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NONLINEAR PREDICTION OF HEAD MOVEMENTS FOR HELMET-MOUNTED DISPLAYS

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In head- and eye-slaved visual systems, lag times in the visual feedback loop are more apparent than they are in conventional fixed display systems. The available technology of digital image generators does not permit lag times to be reduced to the required amount. Therefore, appropriate prediction algorithms have to be developed. Accelerometers were used to measure the step response of the head in three axes of rotation. It could be shown that linear prediction does not provide the necessary accuracy in the simulated position. A further analysis of the recorded data revealed that it is possible to take advantage of the head's latency to improve the prediction. A simple nonlinear prediction algorithm based on acceleration data was successfully implemented in the fiber optic helmet-mounted display.

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This publication is primarily a working paper.
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PREFACE

This report covers research conducted by the Operations Training Division of the Air Force Human Resources Laboratory between January and April 1983. The study was performed in support of the Fiber Optic Helmet-Mounted Display of the Combat Mission Trainer (CMT) project — project manager, Lt Col Peter Cook; assistant project manager, Capt Caroline Hanson; project engineer, Mr. Bruce McCreary; project scientist, Dr. Tom Longridge; and exchange scientist, Mr. Uwe List (Federal Office for Military Technology and Procurement, West Germany). The author would like to express his special thanks to Mr. Bruce McCreary and Dr. Tom Longridge, who provided essential ideas and basic support; to Mr. Dan McGuire and Capt Caroline Hanson for final review; and to Lt Col Peter Cook, Capts James Seat and Caroline Hanson, Dr. Tom Longridge, and Mr. Tom Stanzione, who joined me in sacrificing their heads for the measurements.

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I. INTRODUCTION

The research and development (R&D) question is: "What impact does a head-slaved or an eye-slaved visual system have on the subjective perception of visual lag times?" For a theoretical evaluation of this question, lag time is defined to be the difference between the time in which the simulated event occurs and that of the real system (Figure 1).

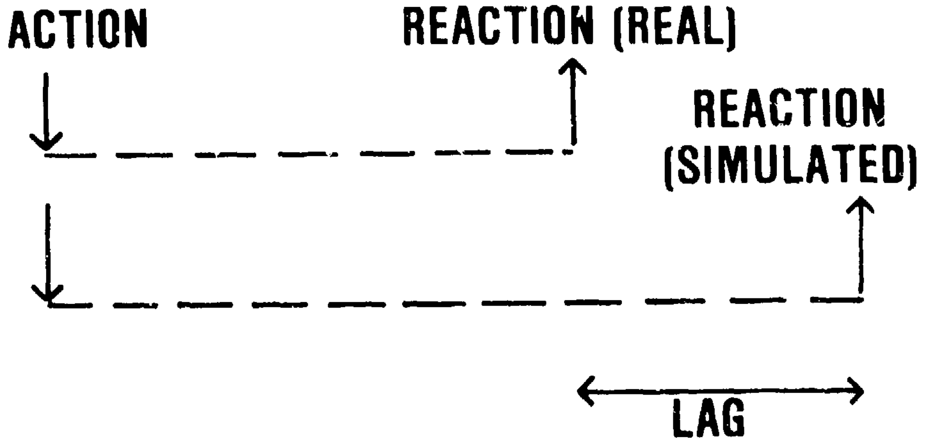


FIGURE 1: DEFINITION OF LAG TIME

Lag times below 100 msec in flight simulator visual systems are not subjectively discernible. However, detailed studies in this area indicate that performance deterioration can be objectively measured, even when time delays as small as 60 msec exist in the visual feedback loop (Queijo & Riley, 1975).

The definition of lag time makes it clear that the lag of a simulator can be subjectively perceived only if the perceiver is experienced with the real system. Performing an action like steering a car or piloting an aircraft raises the conciousness of the experienced driver or pilot to a state of expectation about the upcoming reaction. The driver or pilot will then compare this expectation value with the actual event. Thus, the more experienced pilots will be most sensitive to a time delay in a flight simulator.

In addition, lag perception will depend on the difference between the simulated and the real position at a given time. This difference (DELTA P in Figure 2) increases significantly with increasing acceleration capability of the system. Angular position changes and angular accelerations are essential for high fidelity visual system performance.

