

DESIGN OF AN EYE SLAVED AREA OF INTEREST SYSTEM  
FOR THE SIMULATOR COMPLEXITY TESTBED

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Abstract

The Simulator Complexity Testbed (SCTB) is a highly modular flight simulator for experimental research focused on US Army Aviation advanced rotary wing combat. A major component in the development of the helmet mounted fiber optic display media for this device is an eye slaved area-of-interest (AOI). In order to provide for an accurate, reliable, and robust helmet mounted eye tracker to support proper system operation, the engineering development of competing eye tracking designs was initiated under a cooperative US Army/US Air Force/Canadian cost shared development program. This paper describes the overall design of the SCTB eye slaved, servo driven optical system and discusses the issues involved in its development.

Introduction

Under an Office of the Secretary of Defense approved U.S./Canada Cost shared development program, the Army Research Institute Aviation R&D Activity (ARIARDA) is developing the Simulator Complexity Testbed (SCTB). The SCTB is a highly modular flight simulator for experimental research focused on US Army Aviation advanced rotary wing combat.

The immediate goal of the SCTB program is to establish a flexible flight simulator research tool to address (1) aircrew training device fidelity requirements, (2) development and refinement of new aviation tactics and doctrine, and (3) front-end assessment of proposed required operational capabilities in Army aircraft. The SCTB incorporates an architecture which can be expanded to the level of a Combat Mission Simulator, or shrunk to that of a Part Task Trainer, in order to support research across an entire family of synthetic devices.

Among its many innovative features, the system design includes: (1) microprocessor-based distributed host computer system, (2) interactive tactical environmental management software tailored to the high intensity Army aviation battlefield, (3) the use of eye tracking to drive high detail computer generated imagery in high resolution flight simulator displays, and (4) upfront provisions to support the

requirements for behavioral research in advanced Army aviation combat. An SCTB system overview is provided in Figure 1.

In addition, a tri-service agreement will provide for establishing the SCTB as one node on a long-haul network to the Air Combat Mission Enhancement (ACME) complex (Kamrowski, 1989) at the Air Force Human Resources Laboratory, Williams AFB, Arizona. This network is projected to include the Naval Training Systems Center's Visual Technology Research Simulator as well as PM-TRADE facilities in Orlando, Florida. As the SCTB will also be tied into the SIMNET/AIRNET network (Thorpe, 1988; Longridge, 1989), this arrangement will provide a unique opportunity for the respective service's simulator research activities to conduct cooperative studies on emerging issues in collective/combined arms training.

Its location within the institutional training environment, Fort Rucker, U.S. Army Aviation Center, will provide the SCTB with ready access to a large population of aviators at all levels of experience, as well as multiple types of aircraft, for validation of work accomplished in the simulator.

Recent analyses (Bonzeit & Edwards, 1988; Longridge, 1987) have concluded that the image generation requirements for simulation of advanced rotary wing aviation battlefield environments severely push the state-of-the-art in flight simulator visual system technology. In order to achieve these demanding requirements, a major component in the development of the helmet mounted fiber optic display media for the SCTB is an eye slaved area-of-interest (AOI). In addition to employing the eye position signal to drive wide excursion servo driven mirrors for moving a high resolution inset within a background field of view, the point of regard data is coupled to the SCTB image generator to control polygonal level-of-detail. In this system, level-of-detail falls off as a function of angular horizontal distance from the center of the eye slaved AOI, in addition to the normal polygonal detail switching which occurs with increased distance from the eyepoint towards the horizon. In this fashion the highest level of image generator scene detail can be continuously concentrated in the area of highest display resolution. Different

