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Compensating Lags in Head-Coupled Displays Using Head Position Prediction and Image Deflection

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Images on head-coupled systems are delayed by latencies in measuring head position and generating computer graphics. The objectives of this study were 1) to investigate the effects of time delays on head tracking performance; 2) to evaluate the use of an image deflection technique to reduce deleterious effects of delayed images; and 3) to investigate the application of a head position prediction algorithm to enhance the benefits of image deflection. There were significant decreases in head tracking performance when lags of 40 ms or more were added to a system with an inherent 40 ms lag. Lag compensation by image deflection significantly improved tracking performance with lags up to 380 ms. However, by deflecting the delayed image back to its prelag angular position, part of the picture was displaced beyond the edge of the screen. The amount of deflection required was reduced by a simple means of predicting the position of the head before applying deflection. Improved means of predicting head position would further reduce the required image deflection.

Introduction

Head-Coupled Systems

Head-coupled systems were developed to improve the visual interface between human operators and aircraft flight control, navigation, and weapon systems.[1] The helmet-mounted display consists of an image source that can be mounted on a flying helmet. The image is optically superimposed on the operator's view of the outside world, regardless of the head orientation. The helmet-pointing system is a device that measures angular orientation of the head relative to a fixed reference (see Fig. 1).

There are various potential uses of head-coupled systems. When a helmet-mounted display and a helmet-pointing system are used together, the operator can designate a target by moving the head to place the target behind an aiming reticle presented on the display. Target cueing and other information may also be presented on the helmet-mounted display.

Head-coupled systems can also be used to present views from a camera whose orientation is slaved to the helmet-pointing system. As the head is turned, the direction of the camera follows the head-pointing angle.

Computer-generated images can be presented on helmet-mounted displays to simulate a view of the real world for either research, training, or in-flight assistance. This approach can be extended to present a "virtual cockpit" to the pilot with virtual displays and even multifunction virtual switches.[2]

The Problem

When a helmet-pointing system is used to control the location of images on a helmet-mounted display, any delay between the moment at which head position is sampled, and the moment at which the corresponding image is presented, will result in the image "floating" on the screen. This is subjectively disturbing and may result in degraded performance. For example, a space stationary object may appear to "swim" during the start and finish of head motion.[3] Woodruff et al.[4] reported that during an investigation of helmet-mounted displays for flight simulation (a head-coupled simulator), more than one-third of the pilots who attempted the task were unable to obtain satisfactory results, and this was considered to indicate not inferior flying, but failure to adapt to the inherent delay in the simulation system.[4]

In a head-coupled simulator, the computation delays involved in providing an updated computer-generated scene are dependent on the complexity of the image. When a forward-looking infrared (FLIR) camera is slaved to a helmet-pointing system, the delays depend on the inertia of the system, and the camera may lag behind the line-of-sight by up to 1 s.

Solutions

There are three possible solutions to the problems caused by delays 1) reduction of the time delay at source; 2) deflection of the image to the correct position; or 3) head position prediction to compensate the time delays. In this article the last two solutions are investigated.

Reduction at Source

With the advance in computer technologies, there is potential for reducing the processing time involved in graphics generation. Improvements in management techniques during graphics presentations can also increase the update rate.[5,6] However, these solutions require money and could be bulky. These solutions cannot be applied to a system with moving mechanical parts, such as a head-slaved camera.

Image Deflection

An alternative solution is to deflect the delayed image to the currently correct angular position, so that the image main-

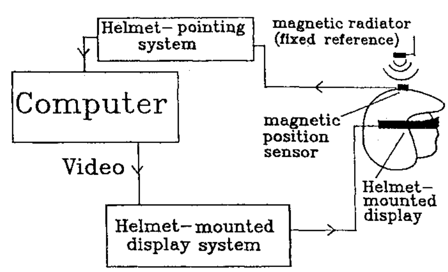

Fig. 1 Block diagram of the experimental head-coupled system.