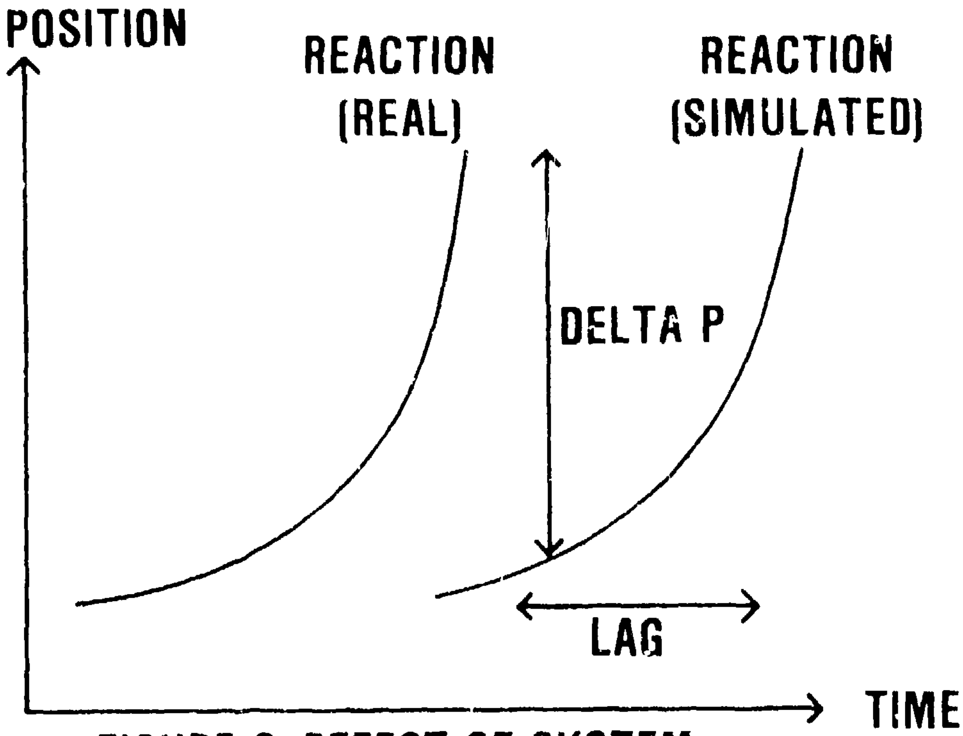


FIGURE 2: EFFECT OF SYSTEM ACCELERATION CAPABILITY

Experience of the observer and acceleration of the system are the two primary parameters that need to be examined for evaluating conventional, as well as head-slaved and eye-slaved, visual systems.

In conventional visual systems, the reaction of the visual scene depends on the movement of the aircraft. Pilots experience this movement only during their flight hours, and they have to adapt each time they change planes. Furthermore, the most rapid movement of a modern fighter aircraft is a roll with typical accelerations of approximately 600 deg/sec^2 and maximum values up to 1200 deg/sec^2.

In head-slaved and eye-slaved visual systems, the reaction of the visual scene depends on the movement of the aircraft superimposed on that of the head and eyes. Head and eye movements are experienced and practiced with every movement in life. Head rotations can be performed with accelerations in the range of 2000 deg/sec^2, and peak values up to 6000 deg/sec^2 are reported. Maximum eye accelerations may be as much as 53,000 deg/sec^2 (Lobb, Barber & Murray, 1979).

Table 1 presents a convenient comparison. The table indicates that lag times will become subjectively more apparent in head-slaved and eye-slaved visual systems than in conventional visual systems.

Table 1. Comparison of Display Configurations

	conventional	head-slaved	eye-slaved
experience in real scene dynamics	trained skill; limited flight hrs; changes with aircraft	lifetime experience and training; only small gradual changes	
normal acceleration deg/sec^2	600	2,000	?
peak acceleration deg/sec^2	1,200	6,000	53,000

Due to technical limitations, there is no foreseeable reduction in lag times. Alternative methods must be developed to make the temporal characteristics of head-slaved and eye-slaved systems acceptable. One such method involves predicting the head and eye movement. This paper discusses approaches to such a prediction for applications in a head-slaved visual system.

II. METHOD TO MEASURE ROTATIONAL ACCELERATION

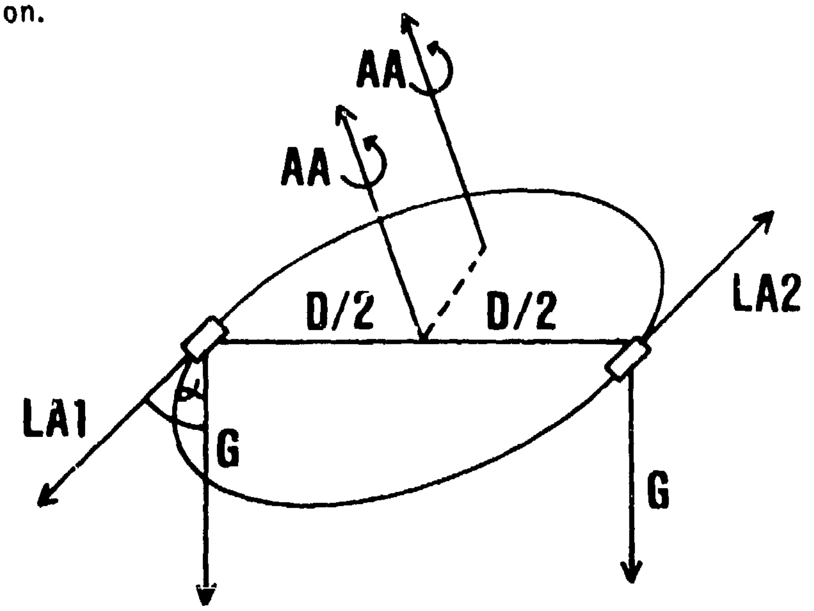
Before developing prediction algorithms, data on actual head movements were gathered. Such records are valuable in characterizing head dynamics and serve as test data for candidate algorithms.