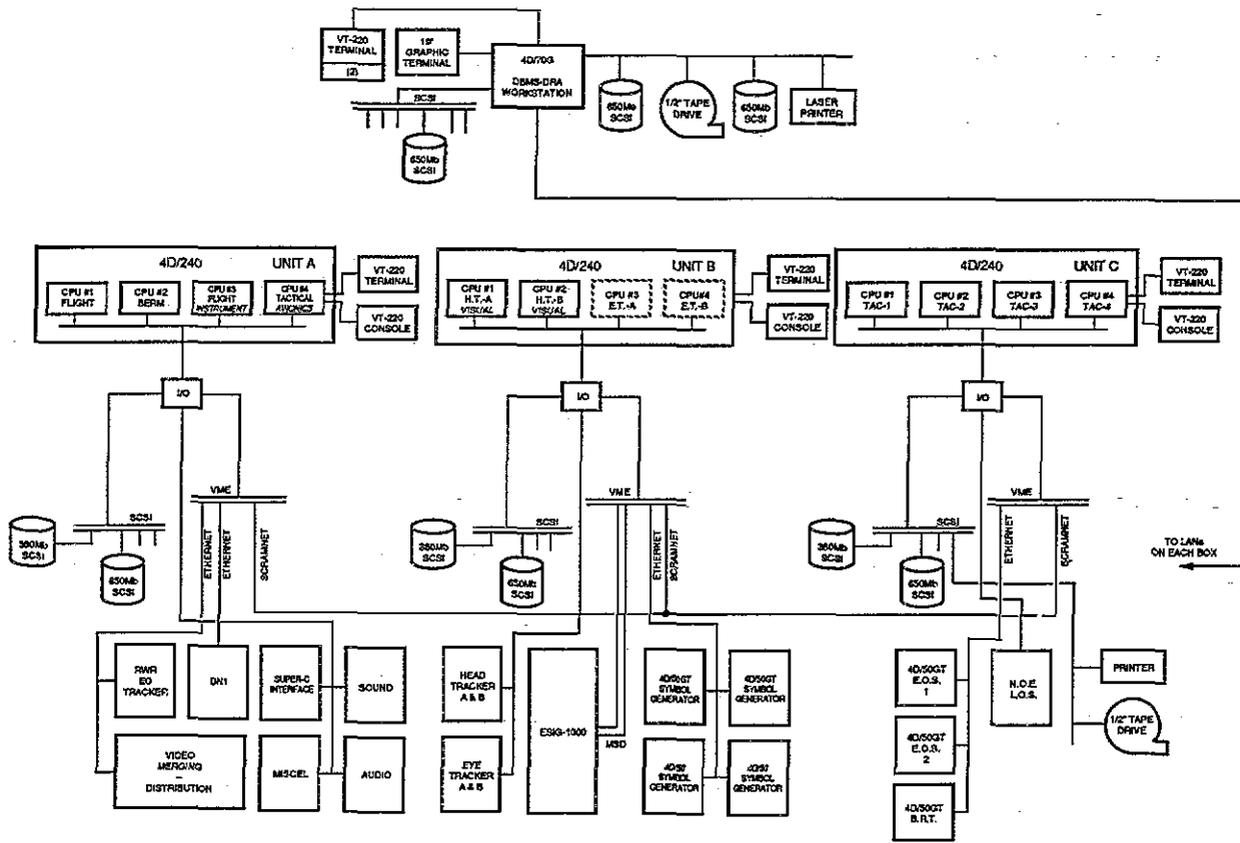


Figure 1. Simulator Complexity Testbed System Overview

angular level-of-detail fall-off functions may be selected. Shape programmable video blending is employed to provide smooth transition between the AOI inset and the background.

This paper describes overall design of the SCTB eye slaved, servo driven optical system and discusses the issues involved in its development.

The SCTB/AOI system is comprised of an eye position monitor, a head tracker, a computer system, a servo controlled optical system, and a video blending system. A block diagram of these components is shown in Figure 2.

The principle of an AOI in a visual display system relies on two characteristics of the human visual system: (1) visual acuity is highest within an approximately 1 degree retinal area called the fovea, and (2) acuity is reduced during, and for a brief period following, a rapid step eye movement called a saccade (Bridgeman, Hendry & Stark, 1974; Stark et al., 1976). This theoretically permits a relatively small area of high resolution imagery within a low resolution field to be perceived as being entirely high resolution, providing the inset accurately and reliably follows the user's point of regard.

