18th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Amsterdam 1996
1.3.3: Sensory and Neuromuscular Diagnostic Instrumentation and Data Analysis I

A FLYING-SPOT LASER SCANNER FOR TRACKING EYE MOVEMENTS

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***Abstract* - A novel system has been developed to provide non-invasive and simultaneous measures of horizontal, vertical, and torsional (rotation about the visual axis) movements of the eye. It uses a flying-spot laser scanner to selectively image landmarks on the eye. A horizontal scan through the centre of the pupil locates the left and right edges of the pupil allowing horizontal eye position to be estimated. Similarly, vertical eye position is estimated from a vertical scan through the pupil. A circular scan records striations on the iris from which torsional movement can be estimated from cross-correlation of successive circular scans. The instrument can measure eye movements with a bandwidth of 25 Hz through a range of movement in excess of ±40° horizontally and ±30° vertically. Preliminary trials have demonstrated the feasibility of using a flying spot scanner to track eye movements. It should prove a valuable tool for the investigation of eye movements in neurological disorders.**

I. Introduction

EYE movement recordings are an important diagnostic tool for assessing vestibular disease and other neurological disorders. Horizontal and vertical eye movements can be measured by electro-oculography or by tracking the position of the limbus optically. Torsion of the eye (rotation about the visual axis, typically within a range of ±10°) is more difficult to measure. Both smooth eye movements and nystagmus can involve a torsional component. In addition, the eye exhibits a normal vestibulo-ocular reflex, called counter-roll, about the torsional axis in response to head tilt. Torsional dysfunction is commonly encountered in patients with vestibular and brainstem disorders.

A common method for measuring torsional eye movements uses magnetic search coils attached to a contact lens [1]. Its application is, however, severely limited by its invasiveness, high cost, and the need to immobilise the head. Non-invasive video-based methods have been developed to measure torsional eye movements but such systems sample too slowly to measure fast components of saccades and nystagmus [2-4].

We have developed a system which uses a flying-spot laser-scanner to provide non-invasive, high bandwidth, and simultaneous measures of horizontal, vertical, and torsional movements of the eye.

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II. System Description

The prototype eye-tracker (Figs 1 & 2) uses a 1 mW red laser (λ = 650 nm). After attenuation by a neutral density filter, scan mirrors, and a half-silvered mirror, the beam gives a measured power at the eye of 50 µW and a spot size of 81 µm. The position of the beam on the front of the eye is determined by two orthogonal beam-steering mirrors attached to two servo-controllers driven by analog signals from the Pentium PC's D/A board (Fig. 2). As the flying spot moves across the eye, the amount of light reflected varies according to the reflectance under the spot. The receiver comprises an array of four photo-diodes (two summed pairs), and two channels of trans-impedance preamplifiers, variable-gain amplifiers, anti-aliasing filters, and A/D converters (Fig. 2). Dual-channel sampling from the photo-diodes was implemented to overcome the deleterious effect of glare artifacts due to specular reflections.

The laser scanner approach was chosen so as to selectively image landmarks on the eye. A horizontal scan through the centre of the pupil locates the left and right edges of the pupil allowing horizontal eye position to be estimated. Similarly, vertical eye position is estimated from a vertical scan through the pupil. Second-order edge detection of the pupil has been

Figure 1. Close-up view of prototype eye-tracker.

