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Adaptive Control Model for Saccadic and Smooth Pursuit Eye Movements

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Introduction

When a human, or a monkey, tracks a target moving in a sinusoidal manner, the subject quickly "locks onto" the target and tracks with no latency or phase lag (Fig. 1). It is as if he 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 (Westheimer, 1954b; Stark et al., 1962), a long-term learning process (Dallos & Jones, 1963), a percept tracker (Yasui & Young, 1975; Young, 1977; Steinbach, 1976), a neural motor pattern generator (Eckmiller, this volume), a state estimator, an observer, and an adaptive control system. When small errors in tracking accumulate, they are used to modify or update the model. In this paper, we will incorporate the concept of an internal model into the oculomotor system model developed in our earlier studies (Bahill et al., 1980).

Open loop experiments have shown that there is a time delay of about 150 msec in the smooth pursuit system. To overcome this inherent time delay and track a sinusoidal target with no phase lag would require the use of an adaptive controller. However, even previous adaptive models (Greene & Ward, 1979) have not been able to do this.

Human Adaptive Eye Movement Control

Humans use adaptive gain control for the saccadic system (Selhorst et al., 1976) and the vestibulo-ocular system. People have worn prism glasses that turned the visual world upside down. After a few weeks they were able to adapt their vestibulo-ocular systems well enough to ski downhill or ride a motorcycle (Stratton, 1896; Stratton, 1897; Smith & Smith, 1962). Neurophysiological effects of wearing prism glasses have time constants on the order of hours or days (Robinson, 1976).

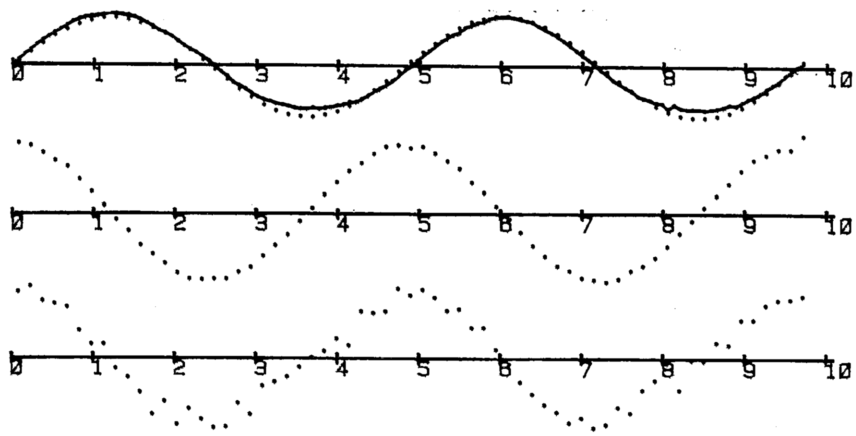


Fig. 1. The top record shows that a human (solid line) can track sinusoidal targets (dotted line) with no latency or phase lag. The mean squared error between eye and target positions was 0.17 deg^2. Both target velocity (middle record) and eye velocity (bottom record) are low pass filtered to attenuate saccadic velocities. For all figures rightward movements are upward deflections, target movements are ±5 deg, maximum sinusoidal target velocity is 6.5 deg/sec, and the time axis is labeled in seconds.

Most engineering adaptive controllers monitor outputs and modify gains to match some performance criterion. Gain adaptation has been discarded in our model because it is not likely that physiological gains can vary rapidly enough to allow a human to predict sinusoidal trajectories after only a half second of tracking. However, there is another class of adaptive control system, a signal synthesis system, in which the controller synthesizes a signal that is then used to modify the plant output (Fig. 2*A*). Adaptation of this type can occur as quickly as the law governing the predictable target motion can be identified. Fig. 2*B* shows a simplified version of the generalized form of the input adaptive control system (Fig. 2*A*) suggested by Landau (1979) which is appropriate for human smooth pursuit (i.e., $K_v = K_p = 1$). The adaptive controller produces a periodic sinusoidal internal target signal (R_A) of constant amplitude which is summed with the error (E) to provide a corrected error signal to the plant. The error represents the difference between the external target signal (R_S) and actual eye position (θ).