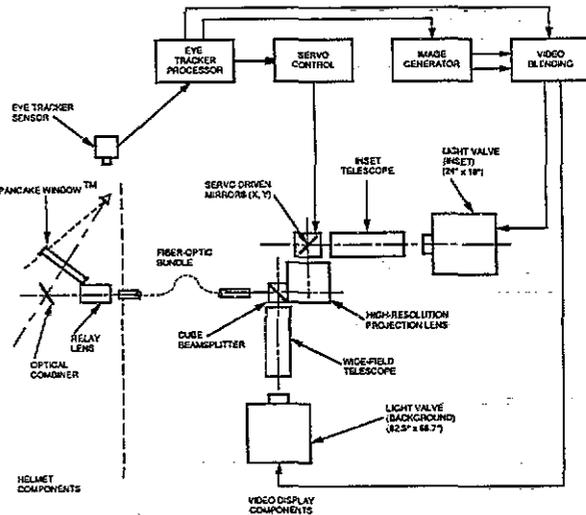


Figure 2. FOHMD AOI Block Diagram

The display media on which this system is being implemented is the Fiber Optic Helmet Mounted Display (FOHMD) (Hanson et al., 1984; Welch & Shenker, 1984; Kruk & Longridge, 1984a). The FOHMD includes a moveable high resolution area as an

integral part of the system design. The visual image is formed from four computer image generator (CIG) channels, two for each eye (Kruk & Longridge, 1984b). One channel is used for a  $25^\circ$  by  $18.9^\circ$  high resolution inset while the second channel is used to produce the  $82.5^\circ$  by  $66.7^\circ$  (monocular) lower resolution background field of view (FOV), for each eye respectively. This provides a total binocular FOV of  $127^\circ$  by  $66^\circ$  (Figure 3). The images are projected by one light valve and optical system for each channel. Servo controlled mirrors are included in the inset optical path to position the AOI as demanded by the computer used to process data from an eye position monitor. The outputs of the two optical paths are combined on the end of a large format coherent fiber optic bundle for transmission to the helmet mounted optics. An electronic blending system operates on the CIG video signals to provide a shape programmable gradual fade from the background to the inset to eliminate sharp edges at the border of the fields.

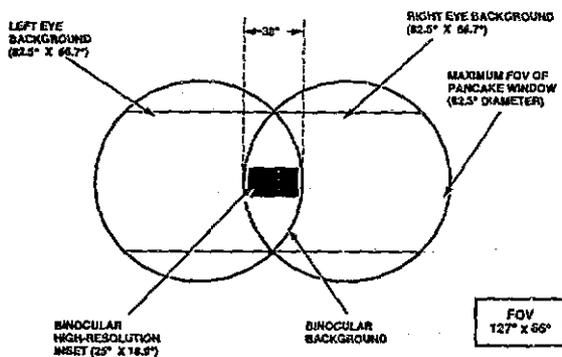


Figure 3. FOHMD: Basic Fields of View

The components of the SCTB AOI control system have been designed to readily support software adjustable parameters, ranging from observer adaptable, real time switchable servo tracking strategies to programmable video blending cutout shape definition.

#### Optical Head Tracker

The display elements of the FOHMD are helmet mounted, and therefore the visual scene also moves with the head. This requires that the viewpoint sent to the CIG must be slaved to the head position to provide a stable picture. On the FOHMD the head position is sensed by a non-contact Optical Head Tracker (OHT). (Welch & Shenker, 1984).

The OHT uses a ring of infrared light emitting diodes mounted on the top of the helmet as targets which are sensed by four solid state optical position detectors. The output of the sensors is transferred to the simulator computer

system where it is used to compute head attitude and position.

If the head position calculated from the LED data were to be used directly to drive the CIG, the system throughput time would result in a lagged display. This problem is resolved through the use of rate sensors mounted to the helmet. A prediction algorithm combines the light emitting diodes (LED) and rate data to supply a compensated head position to the CIG.

#### Eye Position Monitor

Manipulation of the visual scene requires not only a device to measure eye position during rotation and fixation, but also an understanding of the impact that different methods of controlling the inset position will have on the acceptability of the visual display.

To accurately measure eye position relative to the FOHMD, eye position monitors must possess high spatial and temporal resolution, operate over a large field of view, and must distinguish between eye movements and artifacts (Robinson, Thomas & Wetzel, 1989). The range over which the eye tracking device can provide accurate eye position data must at least equal the range that the AOI can be repositioned within the user's instantaneous field-of-view. High spatial and temporal resolution is necessary due to the rapid acceleration rates and high velocities achieved during saccadic eye movements (accelerations can reach several thousand degrees/sec<sup>2</sup> and peak velocities can exceed 800 degrees/sec).

