An Adaptive Control Model For Human Head and Eye Movements While Walking

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Abstract—**When a person walks the head undergoes horizontal and vertical rotations, and also horizontal and vertical translations. To visually fixate on an object while walking, compensatory horizontal and vertical eye movements must be made. Our model for this gaze (head plus eye) control system includes three types of eye movements: smooth pursuit, saccadic, and vestibulo-ocular. The smooth pursuit system uses a target-selective adaptive controller (TSAC) that compensates for the large inherent time delay and produces zero-latency tracking of predictable targets. Target movements were selected to minimize the role of the saccadic control system. Typical tracking is shown while seated with the head restrained, standing with unrestrained head, performing voluntary head rotations, and walking. Each additional degree of freedom produced additional head movements that were compensated by additional eye movements. It is shown that while a human walks the effects of head rotations (yaw) cancel the effects of head translations, thus minimizing the resulting horizontal eye rotations necessary to maintain fixation.**

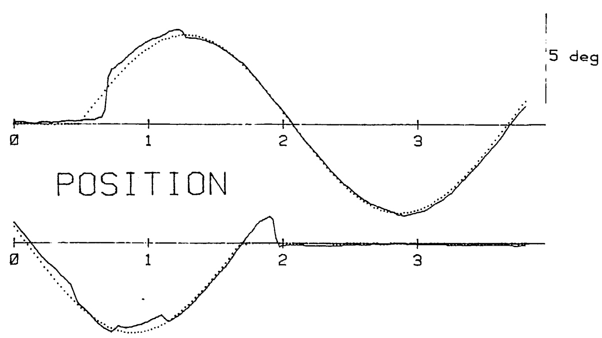

Fig. 1. Effects of time delay for human (solid line) tracking start (top) and stop (bottom) of target motion (dotted line). Time axis is labeled in seconds.

I. Introduction

When you look around a room, read, walk, or drive a car you move your head and eyes in a coordinated manner. This head and eye coordination allows you to direct your gaze to whatever object is of interest. This gaze control system includes a head movement control system and four eye-movement control systems, namely, vestibulo-ocular, vergence, saccadic, and smooth pursuit. This paper will investigate these systems and show some of their capabilities, control strategies, and interactions.

Experiments with transient target waveforms have revealed a time delay in the human smooth-pursuit eye movement system [1]. When a target starts to move there is a 150-ms delay before the eye starts to move, as shown at the top of Fig. 1. When the target stops there is a 150-ms delay before the eye stops (bottom Fig. 1). However when tracking a target that is moving sinusoidally, the subject quickly locks on to the target and tracks with neither latency nor phase lag. It is as if the subject creates an internal model of the target movement and then tracks the output of the model, rather than the actual visual target. This internal model has variously been called a predictor [2], [3], a long-term learning process [4], a percept tracker [5]–[7], a neural motor pattern generator [8], and a target-selective adaptive controller [9]. The target-selective adaptive control (TSAC) model for the human eye movement system, which is the major component of our gaze control model, has three branches: saccadic, smooth pursuit, and an adaptive controller. It can emulate the human and produce zero-latency tracking of smooth predictable target waveforms [10], [11].

The vestibulo-ocular control system is the other major component of our gaze-control model. It becomes involved when the subject is given freedom of head movement. Extensive study has been performed on the vestibular system and on head–eye coordination. Two recent surveys [12], [13] present a thorough review of the pertinent literature. Vestibulo-ocular movements of up to 6 Hz have been recorded with voluntary head movements. These high frequencies were obtained by clenching the jaw and neck muscles tightly [14]. Most locomotory head movements, however, have frequencies in the range 0.5–2 Hz [12]. While walking, the head translates 4–8 cm from side to side [15]. Eye movements must compensate for these movements if a target is to remain fixated.

Head and eye coordination of humans and monkeys who were seated and restrained has been investigated, and various models have been proposed [16]–[24]. The results of these studies are different than ours, because head and

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eye coordination should be different for walking and seated subjects, just as treadmill walking is different from normal walking [25]. Furthermore, these studies used moving targets to study head and eye tracking while our study used stationary visual targets, thus allowing visual tracking to be studied without the effects of the time delay of the eye movement system.

There have been a few studies of head and eye coordination in freely standing humans. One study recorded the eye movements of a subject standing and trying to remain motionless: the best records had about 1 deg of head rotation [14]. The sequel to this study showed that seated subjects made compensatory eye movements in response to voluntary or involuntary head movements with an accuracy of only 30–90 percent [26]. In these studies head translations were forbidden because they would have produced artifacts. Our studies allowed more freedom of movement than these previous studies. On the other hand, our studies were limited in the sense that we did not attempt to model the dynamics of the limbs and body as others have done [27].