To produce a complete picture of a movement, the head position, velocity, and acceleration information must be available. Although the latter two can be derived from the first one by differentiation, it seemed to be impractical because instrumentation noise may cause serious restrictions for subsequent differentiations. For that reason, a method of measuring acceleration, then deriving velocity and position by integration, was selected.

Since linear accelerometers were available, two were attached to a helmet to measure the rotation about one axis. The two accelerometers were oriented in equal but opposite direction and the angular acceleration, AA, was derived from the linear acceleration values, LA1 and LA2, according to the formula

$$AA = \frac{360^\circ}{2\ PI\ D}\ (LA1 + LA2)$$

with D as the distance between the two accelerometers (Figure 3). Due to the geometric arrangement, the averaging of the linear acceleration values has two advantageous effects: first, the influence of gravity is cancelled out, and second, the center of rotation does not need to coincide with the center of the accelerometer configuration. Thus, it was required only to adjust two linear accelerometers to exactly antiparallel positions within a plane perpendicular to the axis of rotation.



$$LA\ 1 = \frac{2\pi\ D/2}{360^0}\ AA + G \cdot \cos\alpha$$

$$LA\ 2 = \frac{2\pi\ D/2}{360^0}\ AA - G \cdot \cos\alpha$$

$$\Rightarrow AA = \frac{360^0}{2\pi\ D}\ (LA\ 1 + LA\ 2)$$

FIGURE 3: ACCELEROMETER CONFIGURATION

The overall error was estimated to be less than 3%. It was composed of the error of the sum signal (LA1+LA2) and the error in measurement of the distance (D) between the two accelerometers.

D was 29 cm and could be measured with an accuracy of 1%. The error in the sum signal was generated from several sources:

1. The tilt with respect to the real axis of rotation was estimated to be smaller than 10 degrees, thus contributing an error of less than 2%.

2. The error in the parallel adjustment of the two accelerometers could be regarded to be constant during one period of measurement; it was accounted for digitally in subsequent data processing.

3. Nonlinearity and zero offset of the accelerometers as claimed by the manufacturer were negligible.

III. PROCEDURE OF DATA SAMPLING

The output of the linear accelerometer configuration was applied to an analog-to-digital board of a microcomputer. A frequency generator triggered the microcomputer to sample the acceleration data at 120 Hz. Each sampling period covered 2 seconds.

Start and end of a sampling period was indicated by a bell. In sync with the start and end bell, one out of eight light emitting diodes (LED) was switched on and off by the microcomputer. The eight LEDs were arranged in an array to stimulate refixations at approximately ±10, ±20, ±30, and ±40 degrees. Each session consisted of 24 sampling periods where the LEDs were switched in a pseudo-random sequence.

Data recording was performed for six subjects consisting of two pilots and four task scientists, including the author, from the Operations Training Division. The subjects had been asked to refixate as fast as possible but to keep the head still before the start bell rang and, again, as soon as the new position was acquired until the end bell rang, thus performing a step response.

Yaw movements were recorded for all six subjects. Pitch and roll movements were recorded for three of the subjects. In order to get some indication of the influence of the helmet, its weight was increased from 4.75 pounds to 12.75 pounds, thereby increasing its moment of inertia from 135 pounds x inch^2 to 525 pounds x inch^2. The corresponding movements were recorded for three subjects.

IV. DATA ANALYSIS

In Tables 2 and 3, the maximum values for acceleration and velocity are presented. The remarkable differences between the subjects can be explained by different eye/head correlations. In order for the subject to fixate on a new target, a combined head and eye movement was involved. Some subjects tended to large eye excursions, thus achieving the same task with a smaller and slower head movement.

Table 2. Maximum Recorded Acceleration (deg/sec^2)

Subject	YAW	YAW+WEIGHT	PITCH	ROLL
CH	653			
CS	2,219	1,390	968	
PC	1,338			
TL	968	460	810	729
TS	1,432			1,482
UL	1,539	1,517	1,447	2,038

Table 3. Maximum Recorded Velocity (MAX) (deg/sec)

Subject	YAW	YAW+WEIGHT	PITCH	ROLL
CH	91			
CS	187	195	90	
PC	144			
TL	88	76	99	124
TS	136			179
UL	154	163	124	240

The required task of fixating on a target without knowing its location in advance did not produce the reported overall maximum values of 6000 deg/sec^2 for acceleration and 370 deg/sec for velocity (Lobb, Barber & Murray, 1979). After changing the task to performing a rapid movement in a predetermined direction (without requiring refixation at a specific point), a maximum acceleration of 5,718 deg/sec^2 and a maximum velocity of up to 437 deg/sec could be recorded.

Figure 4 shows representative acceleration, velocity, and position plots for a single movement. The curves were similar for all subjects, as well as for the three axes of rotation. The steps in the plots correspond to the 120 Hz sampling rate.

