Optik 123 (2012) 11–15

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Pupil detection and tracking for analysis of fixational eye micromovements

Ana B. Roig [a], Marta Morales [b], Julian Espinosa [a], Jorge Perez [a], David Mas [a,*], Carlos Illueca [a]

[a] Dep. Optica, University of Alicante, PO Box 99, 03080 Alicante, Spain
[b] Dep. Fisica Aplicada, University of Alicante, PO Box 99, 03080 Alicante, Spain

ARTICLE INFO

Article history:
Received 4 May 2010
Accepted 15 October 2010

Keywords:
Eye moments
target tracking
Miccrosaccades
ocular drifts
image processing

ABSTRACT

Even with fixed gaze, the human eye is under steady motion (tremor micosaccades and drifts). Detection of these movements requires of invasive techniques or expensive devices with sophisticated detection methods. In this paper we present a technique for pupil segmentation and contour analysis which will provide valuable information about fixational eye movements. The method is based on fitting an ellipse to the pupil contour. Pupillary hippus, microsaccades and drifts are obtained as well as cyclotorsional movements. The method is simple and the experimental requirements are easily available since just a biomicroscope and a digital videocamera are required.

1. Introduction

The human eye is constantly moving even when it is maintaining a stable fixation point. Usually, these movements are too small for being appreciated without specific instrumentation but they play a fundamental role in eye physiology and, unfortunately, increase the complexity of the eye with respect to conventional optical systems [1].

Stable images on the retina rapidly saturate the photoreceptors and fade. The visual system needs of constant stimulation to which it adapts. These constant changes are achieved by fixational micromovements which consists of microtremors, drifts and microsaccades [2–5]. Microtremors are constant high frequency (80 Hz) low amplitude (120–2500 nm) eye tremors. Their role in vision is to avoid image fading due to saturation of retinal photoreceptors. Drifts are smooth pursuit movements associated to the instability of the oculomotor system and microsaccades are sudden jerk like movements of the eye of amplitude varying from 2 to 120 arcmin and around 25 ms of duration. Their possible role is to correct displacements in eye position produced by drifts.

The equipment for eye movement detection has significantly advanced in recent decades from rudimentary and invasive methods, like the electrooculogram [6] or scleral search coils [7–9], to non-invasive systems as the video-oculography [10].

The principle of the "search coil" technique is based on the induction of an electrical field on as small coil [7]. Although it is highly invasive, this method is actually considered the "gold standard" for eye movement measurements. The induction coil is inside a flexible ring of silicone rubber which adheres to the limbus of the human eye concentric with the cornea, through a contact lens [8,11]. The head of the subject is placed inside magnetic fields. Induced voltages in the coil provide data about horizontal and vertical positions of the eyes, as well as cyclotorsions.

Pupil detection has been used for accurate calculation of eye orientation [12]. It is usually assumed that the optical axis (the line through the pupil center and the eye rotation center) coincides with the direction of gaze. Thus, accurate determination of pupil center is crucial for precise eye tracking [13]. Pupil center is usually determined by detecting its border and assuming a particular geometrical shape. The simplest approximation consists on assuming that the pupil is rotationally symmetric [14], however elliptical shape seems to be a better choice [13].

The determination of the pupil shape parameters is also of great interest for non-invasive early diagnosis of the central nervous system response to environmental stimuli [15]. Pupil geometrical features such as area, semiaxis, centroid and orientation can be obtained by image segmentation.

The aim of this work is to present a simple non-invasive optical method for detecting and measuring fixational micromovements. A video camera has been attached to a biomicroscope and the anterior segment of the eye has been captured. The contour of the pupil has been detected and fitted to an ellipse. Through its geometrical parameters we have studied the spontaneous pupil dilation, microsaccades and drifts and also cyclotorsions.

The presented technique is simple and rather inexpensive since the experimental requirements are available in all optometric and ophthalmic faculties and can be easily developed by a graduate student. The principles here explained can be also extended to the

* Corresponding author.
E-mail address: david.mas@ua.es (D. Mas).

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doi:10.1016/j.ijleo.2010.10.049

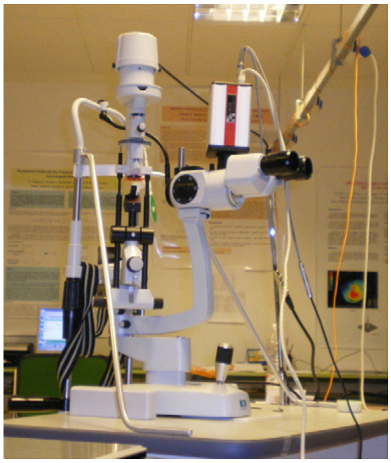

Fig. 1. Slit-lamp and digital video camera used to capture the images of frontal corneal.