A quantitative measure of tracking accuracy was needed. Because the purpose of the gaze-control system is to keep the fovea on the target, the error between the gaze direction and the target position is an appropriate measure of the quality of tracking. Our primary metric is the mean-square error (mse) between gaze direction and target position. Monkeys tracking moving visual targets had mean-square errors of 1.4 deg^2 and 1.56 deg^2, respectively, for restrained and free head [28]. The fovea has a radius of about 0.5 deg. So if the fovea were always on the target, the maximum mean-square error would be 0.25 deg^2. Therefore we expected human mean-square errors to range between 0.25 and 1.5 deg^2.

The unique contributions of this research result from the freedom of movement permitted, the experimental data presented, and the model developed. The subject could either stand freely or walk. The lateral displacement of the subject from the direction of gaze was included in the total gaze computation; other factors in the gaze computation included yaw, pitch, and roll-head angles, and horizontal and vertical eye angles. The model represents the first system that can overcome a time delay and track a target with no latency.

II. Methods

Horizontal eye movements were measured using a standard photoelectric system [29], [30] comprised of light emitting diodes, (LED's) (Xciton XC88PA) and phototransistors (Fairchild FPT 120) mounted on spectacle frames worn by the subject. A calibration check was made at the beginning and end of each experimental run. The linear range for measuring horizontal eye movements extended ± 10 deg from primary position. Linearity was obtained by adjusting the equipment while the subject tracked a sinusoidally moving target. Noise and drift of the instrumentation were less than 1 mV and were, therefore, smaller than signals produced by eye movements of 1 min of arc, which were about 30 mV. Saccades as small as 3 min of arc have been recorded on this equipment. Vertical eye movements were measured with standard electro-oculographic (EOG) techniques. After the EOG electrodes were applied, the subjects were kept in a uniformly illuminated room for 20 min before the experiments began.

We used a television (TV) camera system to measure the position of the head in space. The subject wore three light emitting diodes on the head. The positions of these diodes were sensed with the TV camera. The output of the TV camera was processed with a homemade digitizer that produced the X and Y coordinates of the center of the LED spots. These coordinates, along with the X and Y positions of the eyes, were used to compute the direction of gaze.

The movements of the eyes were sampled at 1000 Hz and stored on a disk in the PDP 11/34 computer. Head position data arrived at a 60 Hz rate. The head and eye movement data files were synchronized and then merged into one file. Bandwidths for the records shown in this paper are 80, 9, 30, and 30 Hz, respectively, for the eye position, eye velocity, head position, and gaze direction records. Programs were written in *C*, the language of PWB/UNIX the time-sharing operating system written by Bell Laboratories.

III. Results

A. Human Smooth Pursuit Eye Movement Tracking

Humans can lock on to periodic targets and track them with no time delay as shown in Fig. 2. The first part of Fig. 2 shows zero-latency tracking of a sinusoidal target waveform, and the last part shows zero-latency tracking of a parabolic target waveform. The velocity records seem to indicate that the human smooth-pursuit tracking changed from sinusoidal to parabolic on the same half cycle that the target changed. With a little practice humans can achieve zero-latency tracking of cubic waveforms, as shown in Fig. 3.

The mean-square error between target and eye position in steady state was about 0.1 deg^2 for these figures. These small mean-square errors show that the subjects were tracking well, and also that the instrumentation system was reliable. These mean-square errors represent the sum of instrumentation noise, measurement nonlinearities, and human error.

These figures show that humans can perform zero-latency tracking of predictable waveforms. This conclusion requires superposition of low-noise high-resolution position and velocity traces. Such records are not available in previously published reports. Furthermore this conclusion is convincing because of the comparison of the target and eye velocity records for the parabolic and cubic waveforms. These waveforms are new to the eye movement literature.

In an effort to understand how the human can overcome the effects of a time delay and attain zero-latency tracking,

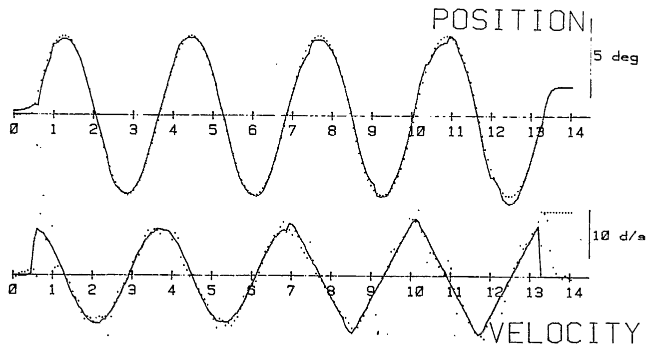

Fig. 2. Human tracking of sinusoidal and parabolic target waveforms. Top record shows target position (dotted) and eye position (solid), and bottom record shows target velocity (solid) and eye velocity (dotted). Rightward movements are upward deflections. Time axis is labeled in seconds. Mean-square error (mse) between target and eye position was 1.2 deg^2; mse became 0.05 deg^2 when starting and stopping transients were excluded.

