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ADAPTIVE FINITE STATE MODELS OF THE HUMAN OPERATOR

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While most of the mathematical models of human operators are based on the operator acting in a continuous manner upon continuous data, this model is based upon the human operator seeing only quantized input data and possessing a small number of internal states. The basic model is shown here and a scheme by which the threshold levels might be adjusted to make the basic model adaptive is presented. Some preliminary results and suggestions for further research are also presented.

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INTRODUCTION

Most of the present mathematical models of human operators are based on the operator acting in a continuous manner upon continuous input data. The model presented here is based on the assumption that the human operator possesses only a small number of internal states and changes state on the basis of quantized observations of error and error rate.

The basic model is that previously proposed by Bekey and Angel (Ref. 1). The model uses the concept of "force programs' (Ref. 2 & 3) (prestored error correction patterns) to give specific responses of the model based on its inputs and internal state. Continuous outputs are obtained by the use of "hybrid actuators" (Ref. 4).

The original model, while only part of a feasibility study and not intended to closely match real human operators, possessed some of the important characteristics of human operators. Specifically, the responses were of finite duration and were not interruptable until an action in progress had run to completion. Furthermore, the model was able to precisely track non-accelerating inputs. However, the model was not adaptive; it could not improve its performance over longer time of observing the same input curve.

BASIC MODEL

The basic model was designed to simulate a human operator in a compensatory tracking task with a pure inertia plant. The system is as shown in Figure 1. The operator sees only error and error rate. He quantizes these quantities and on the basis of these threshold levels and his present state he generates a force program.

In this simple model the operator can do one of three things if he is in a state where he can make a decision, i. e. not already in the middle of a force program: he can do nothing, he can attempt to change his position, or he can attempt to change his velocity. In this model no memory was used so the decision was made on the basis of a table of combinations as shown in Figure 2. Thus for the two error thresholds and one rate threshold model, decisions are made on the basis of this table. In this model only two position and one velocity correction (and their negatives) were allowed. The structure of this process is shown in Figure 3. The time actuators insure that the force program has the proper duration. The model can be simulated with only a very small number of logical gates, actuators, threshold gates and flip flops.

REQUIREMENTS OF AN ADAPTIVE MODEL

An attempt was made to alter the basic model so that it would be able to improve its performance over time. We want to achieve this not by adding many more threshold levels but by having the ability to adjust the few levels used in the basic model.

Some of the necessary features are:

1). Ability to reduce error and error rate to zero for a "simple" input curve.

2). Ability to adjust to a change in input curve.

3). Ability to get "close" to zero errors after three or four corrections.

ADJUSTMENT OF THE THRESHOLDS

We desire a device which on the basis or error and error rate thresholds will decide by use of a finite state machine to make one of a finite number of position or velocity corrections and/or to adjust its threshold levels in such a way as to reduce the error and error rate to zero. The thresholds are to be placed so that if the error, e, and the error rate, $\dot{e}$, remain constant for the duration of the correction, the error (error rate) if it was corrected will be smaller than the smallest error (error rate) threshold.

Let

n = # of positive velocity thresholds

m = # of positive position thresholds

e_i = level of i^{th} position threshold

$\dot{e}_j$ = level of j^{th} position threshold

f_i = correction for $e_{i+1} > |e| > e_i$

$\dot{f}_j$ = correction for $\dot{e}_{j+1} > |\dot{e}| > \dot{e}_j$

Consider first the velocity thresholds. We have 2n + 1 levels to consider:

$$\dot{e}_n > \dot{e}_{n-1} > \quad -- \quad > \dot{e}_1 > 0 > -\dot{e}_1 \quad -- \quad > -\dot{e}_n$$

We wish to map all points of the velocity error $\dot{e}$ into the region $[\dot{e}_1, -\dot{e}_1]$. Thus we seek the set $\{f_1\}$ such that:

$$\dot{e}_1 \geq |\dot{e}| - \dot{f}_i \geq -\dot{e}_1, \text{ for } \dot{e}_{i+1} \geq |\dot{e}| \geq \dot{e}_i$$

This is illustrated in Figure 4 for a number of possible corrections.

In particular, consider the point $\dot{e}_{i+1}$. The corrections $\dot{f}_i$ and $\dot{f}_{i+1}$ must be chosen so that

$$\dot{e}_1 \geq \dot{e}_{i+1} - \dot{f}_{i+1} \geq - \dot{e}_1 \text{ and } \dot{e}_1 \geq \dot{e}_{i+1} - \dot{f}_{i+1} \geq - \dot{e}$$

since $\dot{e}_{i+1}$ is a boundary point.