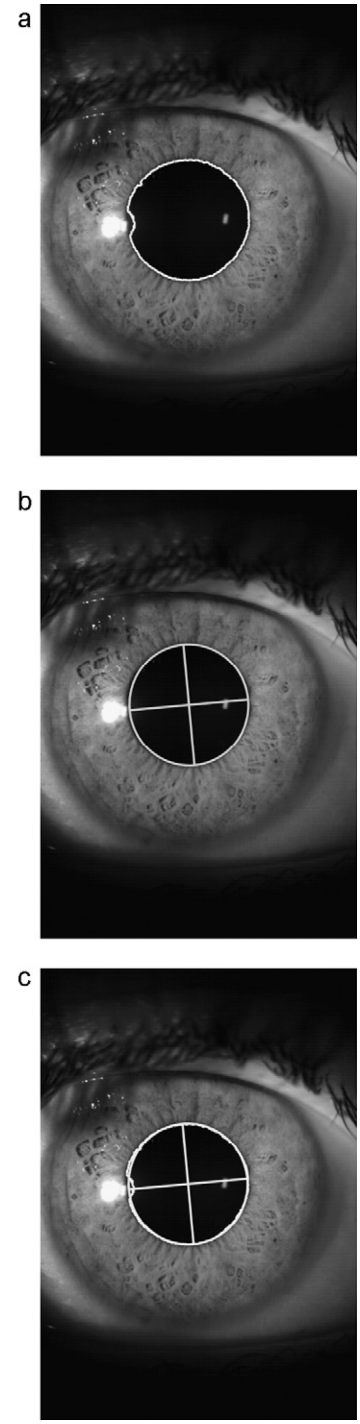

Fig. 2. (a) Image representing the pupil contour in the presence of sparkle, (b) adjustment of contour data, and (c) image representing the pupil contour and adjustment.

analysis of more complex effects, either using a high speed camera or adapting the setup for binocular observation.

2. Subjects and methods

Images of the frontal cornea were obtained by illuminating the eye with a Haag–Street style slit-lamp (SL-990). Video sequences were captured with a digital video camera working at 63 fps and a spatial resolution of 800 × 560 px attached to the lamp (see Fig. 1). Diffused illumination was used to obtain uniform illumination on the whole cornea and a red filter was additionally used to avoid discomfort to the subject.

Five healthy subjects (3 women, 2 men, aged 22–40) among the staff of the Optics Department of the University of Alicante were asked to participate in this experience. We adhered to the tenets of the Declaration of Helsinki during this study. All participants were informed about the nature and purpose of the study and all of them provided informed consent.

Three different sequences were registered for each subject's right eye with the left eye occluded. Measurements were taken in total darkness to avoid reflections and discomfort to the subjects. During the measurements a red LED was used as a fixation point. Residual head movements were restrained by the use of a dental bite bar and firmly fastening the head to the chinrest frame. Finally, the chinrest structure was reinforced with lateral supports, as can be appreciated in Fig. 1. In order to further minimize the head movements the subjects were asked to not breathe during the measuring time, which lasted 10 s.

Obtained images are analyzed off-line using MATLAB. Edge detection algorithms were applied to determine the pupil contour which is fitted to an ellipse. Position of the center of the ellipse gives information about slow (drifts) and sudden eye movements (microsacaddes), while rotation of the axes describes spontaneous cyclo-torsional movements. Furthermore, variation of the pupil area provides information about spontaneous changes in pupil aperture, known as "hippus" [16].

3. Image processing algorithms

The method here applied consists of detecting the pupil contour in all frames and calculating the best ellipse fitting to it. First, a threshold value is selected for hard clipping of the image thus obtaining a black region of interest which corresponds to the pupil. A morphological closing operation is then performed in order to eliminate noise in the image that could distort the pupil contour [17].

Edge detection determines the border of the black area and thus traces the pupil contour. In many occasions, reflections from the illumination system may appear inside the region of interest (see Fig. 2). Isolated reflections inside the pupil area will not disturb the detection process but those close to the border may interfere in the obtained contour. In order to eliminate this interference the size of the sparkle is delimited by selecting all connected saturated pixels in the image. If the area so obtained intersects with the pupil