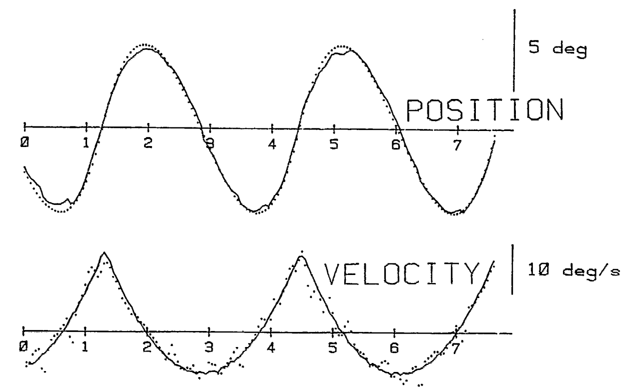

Fig. 3. Zero-latency tracking of a cubic target waveform. Top record shows target position (dotted) and eye position (solid), and bottom record shows target velocity (solid) and eye velocity (dotted). Mean-square error was 0.11 deg^2.

we constructed a model that could do the same. Our target-selective adaptive control model can overcome the inherent time delay and produce zero-latency tracking of predictable targets.

B. The Target-Selective Adaptive Control Model

The target-selective adaptive control model for the eye movement control system, shown in Fig. 4, has three major components: the saccadic branch, the smooth pursuit branch, and the adaptive controller.

The turn-on and turn-off thresholds for the saccadic system and adaptive controller were adjusted after analyzing human data of starting transients, stopping transients, and steady-state tracking, as shown in Figs. 1–3. The adaptive controller turned off if the position error exceeded 0.1 deg while the velocity error exceeded 4 deg/s. It then reevaluated the target motion for 0.5 s before turning on again.

The adaptive controller selected waveforms from a limited menu of candidate waveforms—the menu contained sinusoidal, parabolic, and cubic waveforms. As it learned a new waveform another equation was added to the menu. When tracking targets it chose a waveform from this menu and used it to augment the input signal. It had to identify the waveform and estimate the frequency, amplitude, and phase of the target motion.

Fig. 5 shows the model (solid line) tracking a sinusoidal target (dotted line). In the top record the smooth pursuit branch was turned on, but the saccadic branch and the adaptive controller were turned off. In the middle record the smooth pursuit and saccadic branches were turned on, but the adaptive controller was turned off. In the bottom record all three branches were turned on. The target movement corresponds to ± 5 deg from primary position. The time axis is labeled in seconds. The bottom record resembles the human tracking of Figs. 1–3.

Our target-selective adaptive control model first identifies the target waveform (sinusoidal, parabolic, or cubic). Then it synthesizes a signal using estimated target frequency and amplitude, as well as knowledge about the plant time delay and plant dynamics. It requires measurements of only target position, eye position, and time. It makes only simple calculations. These functions are easily within the capabilities of the human brain.

C. Human Gaze Control

The first 10 s of a typical gaze experiment are shown in Fig. 6. The subject stood in the center of the camera field of view facing a laser spot projected on a wall 2 m away. The subject stared at the target for 1.9 s and then began rotating his head. The subject was instructed to shake his head horizontally as if answering "no" to a question. We requested head movements of about ± 10 deg. In various experiments the subject was asked to vary the rate and amplitude of head rotation. Compensatory eye movements always occurred in the direction opposite to head motion: these eye movements kept the gaze error small. All five of our subjects were able to keep the position mean-square error below 1 deg^2 for voluntary head rotations with frequencies between 0.5 and 3 Hz.

A system's time delay can be observed by studying the transient behavior at the beginning and end of movement. No discernable time delay could be measured on time expanded records of beginnings or endings, such as those shown in Fig. 6. The camera and eye data were synchronized within one frame, or 1/60th s. Therefore, the time delay was between 0 and 17 ms. This value agrees with times derived in other experiments [28]. Fig. 6 was chosen to illustrate the effects of a nonlinearity in the eye movement recording system. The eye recording system entered a soft saturation at extreme left gaze (bottom of Fig. 6). This produced the abnormal shapes in the eye position record and the increased gaze error during these periods.

The data of Fig. 7 were obtained when a subject stood still and simply stared at the target, making as little head or body movement as possible. The mean-square error in gaze direction was greater than for seated subjects with restrained heads (Figs. 1–3), but smaller than for subjects rotating their heads (Fig. 6).