Also, the eye tracking system must operate under conditions of dynamically changing illumination caused by variations in scene brightness which in turn result in variations in pupil diameter. The shape of the pupil also changes with shifts in eye position and considerable variability occurs in the user population with respect to the physical characteristics of their eyes. The eye position monitor must account for all such variations in real time while continuing to provide reliable eye position data.

The basic performance criteria established for the SCTB Eye Tracker (ET) are presented in Table 1. In general, the ET must (1) operate accurately and reliably under conditions of continuous head movement, (2) sample eye position at a sufficiently high iteration rate to effectively drive the real time CIG, (3) accommodate 95% of the target population (Army aviators), and (4) be 100% compatible with the FOHMD. The placement of the ET on the FOHMD is indicated in Figure 4.

Table 1  
Eye Tracker Specifications

Gaze Direction:	$\pm 30^\circ$ Horizontal $\pm 25^\circ$ Vertical
Accuracy:	$\pm 1^\circ$
Resolution:	.1 $^\circ$
Allowable Helmet Slip:	$\pm 5$ mm
Infrared Illumination Level:	Less than 1 mW/cm <sup>2</sup> (non-laser light)
Sampling Rate:	120 Hz
Percentile User:	95 percentile Army aviator
Background Luminance:	30 foot lamberts

delay between the actual eye position and the data describing that position is reduced from approximately 17 milliseconds (ms) to 6 milliseconds. Another feature considered important was the correction for translation artifacts; i.e., head-to-helmet slip. The system design is intended to permit helmet slip of up to 5 millimeters (mm) in all directions relative to the eye without degradation in eye tracking accuracy. The approach uses the magnitude of difference between an image of the pupil and the reflection from the cornea; as the eye rotates, the image of the corneal reflection moves relative to the center of the image of the pupil. When the imaging device slips in position relative to the eye during a head to helmet slip, these images move at the same rate. Thus, the difference measure is not contaminated by error due to translation of the ET relative to the eye (within a limit of 5 mm). Figure 5 shows the effectiveness of this difference measure for a 5 mm horizontal translation of the helmet mounted eyetracker while fixating a stationary stimulus, in comparison to the use of corneal measurement alone.

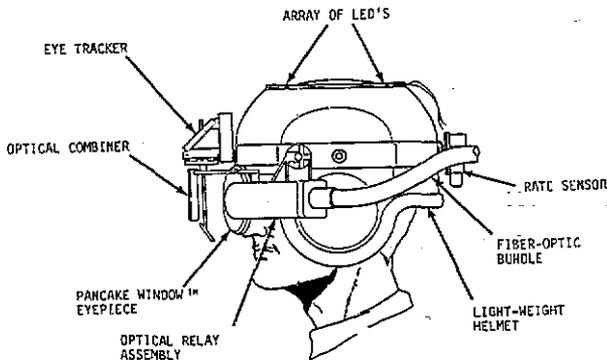


Figure 4. Mounting of Eye Tracker on FOHMD

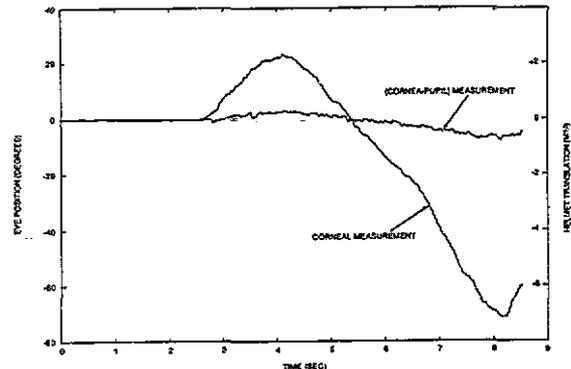


Figure 5. The Effect of a 5 mm Horizontal Translation of the Eye Position Monitor on Measurement Data.

Eye Tracker Design Considerations.

