DEVELOPMENT AND EVALUATION OF EYE TRACKER PERFORMANCE FOR USE WITH THE FIBER OPTIC HELMET MOUNTED DISPLAY

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ABSTRACT

To quantitatively evaluate the performance of eye tracking systems for use with the Fiber Optic Helmet Mounted Display, eye movement experiments were conducted in both the laboratory and in the helmet and the results were compared. Experimental methods for evaluation of an eye tracker system are described and data are presented which characterize the present performance of the eye tracker system.

INTRODUCTION

To evaluate and improve the operational performance of eye trackers for use in area-of-interest display systems, these and previous other experiments have been conducted to measure their performance (Longridge *et al.*, 1989 and 1990, Wetzel *et al.*, 1990). The data reported here describe the most recent experimental work with the El Mar, Inc. two-dimensional array system that has been specifically designed for use with the Fiber Optic Helmet Mounted Display (FOHMD) system. Data describing the performance of the eye tracker have been collected in both the laboratory and in the FOHMD and the results compared. It is assumed that the laboratory eye movement data gathered under stabilized head conditions represents the most accurate characterization of eye tracker performance while the helmet data are current representations of the eye tracker under helmet conditions. The results of both the laboratory and FOHMD experiments have been used to guide further ongoing development of the eye tracker, which have resulted in continual improvements in system performance.

In this paper, experimental data are presented that show the eye movement response as measured by the two-dimensional array eye tracker to sudden step changes in target position under laboratory and FOHMD conditions. In these experiments, target stimuli were presented over large displacement angles along the horizontal, vertical, and oblique stimulus axes while eye position was measured from a number of subjects. The eye position response was then analyzed with respect to target position. The difference between target position and measured eye position provide a method for accurate evaluation and characterization of the eye tracker system.

To accurately evaluate and characterize the performance of any tracker, it is necessary to distinguish oculomotor behavior from eye tracker performance. In this paper, an effort has been made to present data on the positional accuracy of the eye tracker based on the accuracy of subject eye movement response. Therefore, the measurable differences that may occur between the eye tracker estimate of eye position and the assumed positional fixation accuracy of the oculomotor control system are likely attributable to the characteristics of the eye tracker.

EYE MOVEMENT BEHAVIOR

The function of the oculomotor control system is to accurately align and stabilize the high resolution portion of the retina known as the fovea with a visual target or point of interest. Images of objects or points of interest that fall beyond the foveal area of approximately 2mm diameter, or about 5° of visual angle, are poorly resolved. The difference between the image of the target on the retina and the fovea can be thought of as an error signal that provides the driving signal behind many eye movement responses. Generally, if the retinal error signal between the target object and fovea is greater than 0.5°, eye movements are made to reduce the difference error (Wetzel, 1988). The types of eye movements that occur are often dependent on the spatial-temporal characteristics of the visual target. When the head is fixed, the oculomotor control system can be divided into two distinct response branches known as the saccadic and smooth pursuit systems (Rashbass, 1961). To elicit a response from either branch is almost solely dependent on the characteristics of the stimulus. The ideal stimulus for a saccadic eye movement is a sudden step change in target position as shown in Figure 1, whereas for pursuit eye movements, the ideal stimulus is a velocity-limited smoothly moving target as shown in Figure 2. When scanning a scene for a target, saccadic eye movements occur at a rate of usually no more than four to five per second. When tracking a smoothly moving target at velocities less than 30°/s, smooth pursuit eye movement normally occurs. In this case, the eye moves at a rate nearly equal to that of the target as it attempts to stabilize the image of the target on the retina. During smooth pursuit, however, if the position error between the target and eye becomes too great, a saccade will occur in an attempt to reduce the error. An example of a typical saccadic eye movement in response to a 12° step change in target position is shown in the upper portion of Figure 1. In this example, eye position was sampled at a rate of 1000 samples per second using a differential infrared reflectance measurement technique. The velocity and acceleration profiles for the saccadic response have been computed and are also shown in the middle and lower portions of Figure 1 as well. For the response of Figure 1, the observer was initially fixating on the target located at $-4°$ left. At time 0s the position of the target was suddenly displaced to $+8°$ right resulting in a position error of 12°. The eye movement response to the new target displacement is not immediate, however, and is normally on the order of 200 ± 50 msec before a saccadic response occurs. In many instances several saccadic eye movements are required before eye position matches that of the target. Under normal conditions, the primary or initial saccade typically undershoots the position of the target resulting in short fixation pauses followed by additional secondary corrective saccades before reaching the final eye position. The duration of the intermediate fixation pauses is generally less than that of the initial reaction time, while the final positional accuracy of the eye is better than a few tenths of a degree. In this example, the final position error between the target and the eye is approximately 0.1°. To further appreciate the dynamics of the saccadic response, the velocity and acceleration profiles of the saccade were computed. The peak velocity occurs about midpoint during the saccadic trajectory which lasts for approximately 40 msec, while the peak acceleration and deceleration points occur within milliseconds of the onset and end of the saccade. For this example, the peak velocity is reached within 20 msec of the saccade and reaches a maximum velocity of approximately 400°/s.