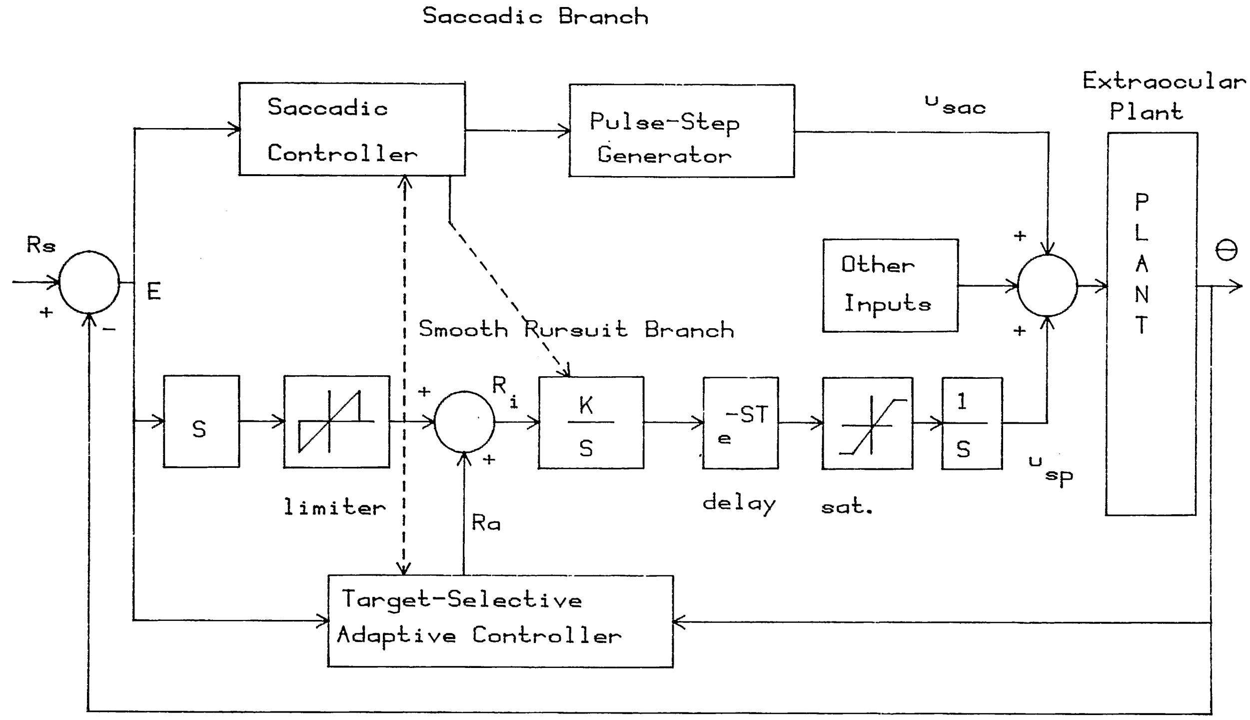

Fig. 4. Target-selective adaptive control (TSAC) model.

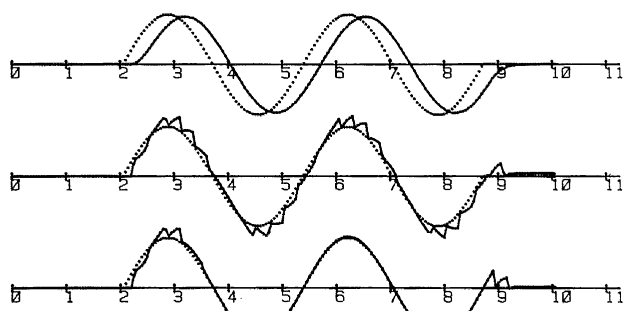

Fig. 5. TSAC model tracking sinusoidal targets with only smooth-pursuit system (top), with addition of saccadic system (middle), and with addition of adaptive controller (bottom).

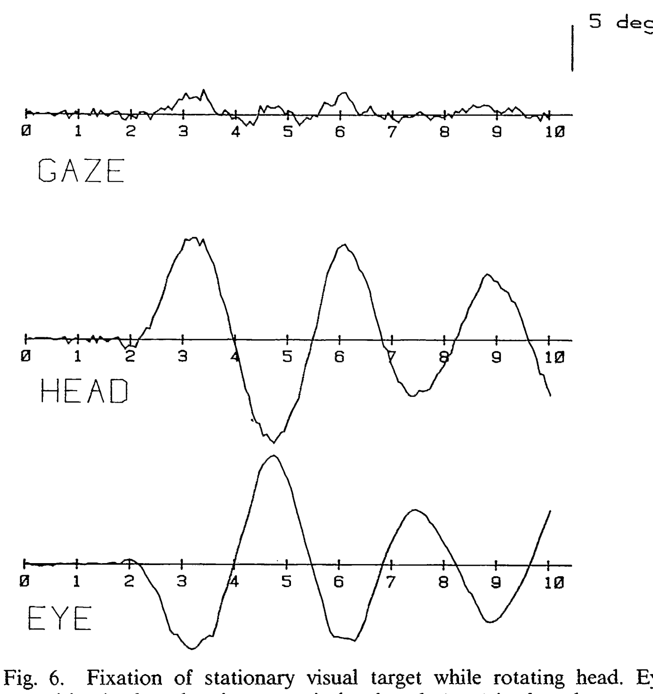

Fig. 6. Fixation of stationary visual target while rotating head. Eye position is plotted on bottom axis, head angle (yaw) is plotted on center axis, and gaze (head plus eye) is plotted on top axis. Time axis is marked in seconds and calibration bar applies to all three plots. Mean-square error was 0.66 deg^2. Subject was JK.

A complete walking experiment is shown in Fig. 8. The first 1.5 s show the subject staring at the target. During the period from 1.5–7 s several saccadic eye movements were performed. From 8–20 s the subject moved his head sinusoidally, and produced compensatory vestibulo-ocular eye movements. At the 21-s marker the subject walked out of the camera field of view.