Given the dimensions of the AOI and the cumulative error over time that could result in drift between the center of the AOI and the measured position of the eye, a design goal of 1 degree of accuracy was established. The resolution and iteration rate were based upon the need to reposition the AOI continuously during smooth pursuit eye movements and measure the onset and termination of high velocity ballistic eye movements (saccades). In addition, for a given sensor array, a higher iteration rate of measured eye position can significantly reduce the lag inherent in an AOI image generation system, as well as reduce noise by providing a larger number of sampling points over which to average per unit time. By increasing the update rate from 60 Hz to 180 Hz, for example, the

Prototype Eye Trackers. A variety of alternative prototype eye trackers have been developed specifically for evaluation on the FOHMD, each of which entailed enhancements to basic laboratory eye position measurement techniques (Young & Sheena, 1975), principally in the area of real time computational analysis. These include: (1) a dual corneal reflection, dark pupil system based on video processing (Razdan & Kielar, 1988), labeled System I, (2) a linear array bright pupil eye position monitor based on signal processing (Eizenman, Frecker, & Hallett, 1984), labeled System II, and (3) a refinement to System II using a two-dimensional charge coupled device (CCD) array capable of being employed in both bright pupil and dark pupil modes, labeled System III.

#### Dual Corneal Reflection Dark Pupil ET.

In order to more accurately quantify the performance characteristics of the System I eye position monitor, eye movement experiments were performed under controlled conditions in the laboratory. System I is a video-based dark pupil/dual corneal reflection device, that operates at a sample rate of 60 Hz over a range in excess of  $\pm 30^\circ$  horizontal by  $\pm 20^\circ$  vertical eye movement. Experiments were performed in the dark with stabilized head and bite bar, while subjects viewed a projected laser target from a distance of 1 meter. The right eye was measured by the System I while the left eye was measured by an infrared differential reflectance measurement technique, a limbus tracker, labeled the Reference System. The Reference System analog output voltage was proportional to eye position over a horizontal range of  $\pm 20^\circ$  which was then low pass filtered with a cutoff frequency of 250 Hz. System noise of the Reference System was less than one arc-minute.

The data of Figure 6 show the typical spatial-temporal relationship between the reference monitor eye position analog signal and the System I horizontal pupil and corneal signal in response to a right-to-left  $21^\circ$  step change in target position. Pupil position from System I lags behind actual eye position by between one and two 16.67 ms video frames. Corneal data are delayed an additional two to three frames behind pupillary data. In these experiments, pupil noise was observed to be roughly  $0.4^\circ$  horizontal  $0.6^\circ$  vertical while corneal noise was roughly  $0.6^\circ$  horizontal and approximately  $1^\circ$  vertical.

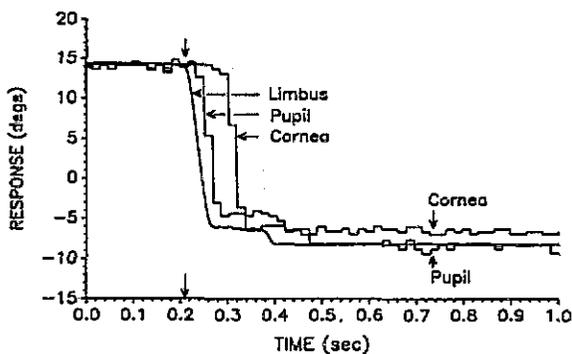


Figure 6. Step Response of System I for Corneal and Pupillary Signals in Comparison to a Limbus Tracker.

The effect of filtering on the pupillary output signal from System I is plotted in Figure 7. Without filtering, (upper trace) average noise level is  $0.5^\circ$ . With filtering, (lower trace) average noise level is reduced to approximately  $0.2^\circ$ . The 5-point filter approximates an exponential weighting function with an added delay time of 24 ms.

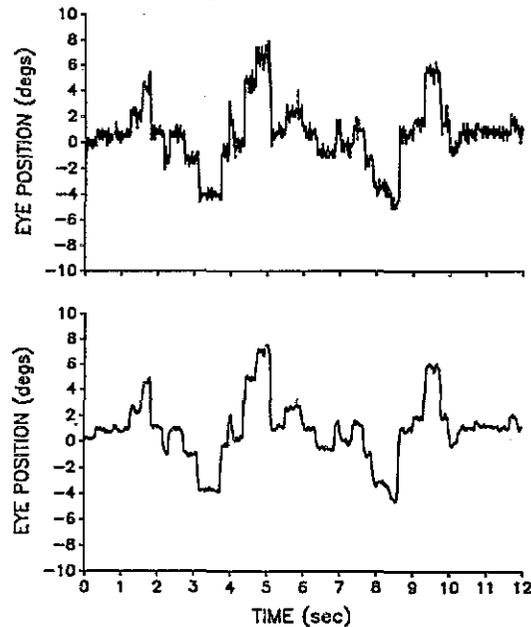


Figure 7. Plot of System I Output (top) and Effect of Digital Filtering Thereon (bottom).