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tains correct correspondence with the outside world. Image deflection on helmet-mounted displays was originally developed in the Human Factors Research Unit at the Institute of Sound and Vibration Research for the stabilization of images on helmet-mounted displays exposed to vibration.[7] Applied to computer-generated images (see Fig. 2), the computational delay is measured and translated into horizontal and vertical offsets, which are then used to deflect the video image on the helmet-mounted display. Applied to images captured from a head-slaved camera (see Fig. 3), the instantaneous angular separation between the camera and the line-of-sight can be measured and used to deflect the video image.

The principle of the image deflection technique is explained in Appendix A. At any time the position error is proportional to both the time delay and the head velocity. If these are large, the image may need to be deflected beyond the field-of-view (FOV); performance would then deteriorate rapidly. This analysis is consistent with results of unpublished studies previously conducted at the Institute of Sound and Vibration Research. Image deflection is, therefore, only applicable to the compensation of small position errors.

Head Position Prediction

This option utilizes a signal processing algorithm to predict the future head position based on the past head movement time history. For random movements of the head, prediction is, by definition, impossible. However, due to the limited tracking bandwidth of the human head (up to 1 Hz[8]), prediction of head position becomes possible. The use of head position prediction to compensate for time delays has been previously investigated. List reported a simulation study of the use of a simple nonlinear prediction algorithm to compensate for time delays occurring during high-velocity step movements of the head.[9] The algorithm used acceleration data and was reported to have been successfully implemented in a fiber optic helmet-mounted display. Albrecht utilized an adaptive least-mean-square predictor to predict pilot head look direction.[10] Simulations showed that the predictor was capable of good predictions for input signals that change their characteristics linearly with time (e.g., a swept sine with decreasing amplitude), but needed improvement to predict head movements whose characteristics change randomly with time.

Head position prediction may bring the calculated head position close to the instantaneous position. However, due to noise and the randomness of the measured head movements, errors remain. Head position prediction may be useful to reduce large position errors due to time delays, but image deflection may be needed to remove remaining errors.

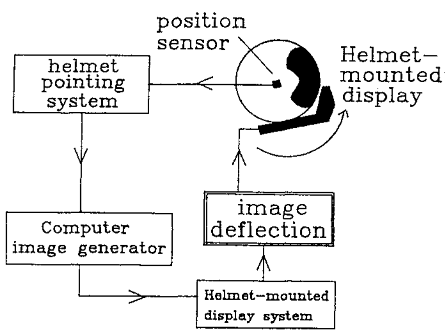

Fig. 2 Diagrammatic illustration of the image deflection technique to compensate lag in a head-coupled system with computer-generated images.

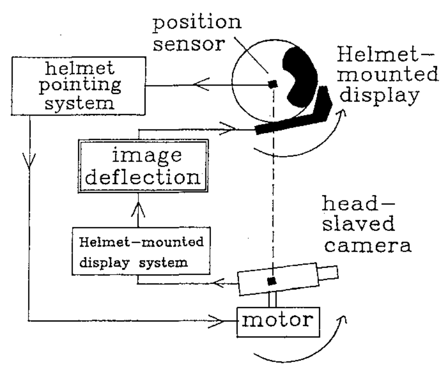

Fig. 3 Diagrammatic illustration of the image deflection technique to compensate lag in a head-coupled system with a head-slaved camera.

Objectives

The experiment reported in this article investigated a lag compensation technique combining both head position prediction and image deflection. A block diagram illustrating the two methods is shown in Fig. 4. Head position prediction was performed first to reduce the difference between the instantaneous head position and the delayed head position. Image deflection was then used to eliminate any remaining difference.

An experiment was conducted to determine the effects of time delays on head tracking performance, and assess the use of a simple head position prediction algorithm to enhance the benefits obtained by image deflection. Measurements of head tracking performance were made with various time delays and combinations of image deflection and head prediction. The hypotheses were 1) head tracking performance would be degraded by time delays between head movement and image movement; 2) image deflection would reduce the performance degradation due to time delays, but introduce a restriction on the FOV; and 3) a simple prediction algorithm would enhance the benefits of image deflection by reducing the restriction on the FOV. Throughout the experiment, computer-generated images were used and additional lags were generated in the software.