The required parameters of the adaptive mechanism can be derived from the error signal, E, and the output eye position, θ. Once the target assumes a periodic sinusoidal form, the adaptive controller generates a corrected control signal to produce, ideally, zero input error. However, variations of input frequency, phase, or magnitude, and discrepancies between the adaptive model and the actual plant will produce small errors. The adaptive mechanism will compensate to correct for them. For large errors the adaptive control ceases, a corrective saccadic eye movement is made, and, if the target is still periodic, adaptation is renewed.

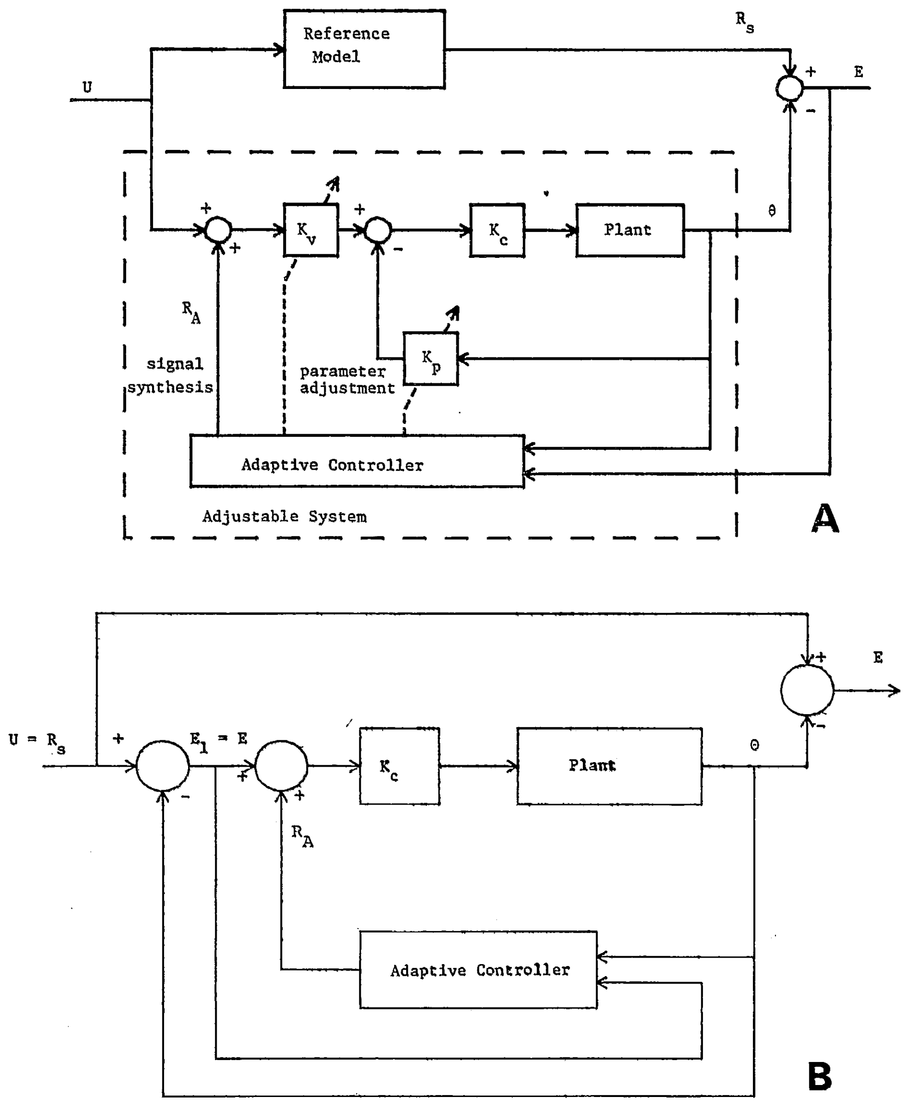


Fig. 2. *A*, a generalized block diagram for adaptive control or system identification based on Landau (1979). *B*, a specialized block diagram appropriate for the human smooth pursuit system.

The model of Fig. 3 results when the adaptive controller of Fig. 2 is applied to the human eye movement system. The elements in the Smooth Pursuit Branch of Fig. 3 are included in K_c of Fig. 2.