In an experiment designed to assess sensitivity to lag between a change in eye position and the repositioning of the AOI in the FOHMD, System I was used with the digital filter. A total of 10 observers participated in the experiment. Each subject was presented with a total of 20 trials that were randomized between 0 and 19 additional frame delays (1 frame = 16.67 ms). The subject's task was to either increase or decrease the frame delay until a just noticeable difference was perceived between the zero added delay condition (four frames). Mean number of additional frames selected by the sample of 10 observers was 4.86 with a standard deviation of 3.55; the range varied between 1.8 to 10.5 additional frames. The worst case total system transport delay for SCTB, including all processes associated with correctly positioning the head/eye slaved AOI and CIG inset image as appropriate to the head slaved CIG background image, does not exceed 103 ms. These results suggest, therefore, that lags associated with inset movement for SCTB are within acceptable limits.

**Linear Array Bright Pupil ET.** The System II ET is based upon a design that measures the horizontal or vertical eye position at each eye. This approach was adopted because it offers the optimal optical alignment at each eye for either the horizontal or vertical measurement. The basic measurement technique employed uses the difference in position of the bright pupil image and the corneal reflection as measured at a separate linear photodiode array for each axis.

Although System II was found to be capable of providing low noise, accurate measurement, it could not maintain that level of performance reliably across a normal range of subjects. The most significant difficulty was found for subjects whose pupil diameters were characteristically less than four millimeters under typical FOHMD luminance levels. The bright pupil is produced by using a retro-reflected image from the retina projected via the aperture formed by the pupil. Changes in the pupil diameter, in response to shifts in brightness, caused variations in the intensity of the bright pupil signal. In addition, as the eye rotates away from the optical axis of the ET illumination source, the efficiency of the retro-reflection is degraded. The effectiveness, however, of the image processor when operating with a clear high intensity image was found to be very good. Figure 8 plots eye position as measured on the FOHMD by System II in response to a step change in target position from  $-7$  to  $+7$  degrees at  $t=0$  seconds when sampled at 180 Hz. Average noise was observed to be better than  $.2^\circ$  over a  $\pm 15^\circ$  range. Figure 9 plots System II data for  $20^\circ$  and  $40^\circ$  eye movements, respectively, sampled at 180 Hz.

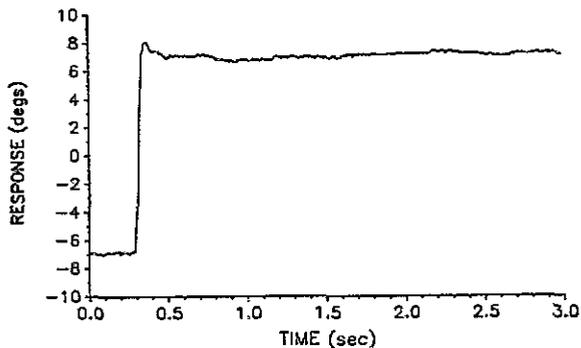


Figure 8. Step Response of System II at 180 Hz.

Two Dimensional CCD Array ET. By applying the signal processing algorithms developed for the System II ET with a two dimensional imaging device to acquire the corneal reflection and dark pupil image, the level of performance needed for this application can be achieved. System III combines the ease of image acquisition associated with a dark pupil format and the technological advantages that can be exploited with a two dimensional camera. The image of a dark pupil formed by the pupil aperture acting as an illumination sink is far more robust than other methods since the signal is not degraded by the effects of small pupil diameter. An instantaneous image of the complete eye, with full detail, is captured and processed, provided sufficiently homogenous eye illumination is available to minimize shadows. System III can also

be used in a bright pupil mode, and in fact could alternate between bright and dark pupil imaging modes, as warranted.