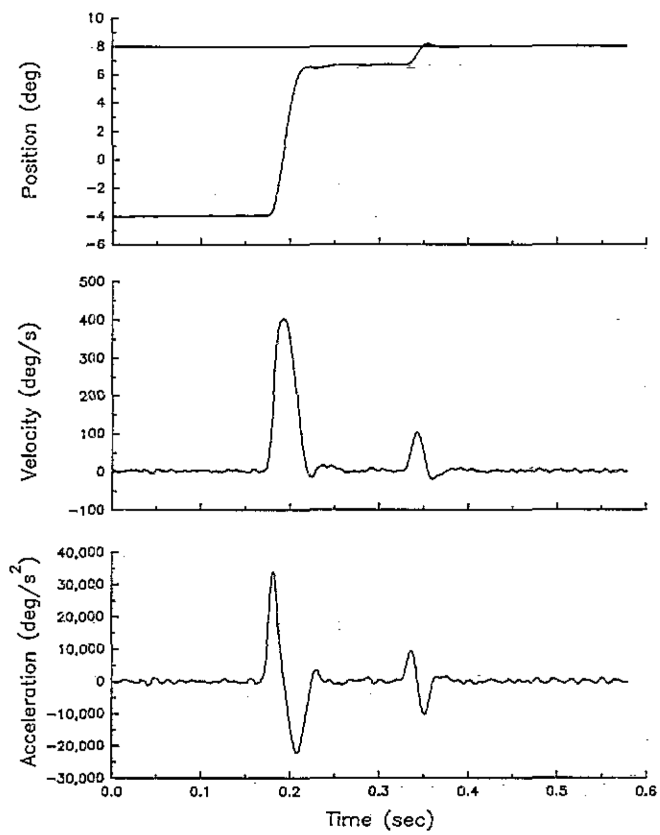

Figure 1. Relationship between position, velocity and acceleration for a horizontal saccadic eye movement in response to a 12° step change in target position. The eye movement response was sampled at 1000 samples per second using a differential infrared reflectance eye position measurement technique. For clarity, individual sample points have been connected. At time +0s the target moves from -4° left to +8° right (straight line). After a latency time of roughly 178 msec a saccadic eye movement results which rapidly moves the eye towards the new target position. The primary saccade undershoots the target by 1.3° and after a short pause of 112 msec, a secondary saccade results, positioning the eye within 0.1°of the target. The duration of the initial saccade is approximately 40 msec, reaching a peak velocity of 400°/s and a peak acceleration of 35,000°/s^2.

The peak velocity increases with the amplitude of the response and can reach velocities up to 600-800°/s. The peak acceleration and deceleration points occur within several milliseconds of the onset and end of each saccade. In this example, a peak acceleration of 35,000°/s^2 was reached and, with larger eye movements can exceed 40,000°/s^2.

In summary, an assumption is made based on previous knowledge of the oculomotor control system behavior which suggests that the function of the eye positioning system is to align the high resolution portion of the retina known as the fovea with that of the point of interest or target. The system is highly accurate and can foveate targets with an accuracy of better than a few tenths of a degrees. It is assumed therefore, that position errors greater than 0.5° that are not reduced by corrective saccades are most likely not attributable to the oculomotor control system. Residual errors that remain after stable eye position has been achieved are, therefore, likely attributable to inaccuracies in the eye tracker which allow characterization of its performance.

THE FIBER OPTIC HELMET MOUNTED DISPLAY

The Fiber Optic Helmet Mounted Display (FOHMD) provides high brightness, wide field, high and low resolution computer-generated color imagery to each eye via coherent fiber optic bundles and Pancake Window^{tm} eyepieces as shown in Figure 3. The imagery that is projected to the pilot is determined by the direction of gaze which corresponds to the angular sum of both head and eye position. Measurements of both head and eye position are used, therefore, to control the high and low resolution areas that are projected to the pilot. The low resolution background imagery is controlled by head position which is measured by an optical head tracker. Linear rate sensors mounted on the back of the helmet minimize additional time delays through the use of prediction algorithms that attempt to estimate final head position. The smaller high resolution inset is controlled by eye position and is measured by a lightweight helmet mounted eye tracker operating at 60 Hz. An enlarged diagram of the eye tracker sensor is shown in Figure 4. The helmet mounted eyepieces collimate the projected imagery to each eye. The projected field of view from the eyepieces is shown in Figure 5. The field of view of each eyepiece is 127°H by 67°V with a maximum binocular overlap of 38° which permits stereoscopic vision. Within a central area of 60°H by 40°V, eye position information is used to provide the command signals for the servomotors which control the location of a smaller rectangularly shaped 25°H by 19°V high resolution inset (Longridge *et al.*, 1989). To minimize the abrupt change between the high and low resolution boundaries, a video blending technique is used to smooth the transition between the two regions.