If every point in $[\dot{e}_1, -\dot{e}_1]$ is to be used, since we want the most efficient scheme, the only solutions to the above equations are:

$$\dot{e}_{i+1} - \dot{f}_i = \dot{e}_1$$

$$\dot{e}_{i+1} - \dot{f}_{i+1} = -\dot{e}_1$$

$$\dot{e}_i - \dot{f}_i + - \dot{e}_1$$

$$\dot{f}_i = \dot{e}_1 + \dot{e}_i = e_{i+1} - \dot{e}_1$$

$$\dot{e}_{i+1} = \dot{e}_i + 2\,\dot{e}_1$$

The solution to this set of equations is:

$$\boxed{\begin{aligned} \dot{e}_i &= (2i - 1)\,\dot{e}_1 \\ \dot{f}_i &= 2(i - 1)\,\dot{e}_1 \end{aligned}} \qquad i = 2, \ldots n$$

Consider now the position correlations. The problem is the same as above except for the fact that the error in velocity may cause an additional position error of $\pm\,\dot{e}_1\,\Delta t$, where Δt is the duration of a position correction (Figure5). Thus we obtain for this case

$$\boxed{\begin{aligned} e_j &= (2j - 1)(e_1 - \dot{e}_1\,\Delta t) \\ f_j &+ 2(j-1)(e_1 - \dot{e}_1\,\Delta t) \end{aligned}} \qquad j = 2, \ldots n$$

Thus with this correction scheme all errors are mapped into the region determined by the smallest thresholds. At this point the threshold levels are changed. Since the error is located in the innermost region, we just break up this region as before.

Let k = number of threshold adjustments

$$e_v(k) = \dot{e}_1 \text{ after } k^{th} \text{ adjustment}$$

$$e_x(k) = e_1 \text{ after } k^{th} \text{ adjustment}$$

Thus we obtain the following set of equations if we allow n velocity thresholds and m position thresholds

$$e_v(k) = \frac{e_v(k-1)}{n}$$

$$e_x(k) = \frac{e_x(k-1)}{m} + e_v(k)\,\Delta t$$

Solving these two equations we obtain

$$e_v(k) = \frac{e_v(0)}{n^k}$$

$$e_x(k) = \frac{e_x(0)}{m^k} + \frac{e_v(0)\,\Delta t}{1 - \frac{n}{m}} \left(\frac{1}{n^k} - \frac{1}{m^k} \right) \quad \text{if } m \neq n$$

$$e_x(k) = \frac{e_x(0) + k\, e_v(0)\,\Delta t}{n^k} \qquad \text{if } m = n$$

In order that the model operates correctly we must have $e_1 < e_2$. This is not always guaranteed because of the $\dot{e}_1 \Delta t$ term. For the case that $m = n$, the following condition will insure that this is true for all k:

$$e_x(0) > 3/2\ e_v(0)\ \Delta t$$

It should be pointed out that the index k only denotes the k^{th} adjustment but does not indicate at what time this adjustment occurs. This makes the adjustment scheme different from a sampled data or synchronous adjustment scheme.

THE ADAPTIVE MODEL

The adaptive model is obtained by using the basic model with the adjustment procedure of Figure 6. Let T(k) be the set of all threshold levels after the k^{th} adjustment. The model then works as follows:

1). On the basis of the original threshold levels, T(0), and an initial table of combinations, Table I, the model tries to reduce errors to zero. This corresponds to some initial rough corrections. When the errors reach the zero region, the rough correction stage is concluded.

2). The threshold levels are adjusted to their next level, T(1), and the same table of combinations or a new one, Table II, is used. Here one of three things can happen. First, the errors can be so small that we are already in the zero region of Table II. In this case we adjust the thresholds again $T(k) \rightarrow T(k+1)$, and go back to Table II. On the other hand, the errors might be so large that on the basis of some determined criteria we assume the input has changed. In this case, we change the thresholds to their original levels T(0) and start again with Table I. Finally, if neither of these things have happened, we make a correction on the basis of Table II.