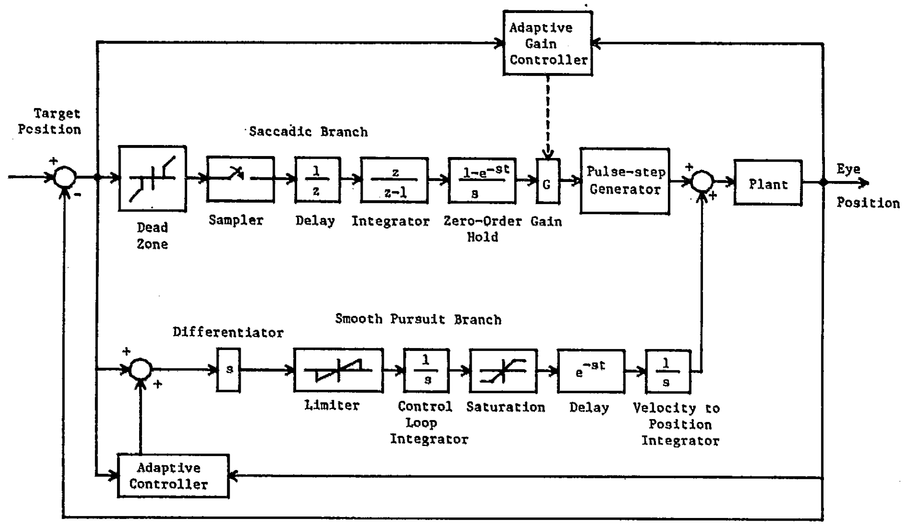
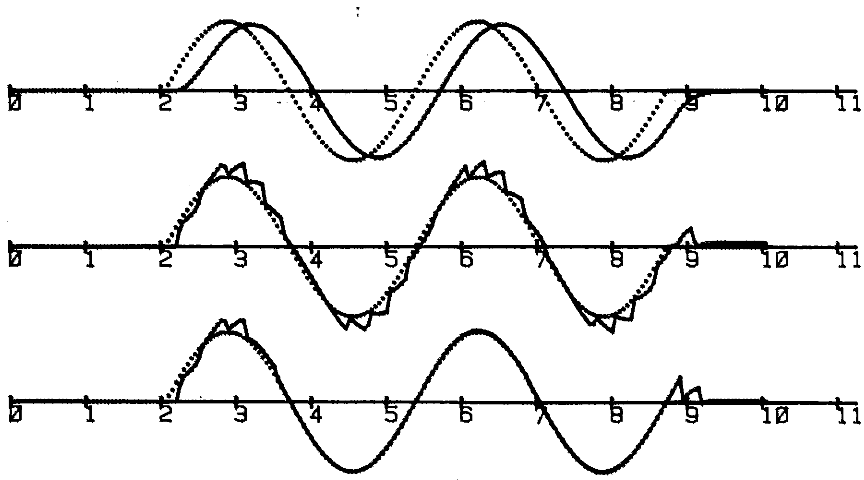


Fig. 3. An adaptive control model for human saccadic and smooth pursuit eye tracking.

Model Results

Typical performance of the adaptive model for predictable targets is shown in Fig. 4. The turnon and turnoff thresholds for the saccadic system and adaptive controller were adjusted after analyzing human data such as those shown in Figs. 1 and 5.

Fig. 4. The model (solid line) tracking a sinusoidal target (dotted line). For the top record the smooth pursuit branch was turned on, but the saccadic branch and the adaptive controller were turned off. For the middle record the smooth pursuit and saccadic branches were turned on, but the adaptive controller was turned off. For the bottom record all three subsystems were turned on. The target moved ±5 deg from primary position. The time is in seconds.



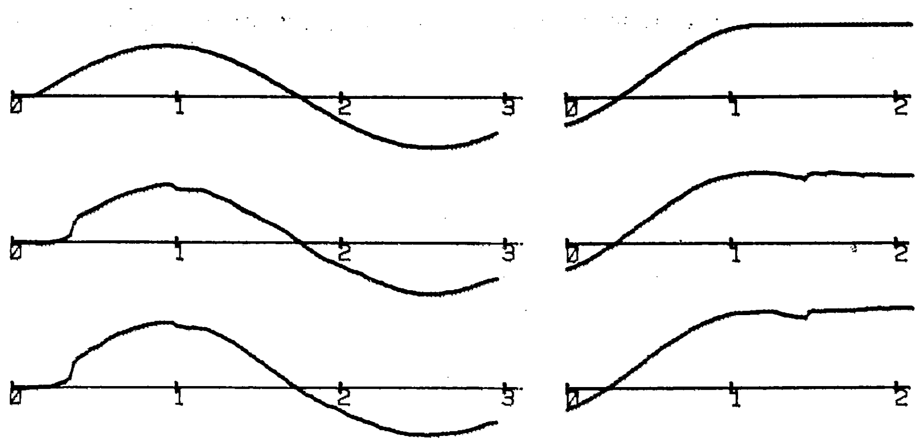


Fig. 5. Target (top), right eye (middle), and left eye (bottom) positions for a typical beginning (left traces) and ending (right traces) of sinusoidal tracking.