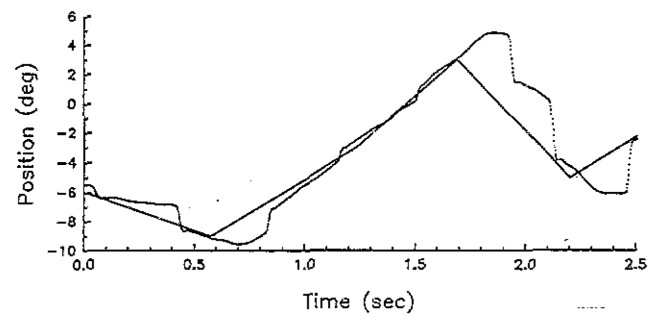

Figure 2. Smooth pursuit eye movement in response to random changes in target velocity and direction. The eye moves smoothly as it attempts to stabilize an image of the target on the fovea. Position errors are rapidly reduced by saccadic eye movements which attempt to reposition the eye on the target.

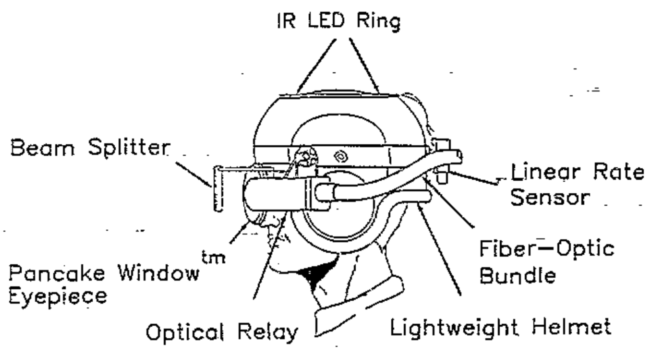

Figure 3. Components of the CAE Electronics Fiber Optic Helmet Mounted Display (FOHMD) as shown without eye tracker.

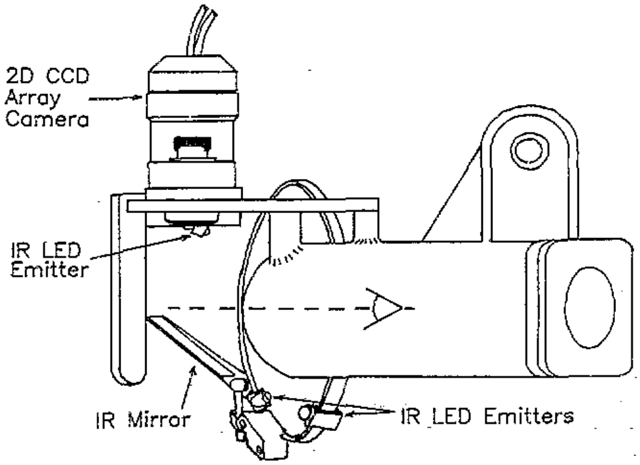

Figure 4. Enlarged view of left eyepiece mount and the El Mar two-dimensional array eye tracker. Using a dark pupil technique, three IR -LED sources illuminate the eye and serve as corneal reflection points. The relative change between pupil center and corneal positions provides sufficient information for discrimination between eye movement and helmet slip. Infrared light reflected from the eye passes through the eyepiece lens to a dichroic mirror which directs the IR image of the eye to the two-dimensional CCD array camera located directly above. Algorithms process the eye image and provide an estimate of eye position at a 60 Hz rate.