The computed mean-square errors are the sum of noise from the camera digitizer, noise from the measurement system, and the inability of the subject to keep the head rigidly still. Comparison of the eye and head channel helps point out artifacts of the digitizer. Those changes in head position that have no corresponding movement in the eye channel were the result of digitizer noise. Two artifacts of the camera digitizer are visible as spikes in the head and gaze records between seconds 16 and 17 of Fig. 8.

When a subject stepped out of the field of view of the camera, as in Fig. 9, three quantities comprised horizontal gaze: horizontal head angle (yaw), horizontal eye angle, and horizontal head-translation angle. Translation is the side-to-side movement of the head. The translation angle is the change in target angle resulting from such head translation. The experimental results shown in Fig. 9 began with the head still, then several horizontal eye movements were made. Next the subject stared at the target for 1 s, and

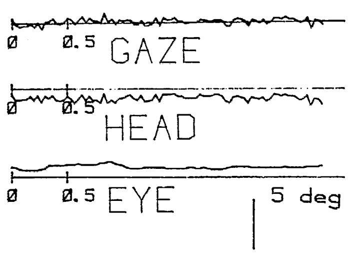

Fig. 7. Fixation of stationary target while standing with head still. Same display format as Fig. 6. Mean-square error was 0.15 deg^2. Subject was JK.

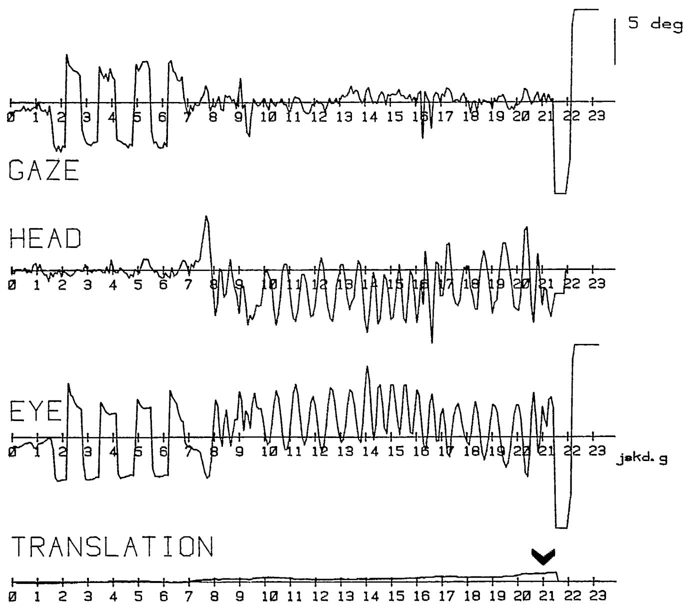

Fig. 8. Complete experiment with subject standing for 20 s, and then walking out of camera field of view. Format is same as Fig. 6, except for addition of lowest trace that presents horizontal translation angle. Arrow near translation angle record signifies approximate start of walking. This format applies to Figs. 8–14. Subject was JK.

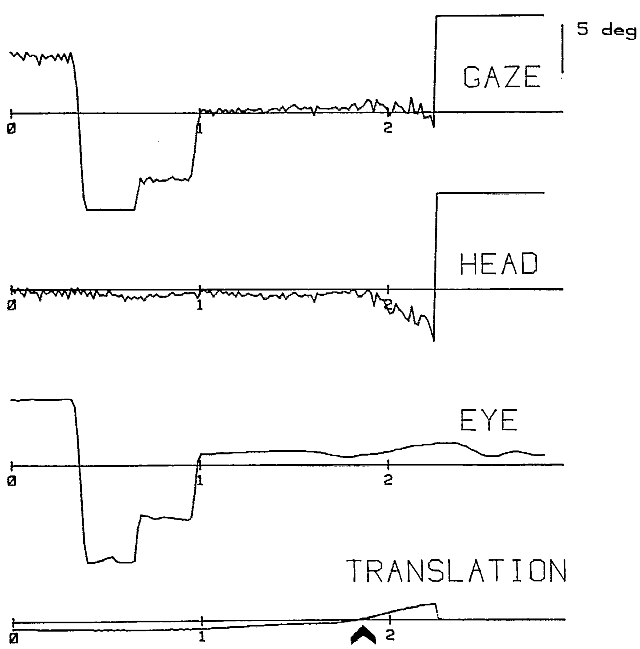

Fig. 9. Subject JM walking out of camera field of view. Mean-square error was 0.35 deg^2.