3). After the correction is made, we check to see the result of it by Table III. Remembering that the threshold levels and corrections were chosen so that for simple inputs the right correction would put the errors into the zero region, we have three possibilities to check for in Table III. First, the correction could have done what it was intended to do; in this case the thresholds are again adjusted, $T(k) \rightarrow T(k+1)$, and we return to Table II. Second, the input could have changed during the correction in which case we return to Table I and the original threshold levels. Third, the correction has not reduced the errors into the zero region which means that the input is accelerating. In this case we assume that it will continue to accelerate and we use a correction which predicts where the input will be at the end of the correction time. Here, the amount of the correction is changed by a constant which is dependent upon the duration of the correction.

RESULTS

Some typical results of the adaptive model are shown in Figures 7 and 8. The points at which corrections are begun are denoted by arrows.

For the case of simple inputs; e.g. ramps and steps, the rate of convergence is almost entirely dependent upon the number of thresholds allowed. The specific table of combinations makes almost no difference at all.

However, for the time varying input the situation is very much different. Here the particular table of combinations chosen is of prime importance. The problem is one of defining a suitable criterion function between error and error rate. For ideal tracking we would like to match velocities but since the corrections are of finite duration, for the time varying input, the time spent trying to match velocities might easily lead to large position errors.

An adjustment system which not only makes the thresholds more sensitive for improving results but also desensitizes the thresholds for poor results was found to be very unstable. This however, is probably due to the fact that a very small number of thresholds were used, two for error and one for error rate.

CONCLUSIONS

As pointed out previously, this project was only a feasibility study. No comparisons were made with actual human operator data. The results are very encouraging. The sample model has many of the characteristics displayed by human operators.

The next step in the development of a more sophisticated model would be to include a small amount of memory. This would enable the model to respond much better to time varying inputs.

Second, some work must be done on choosing the optimal set of initial parameters. Also, we would like to be able to chose the table of combinations by matching parameters with a real human operator.

Third, the duration of the corrections and possibly even the types of corrections can be made adaptive since the convergence rate is dependent on the duration of the correction. This might help explain some time varying aspects of human operators.

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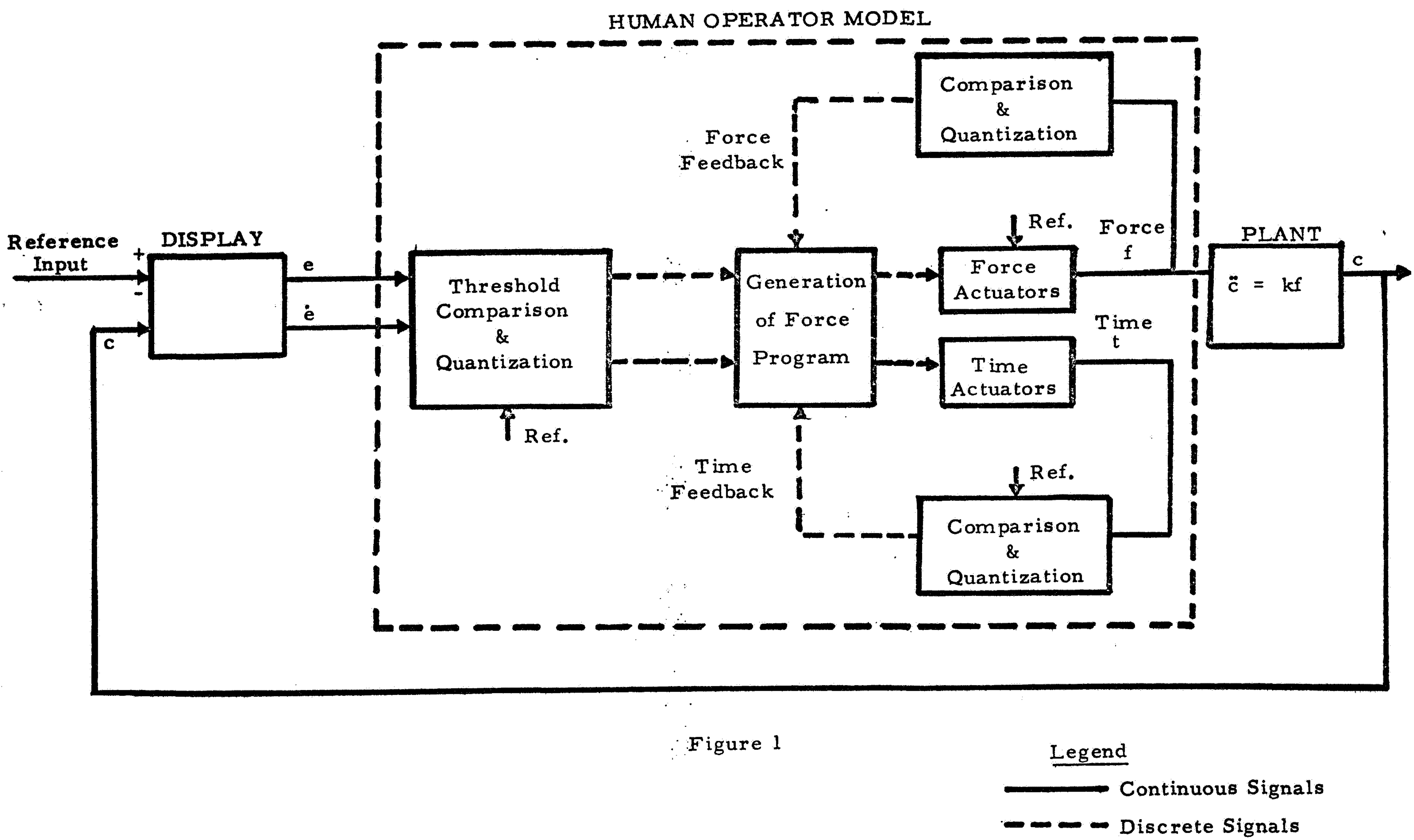