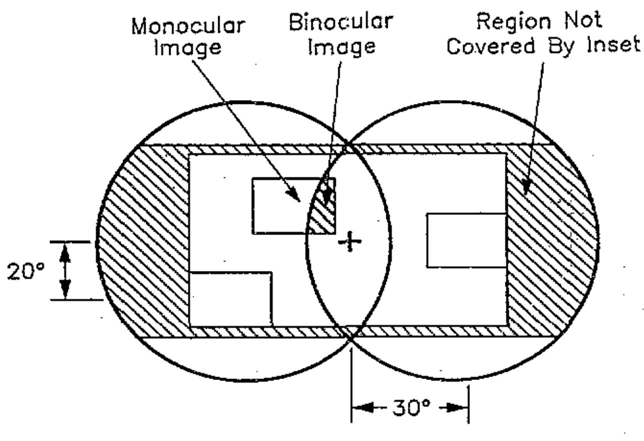

Figure 5. Field of view of the helmet-mounted eyepieces and the region under which the eye tracker must operate in moving the high-resolution inset. From center, the range of inset movement is ±30°H by ±20°V.

MEASUREMENT OF EYE POSITION

The helmet mounted eye tracker sensor as shown in Figure 4 consists of three infrared LED sources, a dichroic mirror and a two-dimensional CCD array operating at 60 Hz. Total weight of the eye tracker components is approximately 50 grams. The eye tracker operates on the dark pupil principle and, as a result, is less sensitive to changes in pupillary size. The relative insensitivity to pupillary changes is an advantage, especially under conditions of high scene brightness, as is often the case in the FOHMD. In comparing a dark pupil to a bright pupil system, the dark pupil system does not rely on a measurement of reflected light from the retina in order to locate the pupil. In addition, the dark pupil technique does not require a collimated or coaxial light source to illuminate the eye. In a dark pupil system, only a small portion of the non-collimated light entering the pupil is reflected back from the retinal layer. Under these conditions, the pupil appears dark and acts as a sink compared to the brightly illuminated surfaces of the sclera and, to a lesser extent, the iris. The three infrared LED light sources that illuminate the eye are mounted to the lower left and right and upper edges of the left eyepiece holder frame. When measured at the position of the eye, the maximum amount of radiated infrared energy from the three pulsed sources is less than 1 mW/cm^2. In addition to the LED sources providing a homogeneous field of illumination of the eye, they also serve as corneal landmarks for estimation of eye position and detection of helmet slip. An estimate of eye position is computed by taking the difference between appropriately scaled signals from the estimated pupil center and the locations of the corneal signals. When an eye movement occurs, the corneal highlights, which are reflections off the nearly spherical surface of the cornea, move at different rates relative to that of the pupil center. When a translation of the eye tracker occurs due to helmet slip, both the corneal highlights and pupil center move at roughly the same rate indicating a translation of the eye tracker rather than a rotation of the eye. The accuracy to which eye position can be estimated and the stability of the measurement are dependent on many factors including the influence of the lid and position of the eye. Partial closure of the eyelid or its lashes can often obscure the pupil and can, therefore, affect the accuracy to which the center of the pupil can be estimated. The position of the eyelid may also cover one or more of the cornea reflections which may result in temporarily estimating eye position based on pupil center information alone. The position of the eye relative to the eye tracker may also affect the accuracy in estimating pupil center. This condition often occurs as the eye rotates farther away from center which causes the normally circular-shaped pupil to appear more elliptical in shape making estimation of pupil center more difficult.

METHODS

Eye movement experiments were conducted in both the Fiber Optic Helmet Mounted Display and the laboratory. In these experiments, subjects were instructed to follow as accurately as possible a target cross while it moved randomly, in separate trials, along the horizontal, vertical, and oblique axes. Horizontal-vertical stimulus coordinate positions were uniformly distributed over a 0° to ±30° range in two-degree increments. The magnitude and direction of the next target position in the stimulus sequence was dependent on the change in target position from one stimulus position to the next.

Experiments were also conducted in both the laboratory and FOHMD to measure the sensitivity of the eye tracker to small random target displacements along all stimulus axes with displacement magnitudes of 0°, 0.25°, 0.5° and 1°.

A total of 10 observers, 9 males and 1 female, participated in the FOHMD experiments. Five of the 10 subjects, 4 males and 1 female, also participated in the laboratory experiments. All subjects possessed normal or corrected vision. An experimental session involved the presentation of 4 groups of 5 trials each, and the same order of trial presentation was maintained throughout all sessions.

Stimuli were composed exclusively of step changes in target position and were randomized for both time and position. Individual trials were composed of horizontal, vertical, oblique along both diagonals, as well as small angle target displacements. Each trial was composed of 31 non-repeatable target positions. Because the stimulus times were randomized, the total duration of each run varied between 47 and 70 seconds. Twenty trials were presented to each subject. During the course of the trials, each target position was presented a total of four times. The complete presentation of the 20 trials and calibration procedures including adequate rest periods between trials required approximately one hour per subject.