Materials and Methods

Apparatus

The head-coupled system used in this study consisted of magnetic coils mounted on top of a helmet to detect helmet movement, and a miniature cathode ray tube mounted to the side of a helmet to present a virtual image 17 by 17 deg through a collimating optical arrangement. The configuration of the experimental apparatus is summarized in Fig. 5. The helmet-pointing system was a Ferranti SPASYN type 101, and the helmet-mounted display was a Hughes monocular display model SD/HMD-001. A host computer was employed to control the target presentation and data acquisition. Image deflection and head position prediction were also performed within this computer (see Appendix B for prediction algorithm). The minimum system time delay was 40 ms.

An open-cross reticle was presented at the center of the display whereas the target was represented by a circle.[8] The position of the circle was derived from the absolute position of the target and the present (or delayed) line-of-sight measured by the helmet-pointing system.

Method and Design

Subjects wearing the experimental head-coupled system were asked to move their heads to place the open-cross reticle on

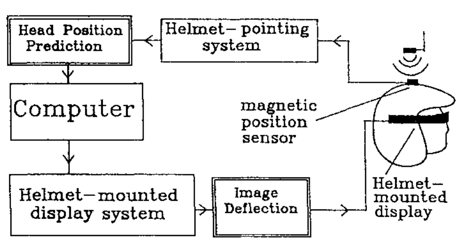

Fig. 4 Diagrammatic illustration of the lag compensation method involving combined head position prediction and image deflection.

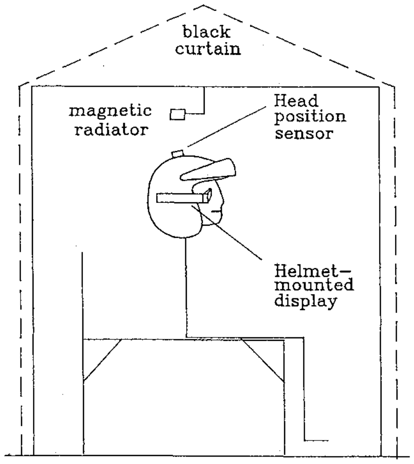

Fig. 5 Arrangement of the subject with helmet-mounted display and helmet-pointing sensor.

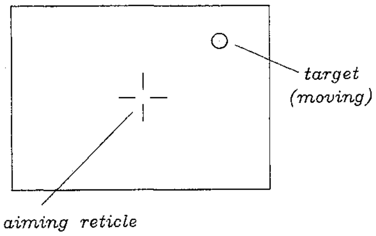

Fig. 6 Computer-generated images presented on the helmet-mounted display.

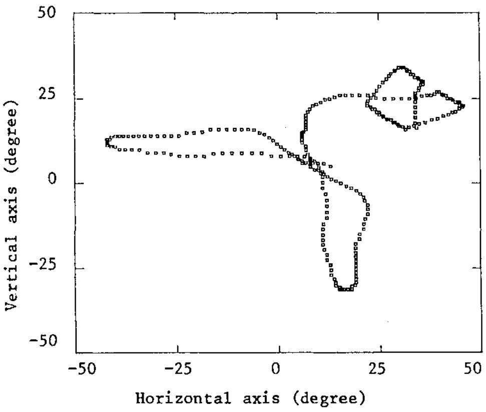

Fig. 7 Typical target motion (each dot separated by 0.2 s).

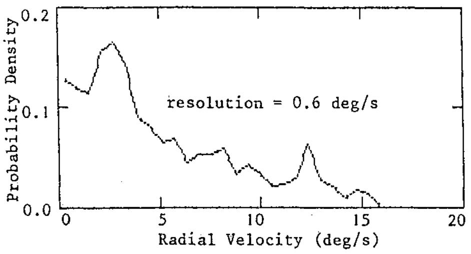

Fig. 8 Probability distribution of target radial velocity.

top of the circular target. All images were viewed at optical infinity on the helmet-mounted display (see Fig. 6). The target motions were Gaussian random functions integrated twice and band-passed between 0.01–0.63 Hz. The same target motions were used in both axes (vertical and horizontal), except one was presented in reverse order. Each tracking task lasted for 60 s. An x–y plot of the target forcing functions, the probability distribution of target radial velocity, and target movement power spectral density are shown in Figs. 7–9.