HUMAN OPERATOR MODEL
Reference Input
DISPLAY
+
-
e
$\dot{e}$
c
Threshold Comparison & Quantization
Ref.
Generation of Force Program
Force Feedback
Time Feedback
Comparison & Quantization
Force Actuators
Time Actuators
Ref.
Ref.
Comparison & Quantization
Force f
Time t
PLANT
$\ddot{c} = kf$
c
Legend
Continuous Signals
Discrete Signals

Figure 1

$-\varepsilon_2$	$-\varepsilon_1$	0	0	ε_1	ε_2	
+p	+p	-v	-v	-v	-p	$\dot{\varepsilon}$
+p	+p	0	0	-p	-p	0
+p	+p	0	0	-p	-p	0
+p	+p	+v	+v	-p	-p	$-\dot{\varepsilon}$

FIGURE 2

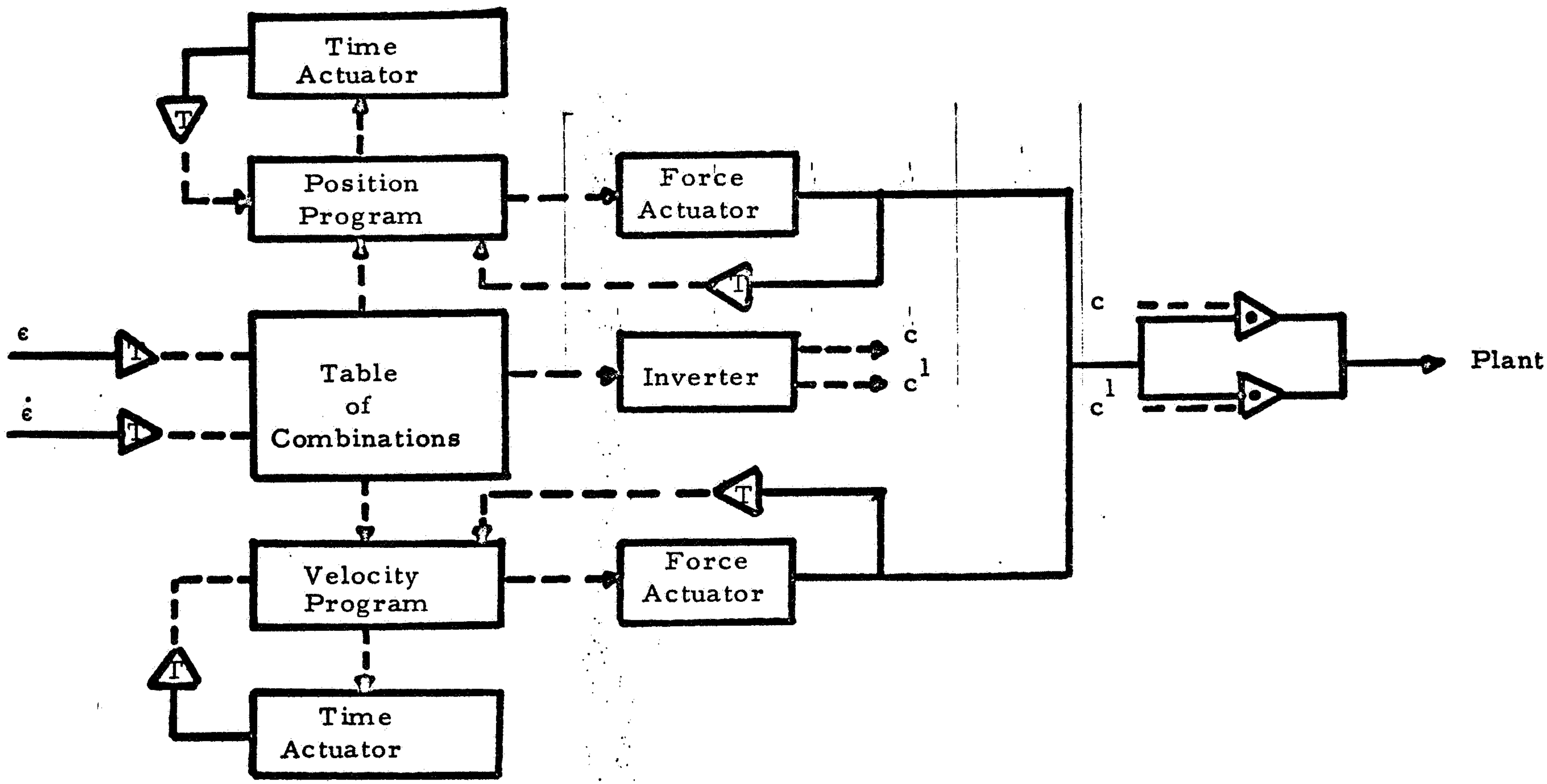
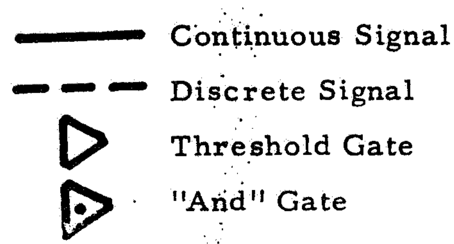