All experiments were conducted with room lights off. Prior to each experiment and between groups of 4 trials, a seven-point, ±15° calibration procedure was performed along the horizontal and vertical axes only. The total calibration procedure required less than one minute. During the calibration procedure, the subject was required to fixate on a calibration point and then press a switch indicating to the eye tracker system computer that stable fixation had been achieved. After each press of the switch, the fixation target would jump to the next calibration position. At the conclusion of the calibration sequence the quality of the calibration data could be accessed by the experimenter through tabular display of the calibration data. For the subject, the accuracy of the calibration was reconfirmed after each trial in the FOHMD via visual feedback of the fixation target. In the laboratory, calibration was confirmed after every fourth trial also via visual feedback.

In the laboratory, subjects were seated a distance of 57 centimeters away from a 1.25H x 1V meter flat display screen while they viewed a rear-projected He-Ne laser target spot that subtended a visual angle of 0.1°. A pair of computer-controlled XY mirror galvanometer motors was used to control the position of the target. Changes in head position were minimized by the use of a molded dental bite bar, head and chin rest support. The FOHMD helmet optics and eye tracker were then mounted to the head support system and the stimulus target was seen through the FOHMD eyepieces. Prior to the start of the experiment, subjects were aligned with respect to the exit pupil of the helmet optics using an external light source. In all experiments, the position of the left eye was measured.

In the FOHMD experiments, each subject wore an individually fitted helmet that supported the aligned helmet optics. The stimulus consisted of an easily distinguishable bright white cross hair that subtended a visual angle of approximately 1.5°. In all trials, the high resolution inset was not used and head tracking was disabled. The fixed background imagery consisted of a village farm scene with a lake and hills in the distance.

In all experiments, six eye parameters were output by the eye tracker which were then sampled and stored by a personal computer for later analysis. These data included the horizontal and vertical estimates of eye position, pupil position, and the position coordinates of the corneal reflection from the nasally located infrared light emitting diode.

The collected data from each subject and trial were first inspected with an interactive display program which visually showed the relationship between the stimulus and response. During this procedure, responses which were suspect due to eye blinks or cases where the subject could not locate the target were identified and subsequently eliminated from further analysis. The mean and standard deviation of the sample population response for each trial was then computed by a response averaging program. An analysis program was then used to compute the weighted position error and standard deviation between the sample population response and the actual target position. The sample population results of these analyses were confirmed again by subsequent inspection of the response data with the interactive display program.

RESULTS

Response data for horizontal, vertical and oblique stimuli collected from the laboratory and FOHMD are presented in Figures 6 and 7. In each of the conditions, the diagonal line represents the ideal response; points deviating from this line indicate either over or underestimation of eye position by the eye tracker.

The laboratory data (Mean ± SD) for twenty trials is given in Figure 6. These data show both over and underestimation of eye position over the stimulus range of ±30°. Along the horizontal axis, the response data are within one standard deviation from left 22° to right 32°. The lone point at 12° may be attributable to the retinal blind spot. Beyond 17° left, the eye tracker appears to overestimate eye position. When the vertical response data are considered, the eye tracker appears to slightly overestimate eye position beyond 15° in both the up and down directions. Overestimation was greater in the upward direction reaching a maximum error of approximately 3° at 22° up. Beyond 22°, the eye tracker begins to underestimate eye position. The oblique responses follow from the horizontal and vertical responses. The sharp drop in output for oblique responses to the upper left and upper right is most likely attributable to obstruction from the eyepiece frames and not to the eye tracker.

The FOHMD (Mean ± SD) for 10 subjects and 40 trials is given in Figure 7. The horizontal data shows good estimation of eye position within a ±18° range with increasing estimation error beyond this range. Overestimation of eye position was more evident for eye responses to the left than for responses to the right. Increasing overestimation of eye position occurred when targets were displaced more than -22° left. The error was nearly 7° at -24° left. Underestimation of eye position occurred only between 20° and 26° right reaching a maximum error of 5.4° at 26° right. The vertical response data remained linear over a ±18° range. Beyond ±18° the response data becomes asymptotic. Over the vertical operational range of the eye tracker the position error was 0.5°. As with the laboratory data the oblique responses from the FOHMD are dominated by the vertical response of the eye tracker.

The average laboratory and FOHMD small eye movement response for an identical small angle stimulus sequence of 12 seconds is shown in Figure 8. Although twice as many subjects participated in the FOHMD study, the laboratory data are more consistent and stable and reveal better sensitivity in detecting small eye movements than was revealed by the FOHMD data. In both examples, small changes in horizontal eye position were more easily resolvable than were those in the vertical direction. Laboratory data showed that changes of better than 0.5° could be detected in both directions, whereas in the FOHMD the overall sensitivity was better than 1°.