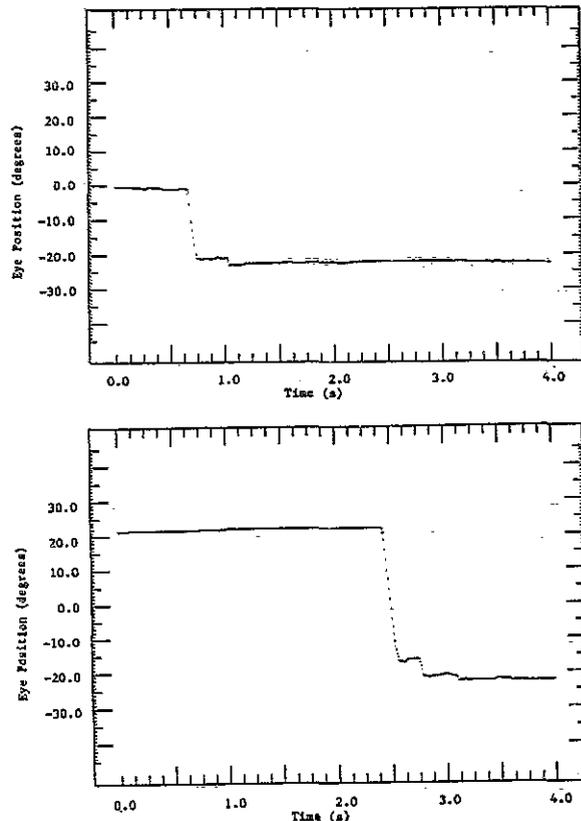


Figure 9. System II 180 Hz Eye Movement Data in Response to  $20^\circ$  (top) and  $40^\circ$  (bottom) Changes in Eye Position

Figure 10 plots System III eye movement data collected on the FOHMD while tracking a smoothly moving CIG target along an elliptical path ( $\pm 15$  horizontal by  $\pm 10^\circ$  vertical) at an average velocity of approximately  $5^\circ$  per second. System accuracy was excellent.

The System III design also permits multiple LED's to be integrated into the optical configuration and to be identified and monitored by the signal processing algorithms. Multiple LED's provide additional corneal reflections that extend the range of eye position measurement into the periphery, and aid in maintaining homogeneous eye illumination.

Illumination Level. An accepted standard for infrared illumination at the eye in the normal laboratory operation of an ET is up to  $10 \text{ mW/cm}^2$  (Frecker, 1988). For all the ETs discussed above the illumination has not exceeded  $1 \text{ mW/cm}^2$ . It is expected that the ET integrated in the FOHMD will operate at a level less than 5% of the  $10 \text{ mW/cm}^2$  standard.

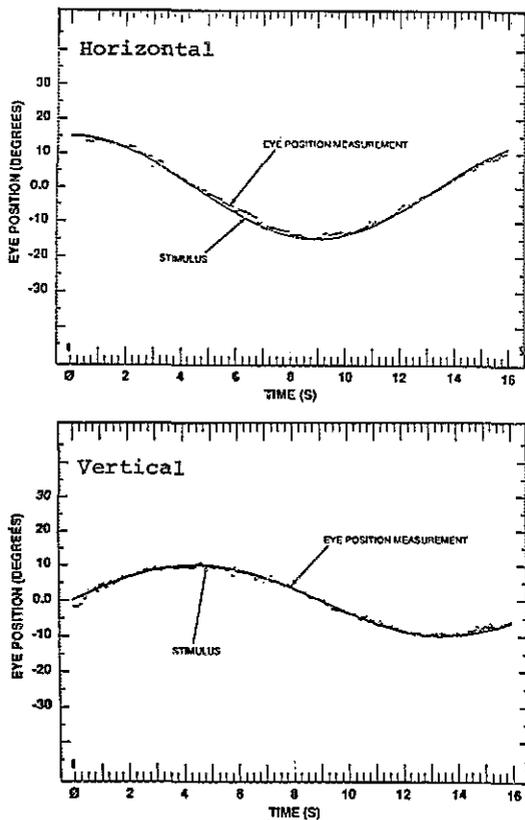


Figure 10. System III Eye Position Data Showing Horizontal (top) and Vertical (bottom) Output while Tracking a Smoothly Moving Target Along an Elliptical Path.