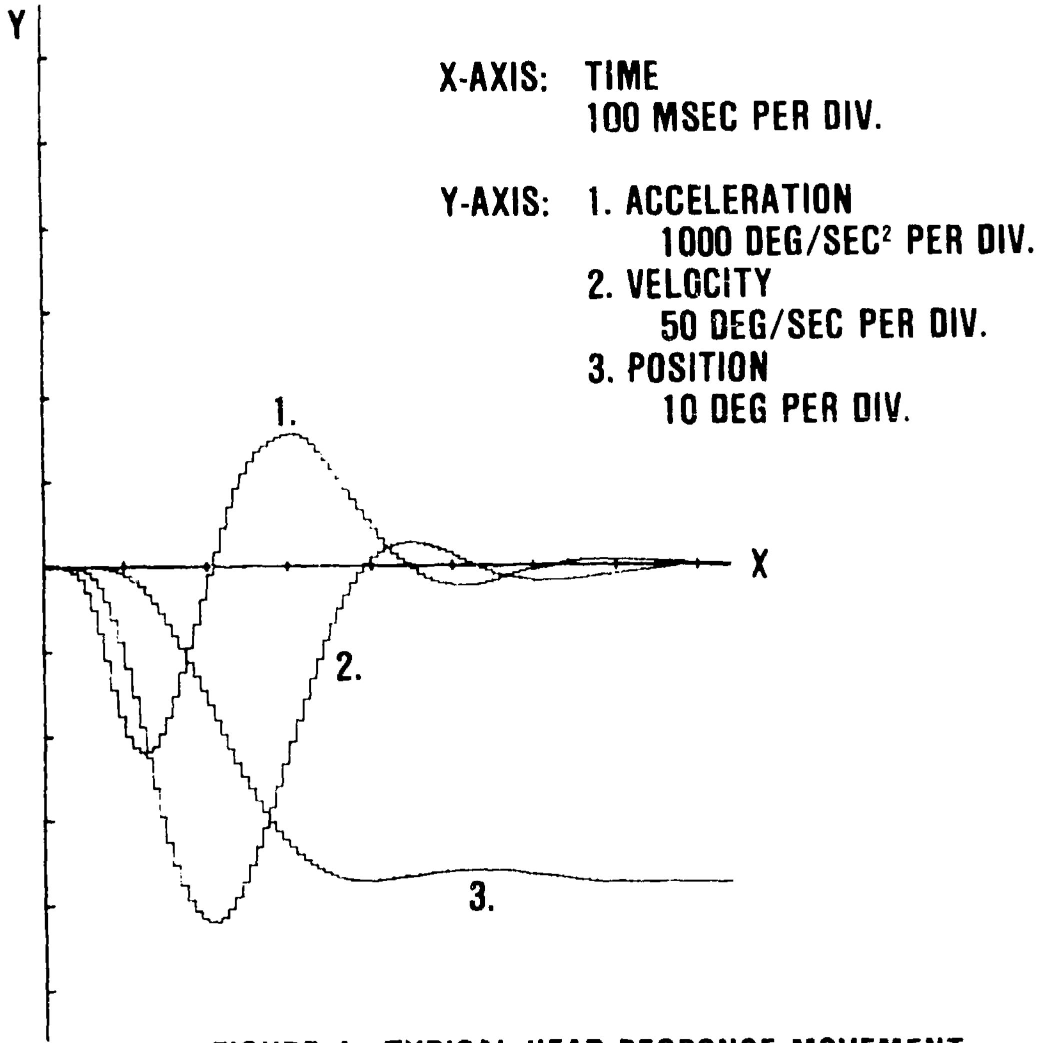


FIGURE 4: TYPICAL HEAD RESPONSE MOVEMENT

Any arbitrary force can be treated as a succession of impulses. The inspection of head acceleration plots revealed resolvable impulses, not sharper than a limited magnitude. This limit can be considered to be a measure of the latency of the head movement. For each session, between 60 and 150 impulses could be resolved. After normalization (e.g., division by maximum value), they were superimposed on one another, thus creating a histogram as in Figure 5. (The blank area in the middle indicates the existence of a unit impulse.) To get a clearer picture of the unit impulse, a weighted average of all impulses was generated. The result was a rather smooth pulse shape like that in Figure 6. It should be mentioned that no curve-fitting process was applied to gain this pulse presentation. The response to a unit impulse is the sharpest step increase in velocity the head is able to perform.