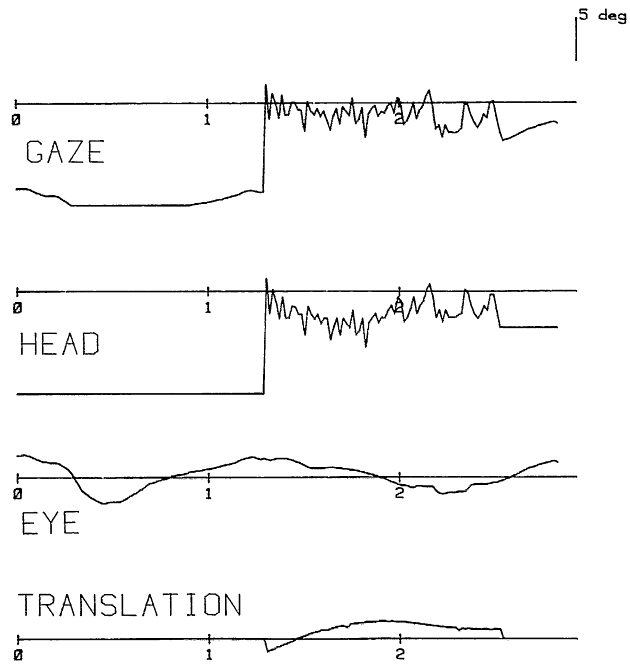

Fig. 10. JK walking through camera field of view. Mean-square error was 1.4 deg^2.

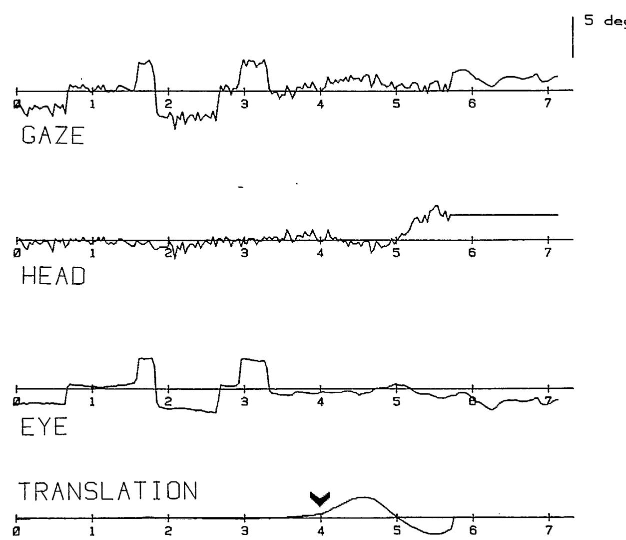

Fig. 11. GB looking between targets and then walking out of camera field of view. Mean-square error was 1.5 deg^2.

finally he stepped out of the camera field of view. The discontinuity in the head angle at 2.2 s indicates when the subject left the camera field of view.

The above walking experiments contained the initial step as a subject moved from rest. Experiments were also performed with the subject walking through the camera field of view. Fig. 10 shows steady-state walking through the field of view at normal speed. At 1.3 s the subject entered the camera field. The subject left the field at 2.7 s. This record shows one complete step cycle. The mean-square error for Figs. 9–14 were computed for only the portion of the data when the subject was walking within the camera field of view.

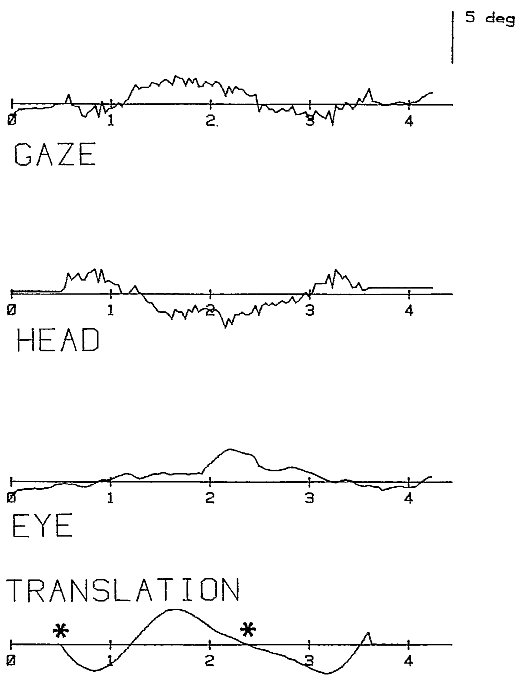

Fig. 12. GB walking through camera field of view. Subject entered field at 0.5 s and left at 3.5 s. Asterisks indicate approximate time of left-heel strike. Mean-square error was 1.7 $\deg^2$.