Laboratory Data

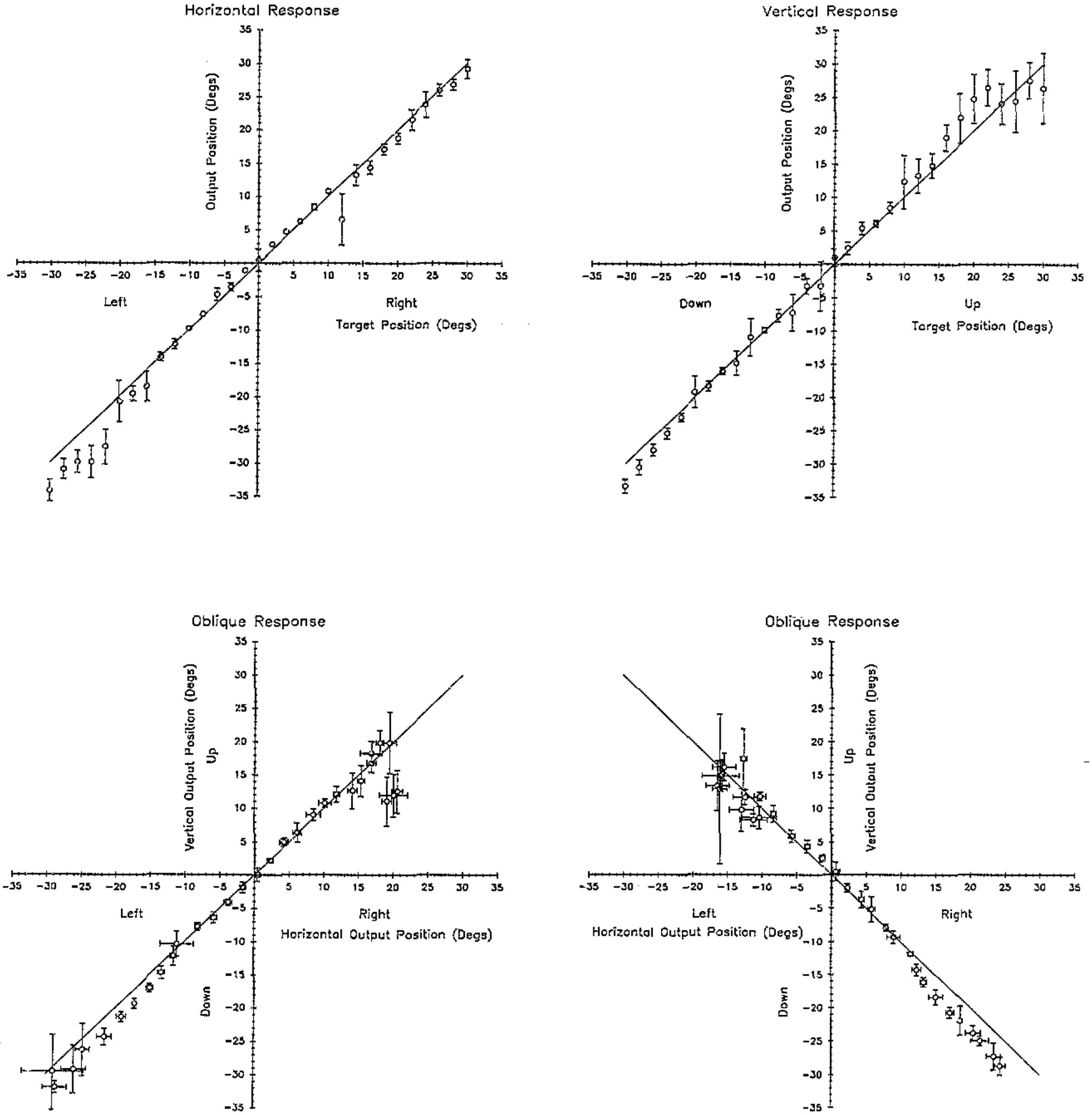

Figure 6. Laboratory output response (Mean ± SD) for two-dimensional array, single cornea eye tracker. (Upper) Horizontal and vertical response. (Lower) Oblique response. The ideal response is given by the diagonal line.