FIGURE 5: PULSE HISTOGRAM

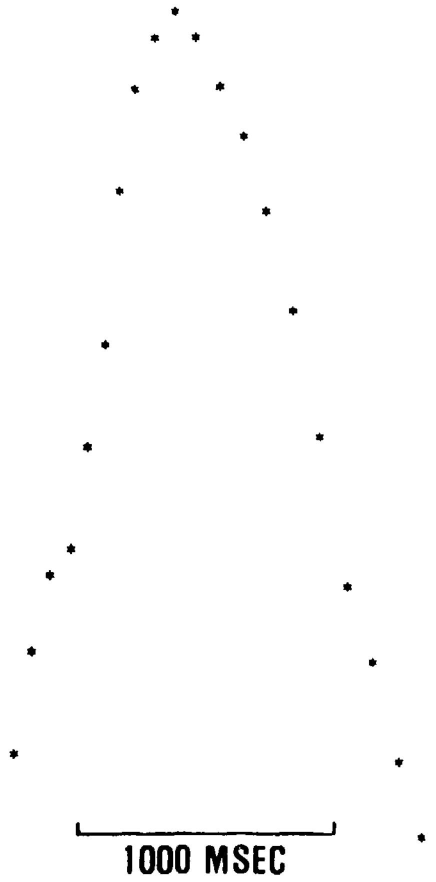


FIGURE 6: UNIT IMPULSE

Table 4 lists the pulse widths at half maximum of the unit impulses of each session. The additional weight on the helmet showed the expected effect of broadening the pulse shape, but the low magnitude of this effect was somewhat surprising. The data in Table 4 show an increase in the pulse width of about 30 %, whereas the helmet weight had been increased by 168 %, thereby increasing the moment of inertia by 290 %.

Table 4. Unit Impulse Width at Half Maximum (msec)

Subject	YAW	YAW+WEIGHT	PITCH	ROLL
CH	108			
CS	79	100	58	
PC	75			
TL	67	108	58	67
TS	83			83
UL	96	133	83	83

In spite of the additional stress to balance more than twice the helmet weight, the neck muscles seemed to compensate well for the additional moment of inertia. It can therefore be assumed that the normal helmet data correspond very closely to bare head behavior.

V. RESULTS OF NONLINEAR PREDICTION

Suppose it takes two frames (one frametime = 33-1/3 msec) to generate a visual scene and another frame to display it (update rate = 30 Hz). Without any prediction, the simulated scene would lag between two and three frametimes, depending on the picture element under consideration. Figure 7 shows the corresponding simulated position with respect to the real position from Figure 4. The steps in the plot are due to the 30 Hz update rate.

The simplest way to perform a prediction is to extrapolate the position with constant velocity. An appropriate choice for the extrapolation time would be two and one-half frametimes (= 83-1/3 msec). This linear prediction may be sufficient as long as the movement does not change too rapidly, or to be more precise, as long as the actual change of velocity over the time of prediction is small enough. Figure 7 shows the respective linearly predicted position. Velocity was assumed to be calculated from position information sampled at 60 Hz.