Figure 3 Block Diagram of Asynchronous Network



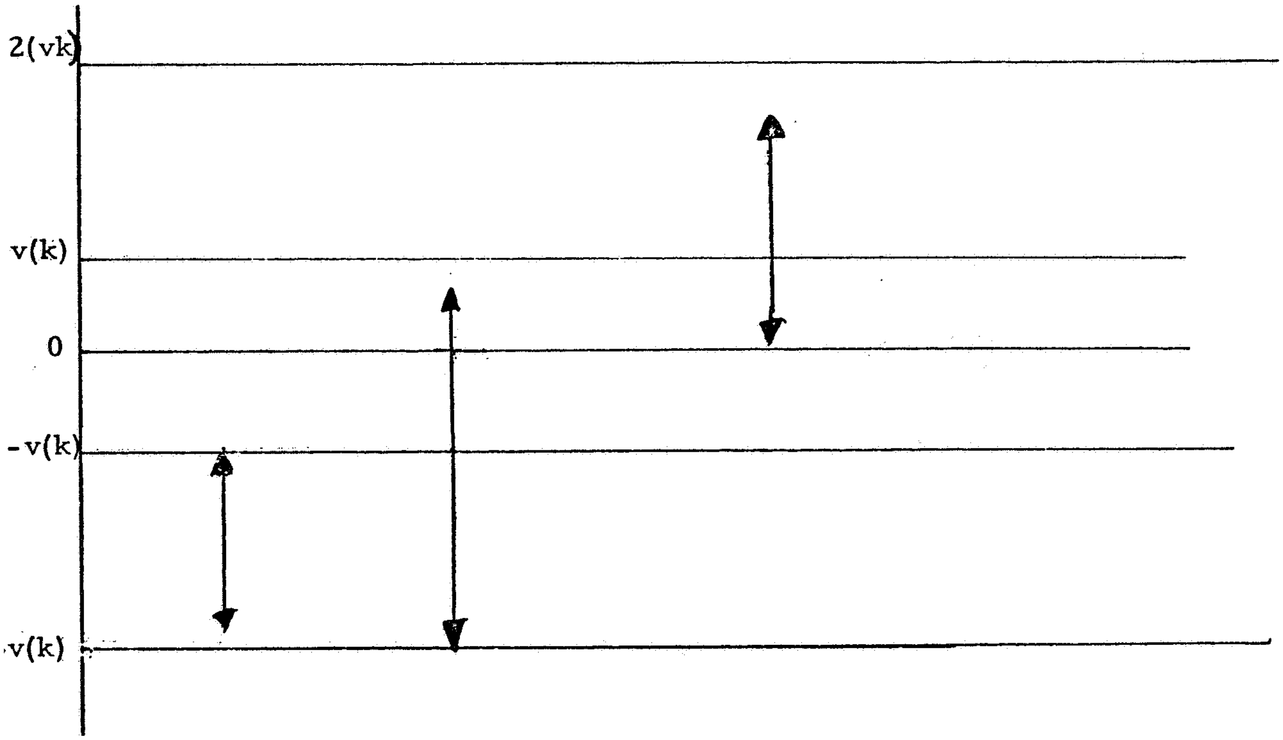