Table 1 Six-point scale of difficulty

0	= not difficult
1	= a little difficult
2	= fairly difficult
3	= difficult
4	= very difficult
5	= extremely difficult

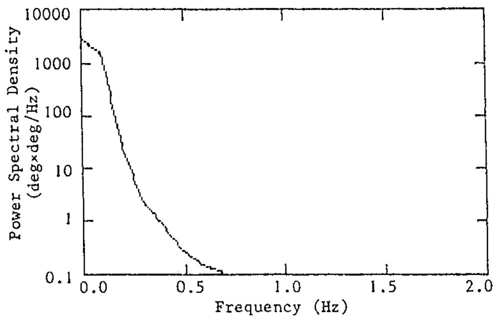

Fig. 9 Power spectral density of the target forcing function angular displacement (same for both axes; 0.097 Hz resolution, 48 DOF).

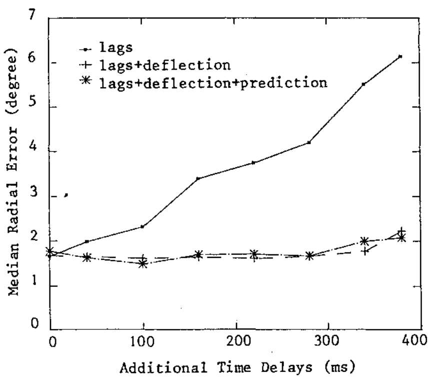

Fig. 10 Mean radial error for different time delays (median of 12 subjects).

Twelve volunteers with normal visual acuity participated in the experiment, their ages ranged from 17 to 29. The subjects repeated the task with eight time delays (0, 40, 100, 160, 220, 280, 340, and 380 ms) and with three lag compensating conditions (no compensation, image deflection, and head position prediction with image deflection). The sequence of presentations was balanced using a random block design. 12 similar target motions were used to minimize learning of target motions. At the end of each tracking task subjects were asked to estimate the degree of task difficulty on a six point scale (Table 1).

Written instructions were given to the subjects prior to the experiment. Four practice tracking tasks, each lasting for 30 s, were then presented to ensure that the subjects were familiarized with the experimental head-coupled system. (Previous studies have found that little learning is required during head tracking.[8]) Throughout the experiment, subjects were screened within a darkened environment to eliminate visual information other than that perceived by the right eye through the helmet-mounted display.

Results

Head tracking performance measured in terms of radial error, percentage time-on-target (calculated with a reticle size of 1.5 deg diam) and subjective difficulty rating are shown in Figs. 10–12.

Friedman two-way analyses of variance were performed to determine effects of time delays within the three lag compensation conditions. Results showed that time delays had a significant effect on tracking performance for the condition where no lag compensation was applied ($p < 0.001$).

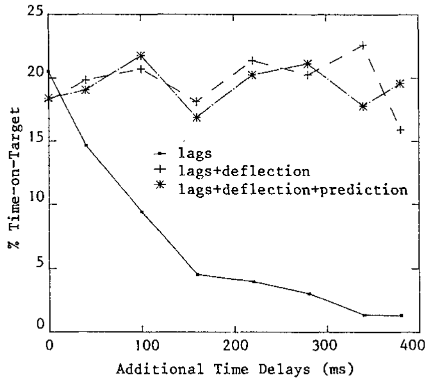

Fig. 11 Percentage time-on-target for different time delays (median of 12 subjects).

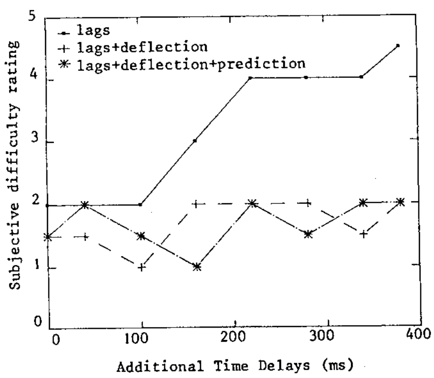

Fig. 12 Subjective difficulty rating for different time delays (median of 12 subjects).