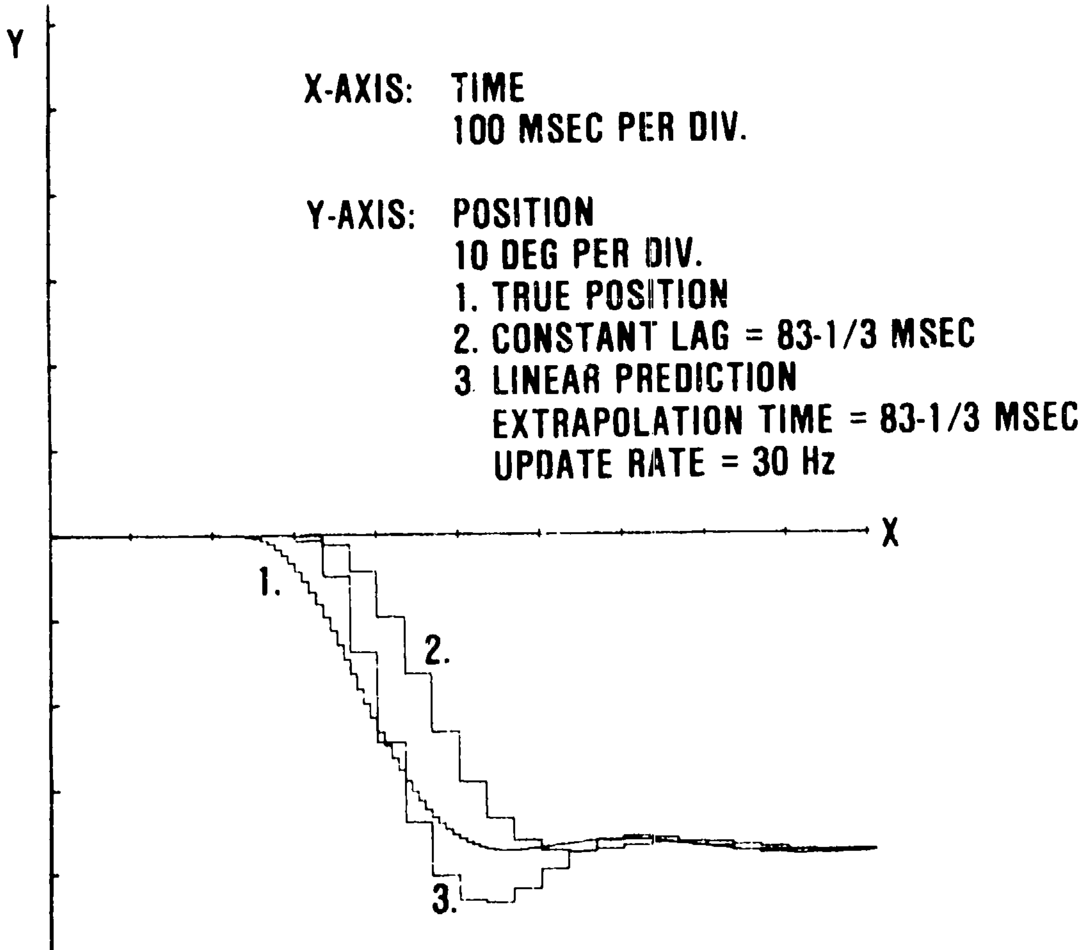


FIGURE 7: SIMULATED POSITION;
WITHOUT AND WITH LINEAR PREDICTION

Since the real velocity changed significantly during the prediction time, the linear predicted position still deviates from the actual position, showing lags and overshoots.

To improve the prediction, the change in velocity (i.e., acceleration) has to be taken into account. Two observations from the sampled head movement data supported the idea that acceleration information could improve the prediction:

1. As Figure 4 illustrates, acceleration reaches significant values some time before the resultant position change becomes apparent.

2. Once a certain amount of acceleration has been attained, it cannot be switched off instantaneously but must at least decrease along the tail edge of the unit impulse.

The minimum amount of change in velocity (DELTA V in Figure 8) during the extrapolation time is given by the corresponding integral over the momentary impulse. Unfortunately, the calculation of this integral requires knowledge about the exact position of this momentary impulse. The frequent overlapping of subsequent pulses and differences in pulse shapes make it difficult to derive this information instantaneously.

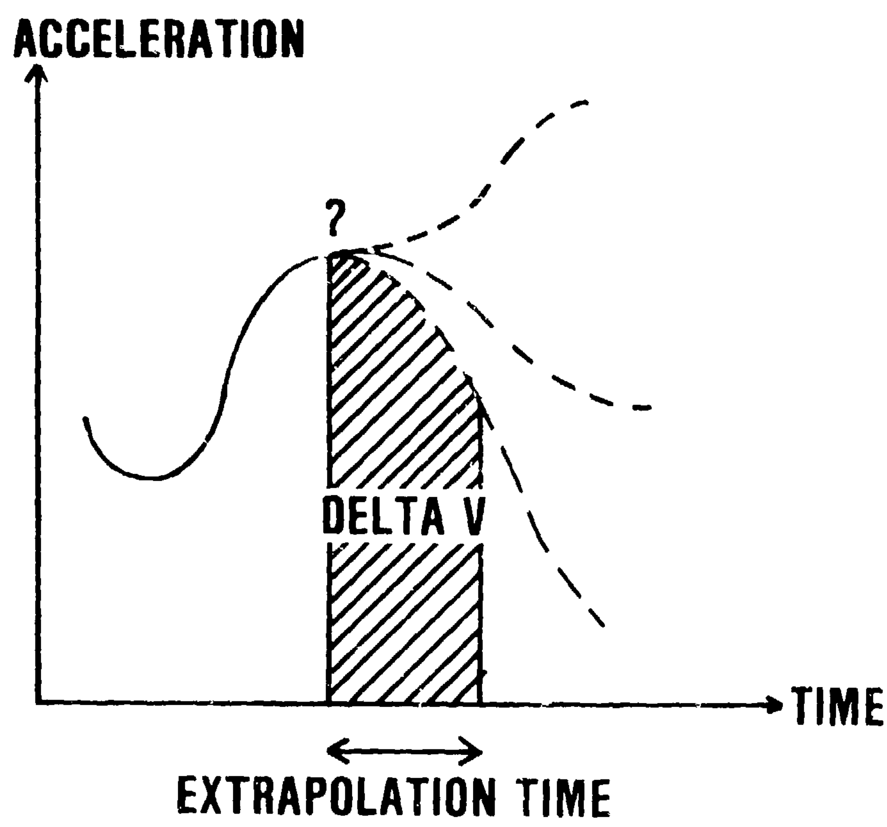


FIGURE 8: MINIMUM CHANGE OF VELOCITY

So, the nonlinear term to be added to the present velocity was approximated by the product of the present acceleration and a constant multiplier. Integration over the impulse in Figure 6 indicated that this multiplier (MULT) had to be somewhere between 0 and 100 msec. Several trials showed that an optimum value existed for best prediction results.

To account for overshooting, which occurred under certain conditions, the extrapolated velocity was limited to a maximum value (MAX).

Figure 9 shows the result of a nonlinear prediction of the movement of Figure 4 with MULT = 50 msec and MAX = 210 deg/sec. To recognize the improvement, these plots have to be compared with those in Figure 7.