Let the dynamics of the plant and the operators (i.e., K_c, Fig. 2*B*) of the smooth pursuit branch be represented by the transfer function H (jω) with magnitude $\bar{H}$ and angle θ_H. From Fig. 2 the eye position, θ, can be calculated as

$$\theta = \frac{H}{1+H} R_S + \frac{H}{1+H} R_A \tag{1}$$

The purpose of the adaptive signal, R_A, is to minimize the magnitude and phase error between input and output, i.e., to minimize E. From Fig. 2

$$E(t) = R_S(t) - \theta(t) \tag{1A}$$

This error attains its minimum value, zero, when $\theta = R_S$. Substituting this relation into equation (1) yields

$$R_A = H^{-1} R_S \tag{2}$$

Estimating the Required Parameters

Our first model tracked only sinusoids. Sinusoidal tracking is natural, because most physical systems can be modeled as linear second-order systems and therefore respond in a sinusoidal manner. The target position was a sinusoid described by

$$U(t) = R_S(t) = B \sin(\omega t + \xi)$$

where B is the input magnitude. If this input signal is substituted in equation (2) then then

$$R_A(t) = A \sin(\omega_A t + \alpha) \quad (2B)$$

where $\omega_A = \omega$, $A = H^{-1}B$, and $\alpha = \xi - \theta_H$. The parameters to be determined by the adaptive controller are the frequency ω, the amplitude B, and the phase ξ.

One way to estimate frequency is to wait until the target has reached its maximum deviation at each extreme, and then compute the time interval between these extremes. If this is the brain's strategy, the eye must move through at least one half of a cycle before it can lock onto the target. Our experiments showed that when humans knew that the initial phase angle was zero, as in Fig. 5 (left traces), they ''locked onto'' the target after about one quarter of a cycle. On the other hand, if the model computes the target velocity it can estimate the sinusoid's frequency after only one quarter of a cycle. This method of estimating frequency, which was used in our model, is demonstrated by these equations

$$R_s(t) = B \sin(\omega t + \xi)$$

then

$$\dot{R}_s(t) = \omega B \cos(\omega t + \xi)$$

and

$$\frac{\max|\dot{R}_s(t)|}{\max|R_s(t)|} = \frac{\omega B}{B} = \omega$$

The amplitude B can be found by

$$B = \max|R_s(t)|$$

If it is known that the initial phase angle is zero, as in Fig. 5 (left traces), then this amplitude can be computed after a quarter cycle. If the initial phase angle is not known, then it will take a half cycle to estimate the amplitude B. The source phase angle ξ can be estimated after the first target turn around.

Human Results

To test the model, subjects' eye movements were recorded with the photoelectric technique (Bahill et al., 1975b). The target was generated by an LSI-11 microcomputer with a mirror galvanometer reflecting a laser spot. The red dot was projected on a curved screen 57 cm from the subject. Keeping the target at a fixed distance eliminated vergence eye movements. The subject's head was restrained with a head rest and bite bar to eliminate the effects of the vestibulo-ocular system. Data collection and analysis were performed with a PDP-11/34 computer using a UNIX operating system.

When the sinusoidal target started, there was typically a 125 to 175 msec delay before smooth pursuit tracking began, and about 50 msec further delay before a corrective saccade occurred (Fig. 5, left traces). By the first target maximum the subject was "locked onto" the target, and further tracking failed to show the reduction of gain and negative phase that exist for nonpredictable targets. When the target stopped, or disappeared, the eye continued to move sinusoidally for about 100 msec, then during the next 50 msec it decelerated to zero velocity, after which a corrective saccade put the eye on target. The stop of Fig. 5 (right traces) was difficult to detect since the target motion stopped when it had zero velocity. Therefore, the human continued to use the adaptive control signal for 350 msec, at which time a corrective saccade was instigated and the smooth pursuit was terminated.