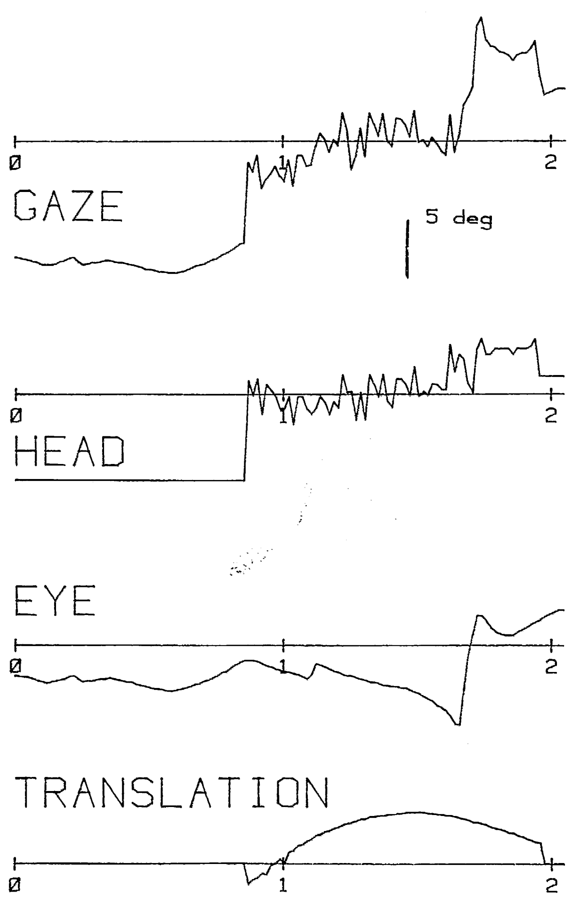

Fig. 13. JK walking through camera field of view with one shoe removed. Mean-square error was 2.8 $\deg^2$.

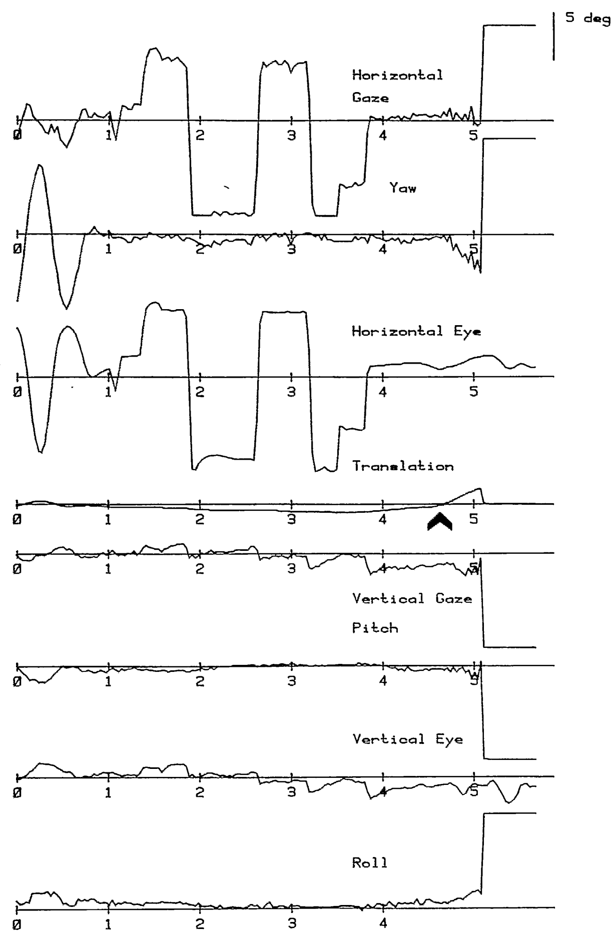

Fig. 14. Horizontal gaze, vertical gaze, and component angles for subject standing and then walking out of camera field of view. Head and eye movements from 0 to 1 s, eye movements only from 1 to 4.7 s, and then walking. Mean-square error was 0.35 $\deg^2$. Subject JM.

One subject, GB, had an unusual gait caused by effects of congenital osteogenesis imperfecta (brittle bones). This subject was locally ambulatory but used a wheelchair for long-distance movement. As shown in Figs. 11 and 12, during walking both the head-translation angle and the head-rotation angle were larger for this subject than for our other subjects. The head-translation angle was typically ± 2.5 deg, which is twice that of our other subjects. When subject GB walked backwards through the camera field of view similar records were recorded.

Fig. 13 shows the results of a different subject (JK) walking through the camera field of view wearing only one shoe. The lack of a shoe affected the gait and increased the translation angle to the same magnitude as for subject GB. However it did not affect the head-rotation angle. The compensatory eye movement and the error in gaze were larger than in previous figures. The mean-square error for this figure was 2.8 $\deg^2$, which is larger than that of subject GB in Figs. 11 and 12, perhaps because GB has been walking with an unusual gait all his life while JK has not had the opportunity to learn the necessary compensation for this new task. The saccade at 1.7 s enabled the subject to change his direction of gaze. The data of Fig. 13 are noisier than those of the previous figures because a 16-mm