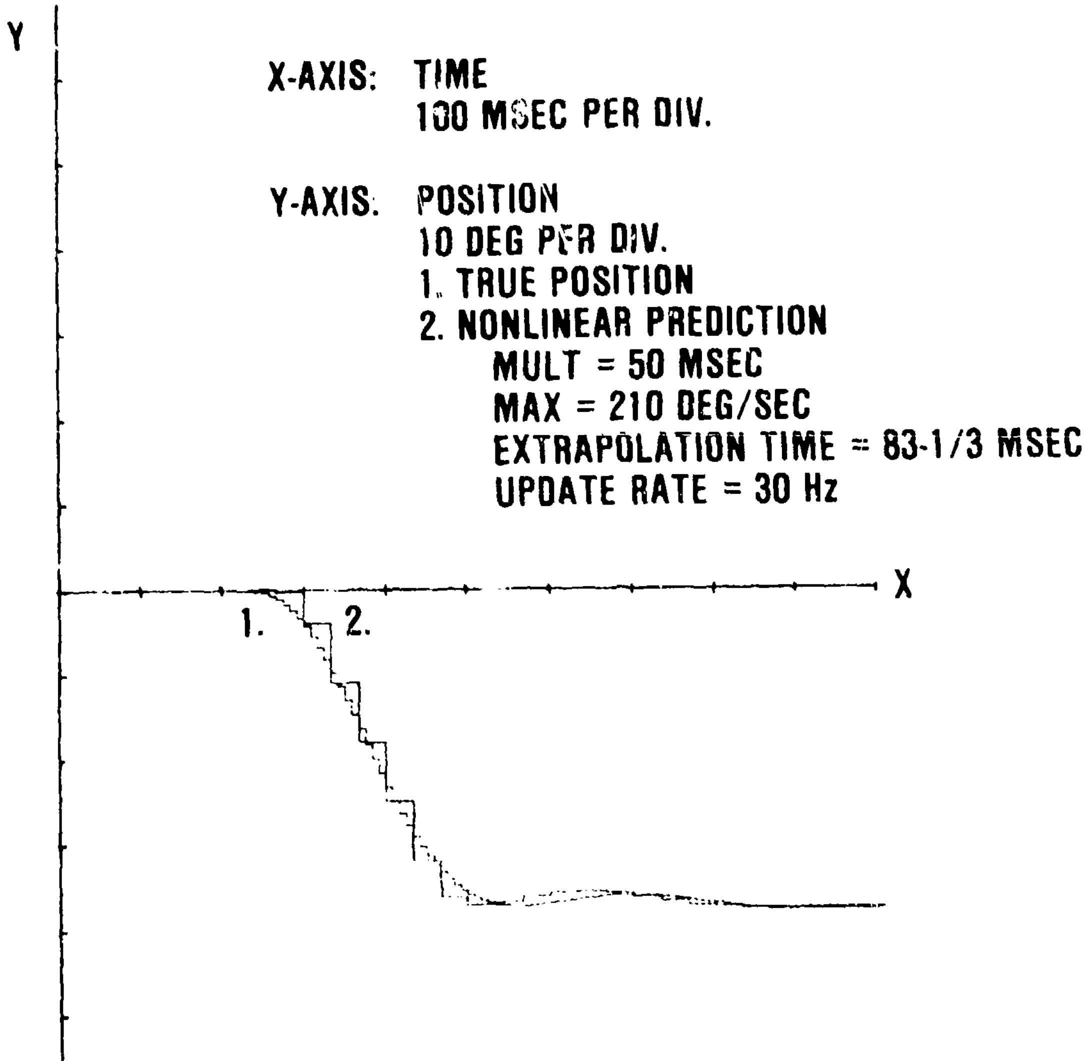


FIGURE 9: SIMULATED POSITION: WITH NONLINEAR PREDICTION

The prediction algorithm written in BASIC consisted of the following statements:

```
REM  DIFFERENTIATE POSITION
     VANG = (ANG-ANGO)/DEL

REM  EXTRAPOLATE VELOCITY AND ANGLE
     VEXT = VANG + ACC*MULT
     IF ABS(VEXT) > MAX THEN VEXT=SGN(VEXT)*MAX
     AEXT = ANG + VEXT*EXT

REM  MEMORIZE OLD POSITION
     ANGO = ANG
```

Table 5 shows the average values for MULT for each subject and axis of rotation. There is no exact correlation between MULT and the pulse widths of Table 4 since MULT is a function of the whole pulse shape and not of the pulse width alone.

Table 5. Multiplier (MULT) (msec)

Subject	YAW	YAW+WEIGHT	PITCH	ROLL
CH	35			
CS	35	36	34	
PC	33			
TL	36	33	26	31
TS	38			34
UL	41	41	34	30

Changes in the values given in Table 5 between -10 msec and +20 msec did not affect the result of the prediction significantly. Increasing MAX was not critical either, but it must not be less than the maximum velocity of the present movement. In an application of this prediction scheme, MAX should be dynamically adjustable to account for individual differences and changing behavior with changing tasks.

The prediction algorithm was implemented in the Fiber Optic Helmet-Mounted Display (Figure 10) using rotational accelerometers attached to the helmet. The actual application showed that the position values, provided by the mechanical position sensing system, were too noisy to be differentiated. For that reason, the algorithm was changed, deriving present velocity by integration, thereby taking further advantage of the acceleration data. The integrated value was reset to zero each time the differentiated position values indicated zero velocity, in order to minimize the integration error.

