LINEAR MULTIVARIATE REGRESSION TECHNIQUE FOR CALIBRATING 2-DIMENSIONAL CORNEAL-REFLECTION EYE TRACKERS

R. C. Frecker, W. J. MacLean

Institute of Biomedical Engineering, and Department of Electrical Engineering, University of Toronto, Toronto, Canada. M5S 1A4,

INTRODUCTION

A variety of eye trackers has been developed at the Institute of Biomedical Engineering (1-5) over the last 3 decades. These have been used to evaluate pilot performance (6), to research the effects of drugs on the brain (7-9), to assess physician performance in reading radiographs (10), as communications aids (11), and to investigate the oculomotor system itself (12-14). Other applications in the aerospace industry have included eye position based placement of computer-generated aircraft simulator images.

Eye tracking devices destined for use in the clinical environment have generally been based on the corneal reflection technique, and have required desk mounting and the use of bite-bar and forehead stabilization to minimize apparent ocular rotation caused by translation of the head (approximately 10 degrees of apparent rotation for each 1 mm of head translation). The eye trackers slated for industrial use have been helmet mounted, and have required other techniques for the elimination of translation through head slippage in the helmet.

RATIONALE

Accurate calibration of eye tracking equipment is a crucial part of the experimental paradigm. Without it, proper comparison and interpretation of results among investigators and laboratories is not possible. Given the variety of methods available for recording eye-movements it is important to have robust calibration techniques. This paper describes a multivariate regression technique used to provide calibration for a fast (1 kHz), two-dimensional, high-precision corneal reflection tracker (4, 5). This technique may also be used with other eye-movement recording techniques, such as those employing magnetic detection of corneal search coils.

METHOD

The regression maps the output from the eye-tracker (**x**, a 2 x 1 vector) onto an eye-position estimate (θ a 2 x 1 vector) via the transformation

$$\theta = \alpha \mathbf{x} + \beta$$

where α is a 2 x 2 matrix and β is a 2 x 1 vector. α represents gain coefficients which map the outputs of the tracker onto the eye position estimates. In particular, the off-diagonal components represent the influence of the horizontal channel output on the vertical eye position estimate, and that of the vertical channel on the horizontal eye position estimate (channel crosstalk). β represents an offset or intercept vector for the regression.

We will discuss how the method takes into consideration the limitations of system optics, detection array construction and alignment, the relationship of stimulus axes to tracker axes, and both within- and between-subject variability.

In the system optics (5) there exists crosstalk between vertical and horizontal channels which is caused by properties of the beam-splitters used, and limitations on the precision with which they may be mounted and aligned. This leads to a *non-orthogonality* in the detector system for which compensation is necessary. We demonstrate that this technique is capable of mapping the signal from the arrays (a projection, or ~~contravariant~~ covariant vector) onto the desired components (~~covariant~~ contravariant) on the non-orthogonal basis necessary to generate an accurate eye-position estimate.

There may also be differences in gains arising from the pre-amplification stages of the two 20-channel linear detector arrays. These are associated with both the fabrication alignment of the discrete array elements, and with the electronic techniques used for weighting the contributions of individual array elements to the eye position estimate. The regression technique finds an optimal least-squares linear solution to compensate for these non-linearities.

Regression parameters are automatically included in a data header which is prefixed to all data files as they are collected. Results from each calibration session are also stored in a log file so that system-subject-operator performance may be monitored over a series of trials. The raw data collected for the regression is saved for later analysis.

The calibration routine itself presents a visual target stimulus sequence and collects and processes responses with respect to a strict set of criteria in order to provide robust data for the regression analysis. Responses are checked for drift and saccadic movements in order that only fixation responses are used in determining the regression parameters. The technique allows the operator to ascertain how close to optimal the equipment setup is for a given subject-occasion. Once the regression analysis is complete, the parameters may be used to estimate the signal position on the detector array when the subject's gaze is directed in the primary position. This allows the operator to verify that the signal has been captured on the array in an optimal sense, and provides a measure of performance when training new operators.

The data collected during calibrations are used to study non-linearities in the tracking system by observing the effect of horizontal position on vertical channel gain, and vertical position on horizontal channel gain. Such non-linearities may occur as a result of imperfections in diode-array construction and alignment, non-linearities in system optics, or subject positioning in the apparatus. Study of such data allows insight into system operation which in turn allows for improvements in instrument design, and methods of operation.

DISCUSSION

In many eye-movement tasks the subject is asked to fixate a target on a stimulus display unit (such as an oscilloscope, or a screen on which is rear-projected a small laser generated dot). It is often difficult to align the stimulus unit so that it is properly centered on the subject's visual axis in the primary position, and also so that the horizontal and vertical axes of the stimulus coincide with those of the detector arrays. A multivariate regression technique compensates for rotation and offset of stimulus-tracker axes with respect to one another. Since the system being used is based on the corneal reflection (first Purkinje) technique it is, as mentioned, highly sensitive to translation of the subject's head in the apparatus. Our eye-tracker is in regular clinical use and was designed to allow subjects to participate with a minimum of training, and intersession variability. In practice, significant differences are observed between trained and untrained subjects.

The regression parameters reflect this, and allow for evaluation of a given subject's performance within and between sessions. The ability to frequently check calibration has proven to be of great clinical utility. It provides information on subject performance, and on the reliability of operator technique. The calibration routine itself is incorporated within a computer-automated data collection and analysis system, and allows for easy and frequent checking of system-calibration.

CONCLUSION

Although this calibration technique has been developed in terms of a specific corneal reflection tracker, it may be readily extended to other systems such as those employing search-coils. The effect of eye-torsion (which is not observable in our corneal-reflection trackers) on the technique will be discussed, and the problems involved in expanding the technique to 3-D systems (in which torsion is the third dimension) will also be considered.

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