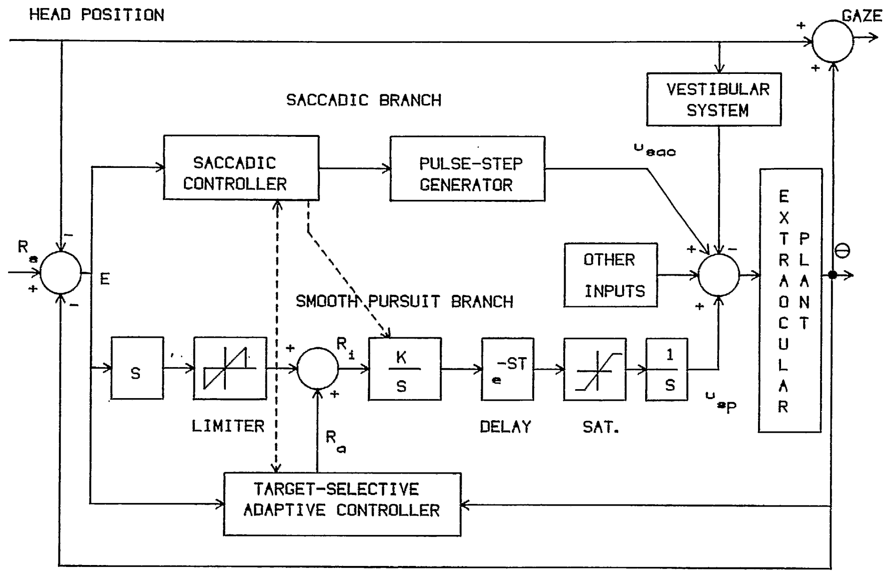

Fig. 15. TSAC model with addition of gaze output.

TV camera lens was used for this figure, whereas a 22-mm lens was used for the previous figures. The larger field of view of the 16-mm lens decreased the resolution of the digitizer producing noisier traces.

Horizontal gaze, vertical gaze, and their components are shown in Fig. 14. The top four axes show, from top to bottom, the horizontal gaze angle, the horizontal head angle (yaw), the horizontal eye angle, and the translation angle. These quantities have been presented in previous figures. The bottom four axes show, from top to bottom, the vertical gaze angle, the vertical head angle (pitch), the vertical eye angle, and the roll angle. The purpose of the roll computation was to assure that the head remained upright. The other components of gaze could only be determined accurately for small roll angles (±3 deg). The vertical eye movements between 0 and 1 s are real; they compensate for a 1.2-deg pitch movement of the head. The vertical eye movements between 1 and 4 s are artifactual; they are produced by crosstalk from the horizontal eye-movement channel. Walking began at 4.6 s. The discontinuity at 5.1 s was the subject leaving the field of view of the camera.

IV. Discussion

Eye movements recorded during voluntary head rotations were remarkably free of saccades; see for example Figs. 6 and 8. This lack of saccades implies that the vestibulo-ocular system was curbing the generation of saccades. This saccadic restraint was a common finding; unfortunately, we can offer no explanation.

The eye movements at the beginning and ending of head rotations indicate that the time delay between head movement and eye compensation was less than 17 ms. This time delay is small compared to the dynamics of the smooth-pursuit eye movement system. Therefore no adaption for time delay is necessary to explain the experimental results for the vestibulo-ocular system.

The target-selective adaptive control model for human eye movements presented in Fig. 4 can be modified so that it includes head movements and produces gaze direction as an output. Fig. 15 shows the block diagram for this model. The head angular position signal is derived primarily from the vestibular system. No dynamics are shown for this signal because the time delay is small. This head position signal is applied to the summing junction before the extraocular plant. The sign inversion causes the movement to be compensatory. Retinal error can be generated by either target, eye or head movements. Therefore the head position must also be applied at the input summing junction.

Gaze direction during walking depends upon eye position and head position, as shown in Figs. 9–14. As a person walks, the head rotates; the semicircular canals, modeled in Fig. 15 with the box labeled *Vestibular System*, sense this head rotation and produce an equal but opposite compensatory eye-movement signal. However, while walking the head also translates. This translation produces a change in the direction of gaze that also requires a compensatory eye-movement signal. What is the source of this translation compensation signal? Head translations are sensed by the utricle of the vestibular system. These signals could be processed to produce the translation compensation signal. The necessary computations require not only the amount of head translation but also the distance to the target. Such computational complexity may be resident in the utricle system [31]–[33]. Alternatively the translation compensation signal could be produced by the adaptive controller of the smooth-pursuit system. When a lifetime of learning is disrupted, as in the one shoe experiments of Fig. 13, the adaptive controller produces an inappropriate translation compensation signal and fixation errors increase. Given time, the adaptive controller can learn to provide signals appropriate for this new walking pattern.

The box labeled *Other Inputs* represents systems such as the cervical-ocular, optokinetic, and vergence systems that were not explicitly included in the model of Fig. 15, because either we could not measure their signals or they had little effect on our data. For example, the vergence system was not explicitly included because our data contained practically no vergence eye movements. As the subject walked through the camera's field of view, the distance to the target decreased from 3 m to 2 m. This change in distance would have induced vergence eye movements of less than 1/2 deg.

The mean-square error between target and gaze direction increased as freedom of movement increased. Smooth-pursuit tracking with a restrained head was measured with a mse of 0.05 deg^2 in Fig. 2. A standing subject holding his head still had a mse of 0.15 deg^2 in Fig. 7. A standing subject moving his head had a mse of 0.66 deg^2 in Fig. 6. For a walking subject the mse grew to 1.4 deg^2 in Fig. 10. Therefore in normal everyday activities humans do not fixate objects with great precision; it is surprising that we are not aware of these large errors.

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