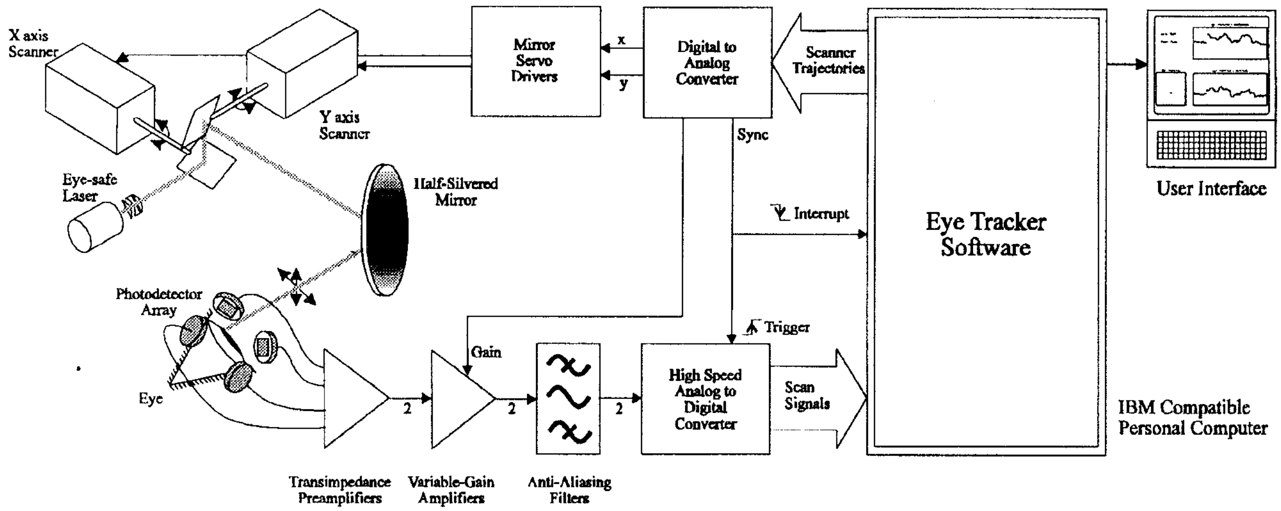

Figure 2. Block diagram of laser-spot eye-tracker.

incorporated in both the horizontal and vertical scans to minimise the effect of any marked gradients across the scans. Finally, a circular scan records striations on the iris from which torsional movement can be estimated from cross-correlation of successive circular scans. The eye is scanned at 170 cycles/s. Tracking the pupil has been optimised by the use of a Kalman filter based upon a position-velocity-acceleration state-model.

III. System Performance

The instrument can measure eye movements (Fig. 3) through a range in excess of ±40° horizontally and ±30° vertically, and with an accuracy of ±9 minutes of arc horizontally, ±11 minutes of arc vertically, and ±25 minutes of arc in torsion. It has a bandwidth of 25 Hz and is 7 dB down at 50 Hz.

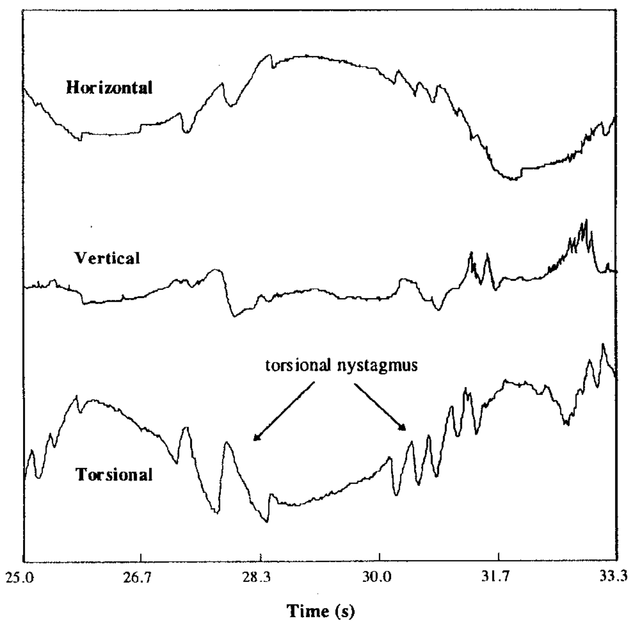

Figure 3. Horizontal, vertical, and torsional eye movements during ocular counter-rolling in a normal subject.

IV. Discussion

By using partial images to track eye movement, the amount of data which must be collected, stored, and processed is two orders of magnitude less than that required if full raster images were used. This allowed a significantly higher bandwidth to be obtained than that possible with a system which tracks full raster video images of the eye. Other features in the current eye-tracker, important in the investigation of several neurological conditions, include ability (a) for subject's head to be moved freely and (ii) to observe eye movements in response to a variety of visual stimuli.

Preliminary trials have demonstrated the feasibility of using a flying spot scanner to track eye movements. Further developments are well underway aimed at increasing the instrument's eye tracking accuracy and robustness and, hence, clinical and research utility.

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