The modified prediction proved to be successful. Smooth scene movement was observed with significantly decreased lag.

```
REM  DIFFERENTIATE POSITION
     VANG = (ANG-ANGO)/DEL

REM  RESET INTEGRATION CONSTANT
     IF VANG*VANGO < 0  THEN VACC=0

REM  INTEGRATE ACCELERATION
     VACC = VACC + DEL*(ACC+ACCO)/2

REM  EXTRAPOLATE VELOCITY AND POSITION
     VEXT = VACC + ACC*MULT
     IF ABS(VEXT) > MAX  THEN VEXT=SGN(VEXT)*MAX
     AEXT = ANG + VEXT*EXT

REM  MEMORIZE OLD VALUES
     ANGO = ANG
     ACCO = ACC
     VANGO = VANG
```

input parameters	:	ANG	present position
		ACC	present acceleration
output parameters	:	AEXT	extrapolated position
time constants	:	DEL	time between present and previous position
		EXT	extrapolation time
velocities	:	VANG	differentiated position
		VACC	integrated acceleration
		VEXT	extrapolated

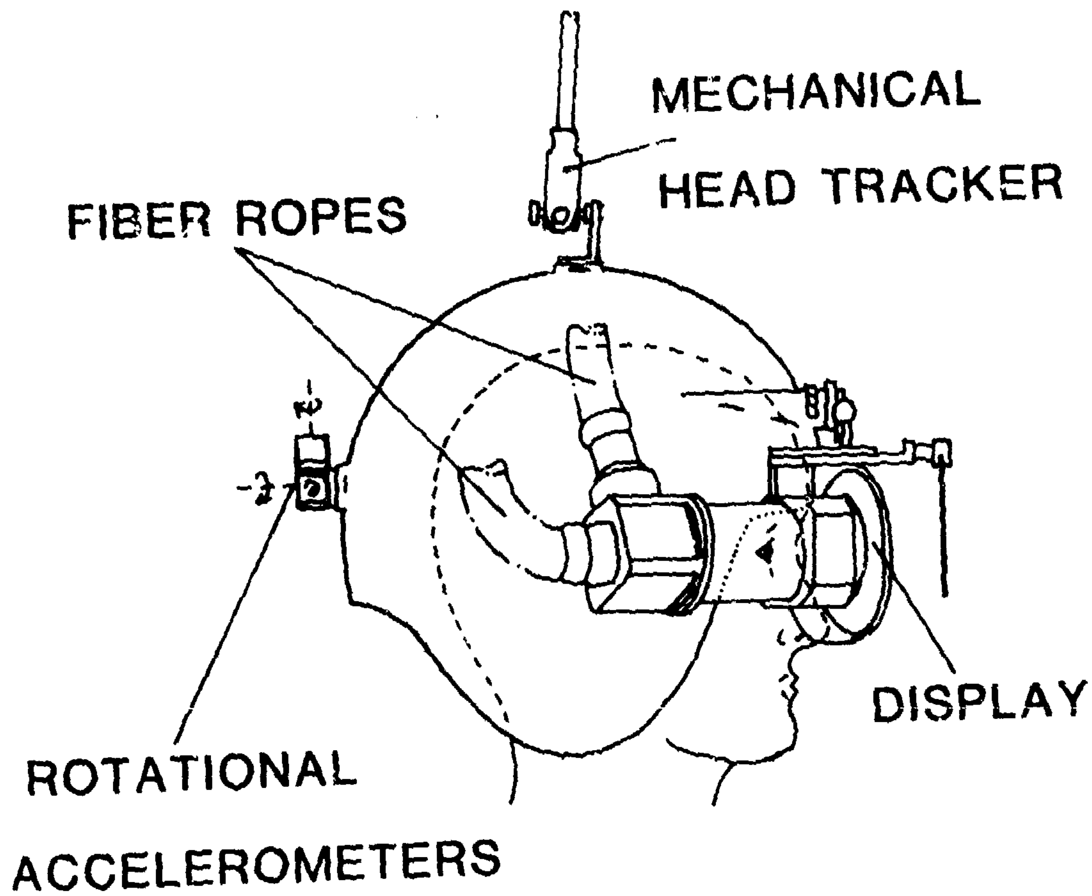


FIGURE 10: FIBER OPTIC HELMET-MOUNTED DISPLAY

VI. SUMMARY

In head-slaved or eye-slaved visual systems, lag times in the visual feedback loop are more apparent than they are in conventional fixed display systems. The available technology of digital image generators does not permit lag times to be reduced to the required amount. Therefore, appropriate prediction algorithms have to be developed. Accelerometers were used to measure the step response of the head in three axes of rotation. It could be shown that linear prediction does not provide the necessary accuracy in the simulated position. A further analysis of the recorded data revealed that it is possible to take advantage of the head's latency to improve the prediction. A simple nonlinear prediction algorithm based on acceleration data was successfully implemented in the Fiber Optic Helmet-Mounted Display.

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