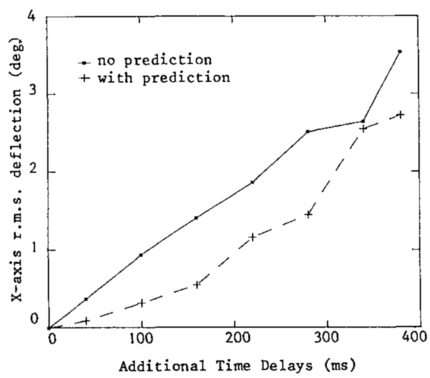

Fig. 13 Values of image deflection (rms) used to compensate for different time delays (horizontal axis, median of 12 subjects).

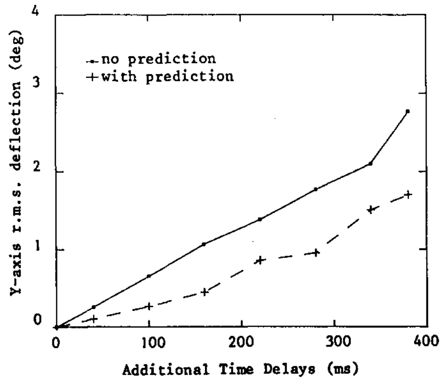

Fig. 14 Values of image deflection (rms) used to compensate for different time delays (vertical axis, median of 12 subjects).

To assess the benefits of head position prediction, the amount of image deflection used in both axes was recorded during the conditions where image deflection was applied with and without head position prediction. Results in both axes are shown in Figs. 13 and 14. Friedman two-way analyses of variance showed that for lags less than 280 ms, the deflection required was reduced significantly by head position prediction ($p < 0.01$).

Discussion

Effects of Lags

For all objective measures of head tracking performance, there was a significant degradation with lags greater than, or equal to, 100 ms ($p < 0.01$, excluding the system lag of 40 ms). With the percentage time-on-target measurements, the threshold delay for significant degradation in tracking performance was 40 ms ($p < 0.05$, excluding the system lag of 40 ms). Since complex computer-generated graphics scenes presented on helmet-mounted displays, can suffer lags of the order of 80–100 ms,[3,11] the finding of such a short threshold lag has important implications on the future development of head-coupled systems.

Effects of Lag Compensation by Image Deflection

Inspection of Figs. 10–12 reveals that the image deflection technique (both with and without head position prediction) significantly reduced radial error, increased percentage time-on-target, and improved the subjective difficulty rating. This is confirmed by the results of the Friedman two-way analysis of variance by ranks; there was no significant degradation in performance for any lag condition when using image deflection. This confirms that the image deflection totally restored the image to the correct position. Tracking performance was the same as without any lag, despite the restricted FOV. The lack of an effect of the restriction on the FOV may be because once the target was captured within sight, it could be kept around the center part of the total FOV. The absence of any rapid search movements also meant that the reduction in the FOV was not large.

The perfect lag compensation by image deflection used here relied on two assumptions 1) a knowledge of the total system time delay; and 2) no distortion in the image from deflection in the vertical and horizontal axes. The former assumption will often be valid for computer generated displays. The latter assumption will not be valid if the graphics presents three-dimensional views. In such cases, the parallax distortion will depend on the amount of deflection used, with smaller deflections giving less distortion.

Effects of Lag Compensation with Head Position Prediction and Image Deflection

The image deflection alone overcame the performance degradation due to time delays, but the simple head position prediction algorithm significantly reduced the amount of deflection required (Figs. 13 and 14). This reduction, in required image deflection, reduces the restriction on the FOV and the image distortion imposed by deflection. Because the target was always captured near the centre of the FOV (as explained above) the benefits of this reduction were invisible to the subject and are not apparent in the tracking performance measures obtained from the experiment.

