye is under the direct light beam of the flashlight, the pupil narrows to prevent an excessive passage of light. This behaviour is automatic in all subjects, because it is not a voluntary action. Some problems have been analysed such as the presence of shaded areas or reflections that hinder the correct identification of the pupillary contour. All these problems have been solved with a median filter which improved the next steps of images processing. The static approach was effective in highlighting a great pupil size shrinkage with the increasing of the light intensity. Maximum and minimum values calculated with the static method are reported in Table I. These values are measured for both the analyses, static and dynamic, since the subjects that participated in the tests are the same. With the dynamic study we are able to show the pupil size time variation trend. Fig. 4 is indicative of the great variation in the pupil size during the experiments. In fact, the increasing of light intensity around 10 s causes a negative slope of the curve, corresponding to a pupil contraction, that returns to a normal level after 15 s. This means that the flashlight went off and the pupil is dilated. The variation in the light intensity causes a changing in binarization level. If it is not modified during this light intensity variation, the tracking of the pupil is lost, condition visible in Figure 3a. On the contrary, by taking into consideration this variation during processing, the binarization level is automatically corrected when the light intensity changes. The binarization level correction, visible in Fig. 3b, allows tracking the pupil diameter trend in a clear fashion and the measurement errors reduced.

The maximum and minimum values with respect to the ground truth (GT) values obtained by measuring the pupil diameter with a calibrated ruler, like Figure 6 shows, are saved in Table I. In order to get the tracking error, the relative errors between the GT values and the maximum and minimum diameter values are calculated as follows:

$$ErMD = \frac{|GTM - MD|}{GTM} \qquad (3)$$

$$ErmD = \frac{|GTm - mD|}{GTm} \qquad (4)$$

They are visible in the last columns of the Table I. As the Table I shows, the errors measured are quite small, except for two cases (i.e. the experiments 3 and 8) that have shown absolute error values of 0.25 and 0.21 corresponding to percent errors of 21% and 25% respectively. These errors are obtained by acquiring people with dark eyes, in fact the system achieves better performances with light eyes, since
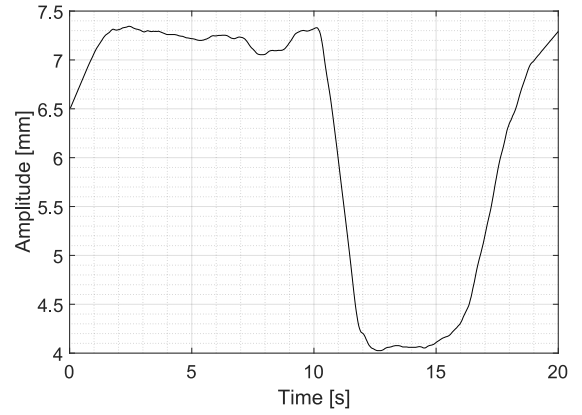

Fig. 4: The pupil diameter variation in a time sequence of 20 seconds (at 30 fps). The slope between 10s and 15s indicates a strong increase in light intensity and a consequent reduction of the pupil diameter size.
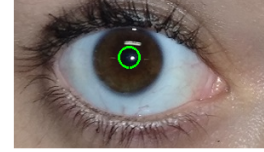

Fig. 5: The algorithm detects and tracks also dark eyes thanks to the application of the Hough transform.

the colour contrast between iris and pupil is sharper. The absolute errors in the range $[0-0.07]$ are obtained by testing light eyes. Therefore, the algorithm performance highlights a great precision for the pupil contraction and dilation and, to prove this, Figure 5 shows the processing of a dark eye.

The relative tracking errors mean values resulted, respectively ***ErMDAvg*** = 0.04 and ***ErmDAvg*** = 0.08.

IV. CONCLUSIONS

The present paper aims to propose a contactless estimation method, unobtrusive for the subjects under test and based on a visible-light camera, of the pupil variations due to contraction and dilation to varying of the lighting conditions. Two methods were conducted, the first static and the latter dynamic. In the first case two images are compared in order to extract a single diameter value. With the dynamic approach we are able to analyse the trend of the pupil size variation, by tracking the pupil diameter. The average tracking relative errors proved the precision of the adopted approach even though we carried on the experiments in a visible light, unlike the clinical investigation which take place usually in infrared light. Similar to the clinical results, the presence of anomalies in the graph resulting from the dynamic analysis can provide important considerations on some pathological cases. If the pupil does not contract when light conditions change, this may be evidence of a possible nervous system disease or visual impairment. It would be of interest to apply the proposed method to a study on Heart Rate Variability

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Fig. 6: The calibrated ruler used as the ground-truth for the pupil diameter measurement.

ID	MD [mm]	mD [mm]	GTM [mm]	GTm [mm]	ErMD	ErmD
01	7.3	5.2	7.8	5.5	0.06	0.05
02	5.5	5.1	5.8	4.9	0.05	0.04
03	7.0	6.8	7.2	5.6	0.03	0.21
04	7.9	6.3	7.7	6.7	0.03	0.06
05	8.4	6.4	8.7	7.2	0.03	0.11
06	8.5	6.1	8.5	6.3	0.00	0.03
07	7.1	5.8	7.3	6.0	0.03	0.03
08	8.3	5.2	8.6	6.9	0.03	0.25
09	5.0	4.2	5.3	4.6	0.06	0.09
10	8.7	7.0	9.2	7.4	0.05	0.05
11	5.8	4.6	5.3	4.6	0.09	0.00
12	7.5	4.2	7.4	4	0.01	0.05
13	6.4	5.2	6.4	5.0	0.00	0.04
14	7.7	6.7	7.2	6.5	0.07	0.03
15	6.3	5.9	6.4	5.5	0.02	0.07
16	6.7	5.5	6.6	5.2	0.02	0.06
17	6.8	4.8	6.5	5.5	0.05	0.13

TABLE I: Results with the static and dynamic approaches. ID is the subject Identification Number, MD stand for Maximum Diameter, mD stand for minimum Diameter, GTM is the comparison with the Ground Truth MD, GTm is the Ground Truth mD, ErMD is the relative error between GTM and MD, ErmD is the relative error between GTm and mD.

(HRV), being HRV and pupillary oscillations both influenced by the autonomic nervous system. Further applications of the proposed work may also concern the pupil size investigation in visible light for driver fatigue or stress level monitoring in real time.

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