### Servo Design

The use of an eye slaved area of interest (AOI) requires a device to optically steer the high resolution AOI in elevation and azimuth within the lower resolution background image. For the FOHMD this is accomplished by two servo driven mirrors rotating about orthogonal axes in the optics chain for each eye. Since the FOHMD has the helmet position as its reference frame, the servos are therefore required only to move the inset over a range equivalent to the range of the eye position monitor. There is no need to provide 360° servo range.

The output of the projector falls first on the elevation axis mirror. The centerline of this mirror is not co-axial with the motor shaft resulting in a high inertia load. A high torque DC servo motor is used in this application. The range of the elevation servo is  $\pm 20^\circ$  (optical). The image is then passed to the azimuth axis mirror which is driven by a galvanometer motor. The azimuth servos have a range of  $\pm 50^\circ$  (optical) which is greater than the current performance of the eye position monitor,

thus allowing for future enhancements. When the servo range is combined with the large inset size, a useful AOI range of approximately  $\pm 60^\circ$  by  $\pm 25^\circ$  is provided. Step response times of less than 8 ms are typical for the servos.

The servos are controlled by high speed digital processors which receive position and velocity commands from the eye data processor. This data is used to compute demanded motor torque profiles to move the mirror along the required path (Figure 11). Various modes of operation such as "step immediately to final position" and "maintain continuous movement" are available for selection depending on the characteristics of the eye movement data. Saccadic eye movement will result in a rapid servo step response while smooth pursuit type movements will make use of the continuous movement strategies.

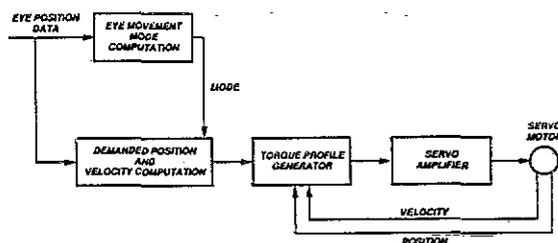


Figure 11. Eye Slaved Inset Servo Control

### Eye Tracking Processor

Since part of the SCTB FOHMD project involves developing and assessing different eye trackers which may have different characteristics, the algorithms to process the data must be flexible. In addition, monitors with increased capabilities can be expected in the coming years and the SCTB must be capable of taking advantage of these improvements. This has required the use of a processor configuration which can be easily adapted to new data characteristics.

Raw data from the eye position monitor is transferred to the simulator computer complex for processing. The rate at which the data is transferred is slaved to the output rate of the monitor and can be at a higher rate than that of the rest of the simulator. The algorithms for determining the required AOI position also run at this rate. Processing is done in FORTRAN to maximize flexibility for investigation of alternative algorithms. The output of the processing algorithms is then combined with the head position as determined by the OHT to compute the viewpoint of each channel in the CIG.

The timing between each element of the FOHMD is synchronized by the processor such that data is calculated just before it is required by the next item in the loop.

#### Video Blending

The image seen by each eye is composed of the output of two projectors. If unprocessed video from the CIG were to be used by the projectors the result would be the production of a sharp edge at the border between the inset and background images. These edges attract the user's attention and may disrupt the perceptual effect of a full high resolution image.

The reduction of the visibility of the transition between the background and inset relies on processing the video signals in real time. The inset is defined as an arbitrary symmetrical shape and parameters are set to determine the width (typically 3 degrees) and characteristics of the blending region such as display gamma. The circuitry then creates a cutout in the background with a gradual transition region and operates in a complementary manner on the inset video. The net result of this is a high resolution area smoothly integrated into the lower resolution wide field of view background. The position of the cutout is determined by the eye position processor, and is timed so that synchronization between CIG output, blending region position, and servo mirror position is maintained.

#### Summary

In order to achieve the demanding visual system requirements necessary to simulate the high intensity Army aviation airland battlefield, an approach for the implementation of an eye slaved area-of-interest has been developed for the Simulator Complexity Testbed. The SCTB program will employ custom developed eye tracking technology to drive both CIG scene detail and servo-driven inset optics in a binocular fiber optic helmet mounted display system. A variety of alternative eye tracker prototypes have been fabricated for evaluation on the FOHMD as well as in a controlled laboratory setting, culminating in the development of a helmet mounted eye tracker with acceptable performance characteristics for this application.

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