FOHMD Data

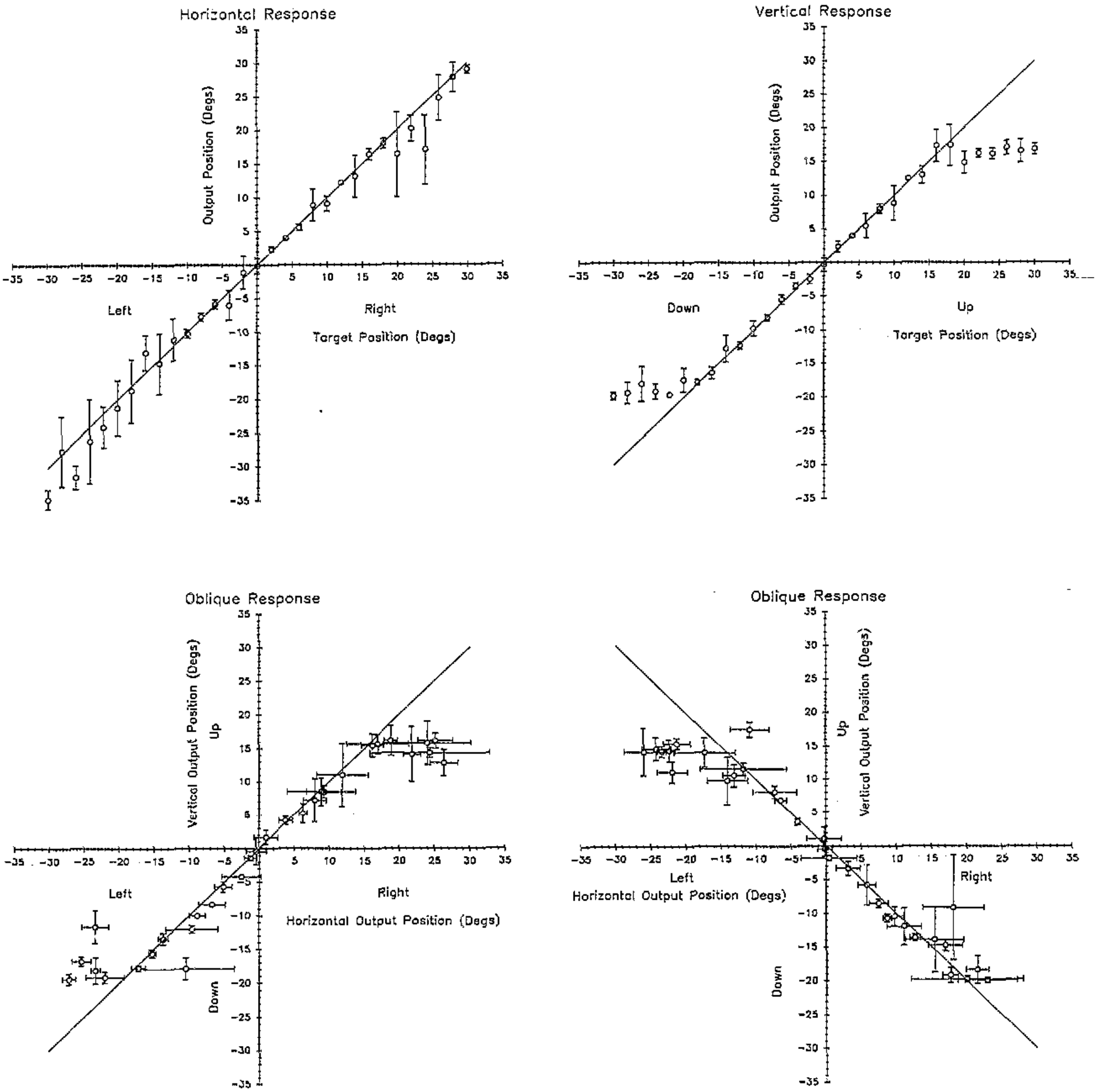

Figure 7. FOHMD output response (Mean ± SD) for two-dimensional array, single cornea eye tracker. (Upper) Horizontal and vertical response. (Lower) Oblique response. The ideal response is given by the diagonal line.