Conclusions

The mean radial error in two-dimensional head tracking performance was significantly degraded by lags greater than, or equal to, 100 ms. Percentage time-on-target measurements, showed a significant degradation in tracking performance with lags greater than 40 ms. These lags are in addition to a 40 ms system lag. The finding that such short lags degrade head tracking performance, has important implications for the future development of head-coupled systems.

Image deflections significantly improved tracking performance in the presence of time delays up to 380 ms, and performance was restored to that without a time delay.

The amount of image deflection required to compensate for the lags increased with increasing lag and there was a corresponding reduction in the FOV. For lags less than 280 ms, the use of a simple head position prediction algorithm significantly reduced the amount of image deflection required, and would therefore, reduce any image distortion and restriction on the FOV.

Although the use of head position prediction to enhance the benefits of lag compensation by image deflection has been demonstrated, further studies to optimize the prediction algorithm are required. The above findings are based on data collected with two-dimensional tracking tasks, however, the principles also apply to one-dimensional tracking tasks.

Appendix A

Image Deflection: Benefits

Although computer-generated images were used in the experiment, it is easier to illustrate the principle of the image deflection technique with a head-slaved camera. Consider an application in which a head-coupled system is used to present images captured from a head-slaved camera which follows the line-of-sight of the observer with a time delay. Figure A1 shows the effect on the displayed image when the head of the observer moves to acquire a stationary target at a constant angular velocity, $\dot{\theta}_h$ assuming the head-slaved camera follows with a constant time delay, τ. After a time t, the head has traveled an angle of

$$\theta_h = \dot{\theta}_h t \tag{A1}$$

but the camera and images captured have only moved to θ_c, where

$$\begin{aligned} \theta_c &= \dot{\theta}_h(t - \tau) \\ &= \theta_h - \dot{\theta}_h \tau \end{aligned} \tag{A2}$$

Therefore, by deflecting the screen with an offset of $\dot{\theta}_h \tau$, the image is restored to its correct position.

Image Deflection: Restriction in Field-of-View

Suppose the target is separated from the initial head position by an angle, θ_{ta}, and that the FOV of the camera subtends an angle of φ. The image of the target will only be captured if it falls within the FOV of the camera i.e.

$$\theta_{ta} - \theta_c \leq \varphi/2 \tag{A3}$$

substituting θ_c from Eq. (A2)

$$\theta_{ta} - \theta_h + \dot{\theta}_h \tau \leq \varphi/2 \tag{A4}$$

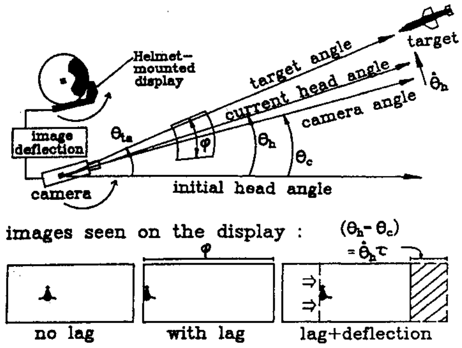

Fig. A1 Diagrammatic illustration of effects of time delays between head movement and image movement on images captured by a head-slaved camera. The effect of image deflection is also shown.

If we rearrange Eq. (A4) we get

$$\theta_{ta} - \theta_h \leq (\varphi - 2\dot{\theta}_h \tau)/2 \tag{A5}$$

where $(\varphi - 2\dot{\theta}_h \tau)$ is defined as the effective FOV, that is two times the maximum angular separation allowable between the target and the observer's line-of-sight, so that the target will fall within display.

From Eq. (A5), one can see that this effective FOV is reduced by any time delay present (τ).

Appendix B

The simple extrapolation algorithm used to predict the head position was based on a constant velocity assumption

$$\hat{H}(t + n) = H(t) + (\text{head velocity}) \times (n)$$

where

$$\text{head velocity (instantaneous)} = [H(t) - H(t - 4t_s)]/4t_s$$

Key

$H(t)$ = measured head position at time t ms
n = prediction time (ms)
$\hat{H}(t + n)$ = predicted head position at $(t + n)$ ms
t_s = 20 ms (sampling period)

Acknowledgments

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