Humans can track sinusoids quite well. They can also track other smoothly moving targets. The target waveforms of Fig. 6*A* are very similar: there is very little positional error between the two. In a forced choice test, 95% of the time our subjects could differentiate between the two waveforms, although they could not say how they were differentiating them. In Fig. 6 the smooth pursuit tracking changed from sinusoidal to parabolic on the same half cycle that the target changed.

Discussion

The smooth pursuit system is a velocity servo system: it tries to reduce the velocity error to zero. In so doing, it also aids the saccadic system in minimizing the positional error. By synthesizing appropriate velocity signals it can maintain zero positional error for smooth target waveforms.

It has been reported that monkeys continue sinusoidal tracking for more than a second after the target disappears (Eckmiller & Mackeben, 1978, 1980). Our human subjects did not do this. When we instructed them to continue tracking, we increased the interval of sinusoidal eye movement after the target disappearance. However, this interval never exceeded a half second.

Signal synthesis adaptive control systems are not common in the engineering literature. They are appropriate for target tracking. However, most engineering systems are not target trackers; they are regulators trying to maintain a desired output in spite of disturbances. If a target is to be tracked, a human is usually used. An exception is television and radar tracking of missiles immediately after launch. One of the drawbacks of signal synthesis systems is that a prior knowledge of the target movement's mathematical describing function is required. This is the limitation that prevents our sinusoid expecting adaptive controller from tracking parabolic waveforms the same way humans do. We plan to modify our model so that it can

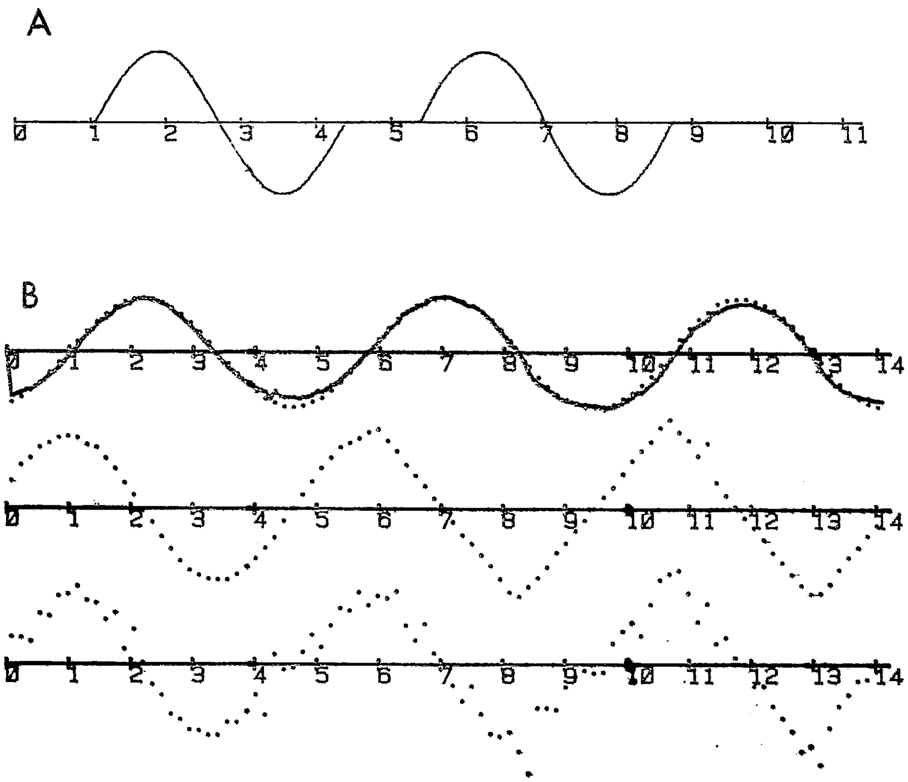


Fig. 6. *A*, two smooth, periodic target waveforms, the first based on a sinusoid and the other based on parabolic segments. The mean squared error between the two waveforms is 0.03 deg^2. *B*, human pursuit tracking of sinusoidal and parabolic waveforms. Top trace is target (dotted) and eye (solid) positions, middle trace is target velocity and bottom trace is eye velocity. The human can track the two waveforms equally well. The mean squared errors between target and eye positions were 0.16 deg^2 for the sinusoidal target and 0.17 deg^2 for the parabolic target.

choose a target waveform from a restricted menu of functions consisting of square, triangular, parabolic and sinusoidal waveforms. The model will track other target motions with waveforms from this menu in conjunction with saccades.

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