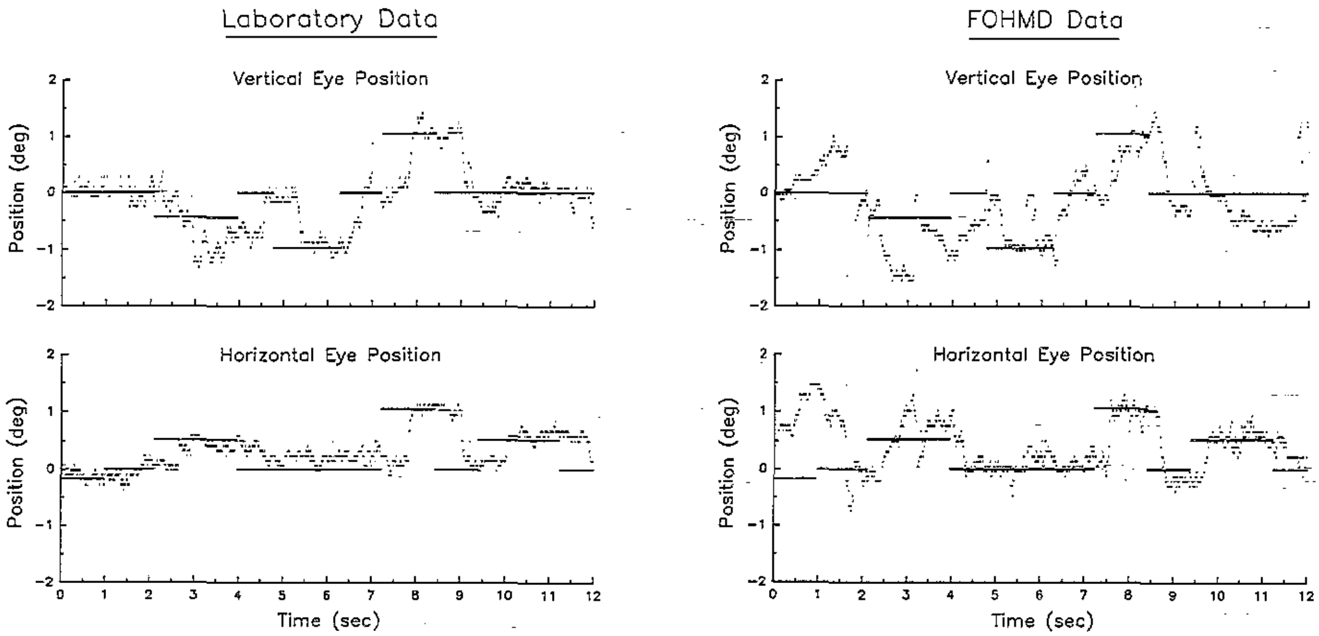

Figure 8. Comparison between laboratory and FOHMD eye movement responses for small target displacements of identical stimulus sequences. Laboratory data represents the mean response of 5 subjects whereas the FOHMD data represents an average of 10 subjects. All target displacements originated from the central fixation position.

DISCUSSION

Comparative eye movement experiments were conducted in the laboratory and the FOHMD in order to characterize the functional performance of the El Mar, Inc. two-dimensional array eye tracking system. In the laboratory, head position was fixed while subjects tracked a small, high contrast, laser target spot while experiments in the FOHMD were conducted with the low resolution background with fixed scene content and disabled head tracking. In these experiments, a basic assumption was made that the oculomotor control system is sufficiently precise in controlling the eyes such that the final fixation error is less than 0.5°. Fixation errors greater than 0.5° were assumed to be attributable to the characteristics of the eye tracker system and not to the oculomotor control system.

In both the laboratory and FOHMD experiments, the large eye movement response data for horizontal stimuli showed unequal response between leftward versus rightward stimuli. The directional differences observed might, in part, be attributable to the fact that only the pupil and the nasal corneal signals were used for computation of eye position. Consequently, as the eye rotates farther to the left, the corneal reflection resulting from the nasal IR LED moves closer to scleral surface whose radius of curvature is roughly half that of the cornea. In the present version of the eye tracker, all three corneal signals are contributory in estimation of eye position. Thus, if a particular eye position results in a corneal reflection entering the scleral surface, it can be ignored in favor of the other corneal signals. It is anticipated that with the incorporation of additional corneal signals, the linearity and range of the eye tracker should increase. The calibration range of the eye tracking system will also be extended to match operational range of the device as well.

Data from the small target displacement studies collected in the laboratory indicated that the eye tracker can consistently resolve changes in eye position as small as 0.5°, the signal-to-noise ratio being the limiting factor. Under laboratory conditions, head position was stabilized while it was not during the helmet experiments. The differences between the sensitivities may, in fact, be attributable to small amounts of helmet slip or to helmet slip compensation schemes. Another factor that may account for these differences were the methods used to display the stimulus targets. In laboratory experiments, the stimulus was the only object present in the display area whereas in the FOHMD, target contrast and display resolution were less and, therefore, detection of the target may have been more difficult for the observer. The amount of noise present in the system determines the boundary conditions under which area-of-interest display systems operate. As such, output noise from the eye tracker or other systems will determine the amount of jitter present in the high resolution area of interest. At the present time however, the amount of noise or jitter in the FOHMD is not a serious factor since the size or area of the high resolution inset is considerably greater than that of noise level. However, if the size of the inset were to be significantly reduced, such as in proposed eye controlled variable acuity displays, then the level of noise would become a far more serious concern. At present, during flight simulation, the eye position signals are passed through a 1° deadband with hysteresis which effectively eliminates all inset jitter during fixation.

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