FIGURE 4

VELOCITY THRESHOLD LEVELS

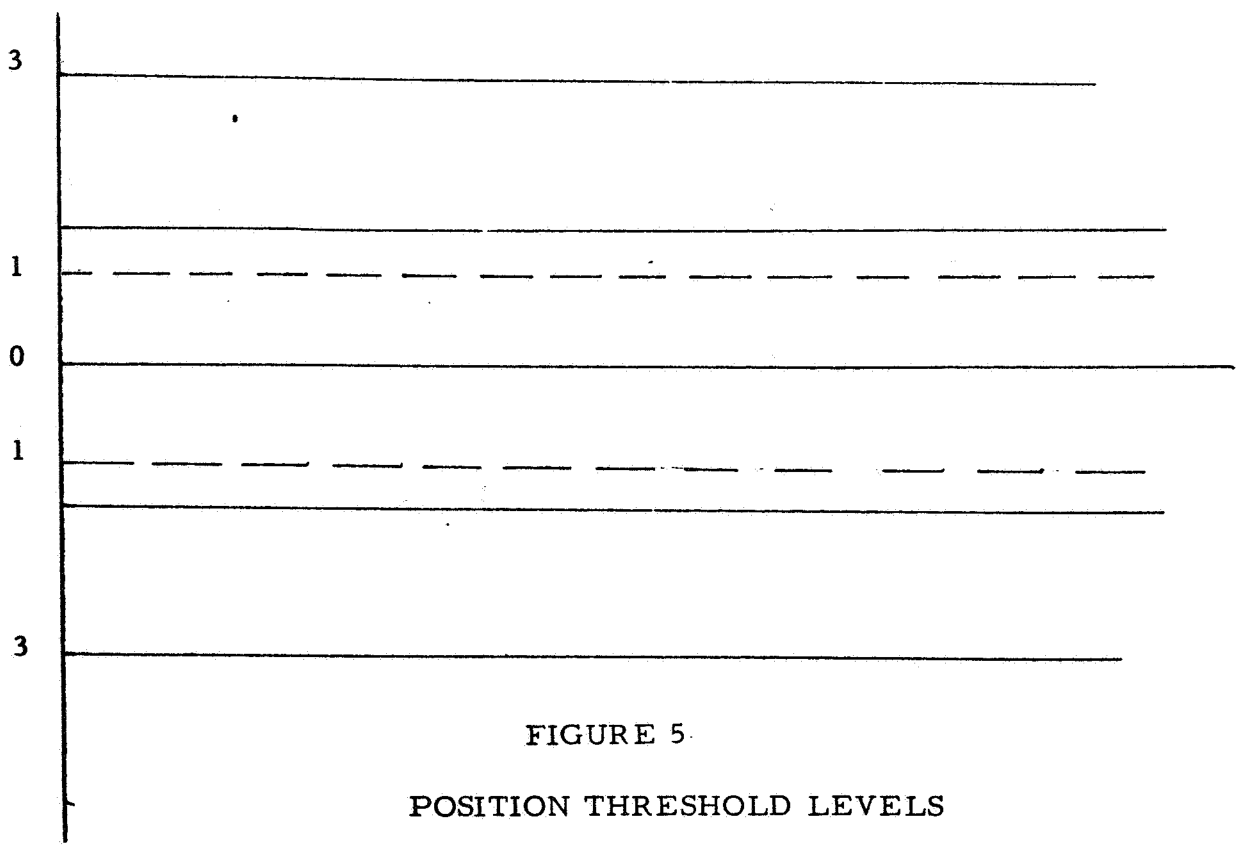
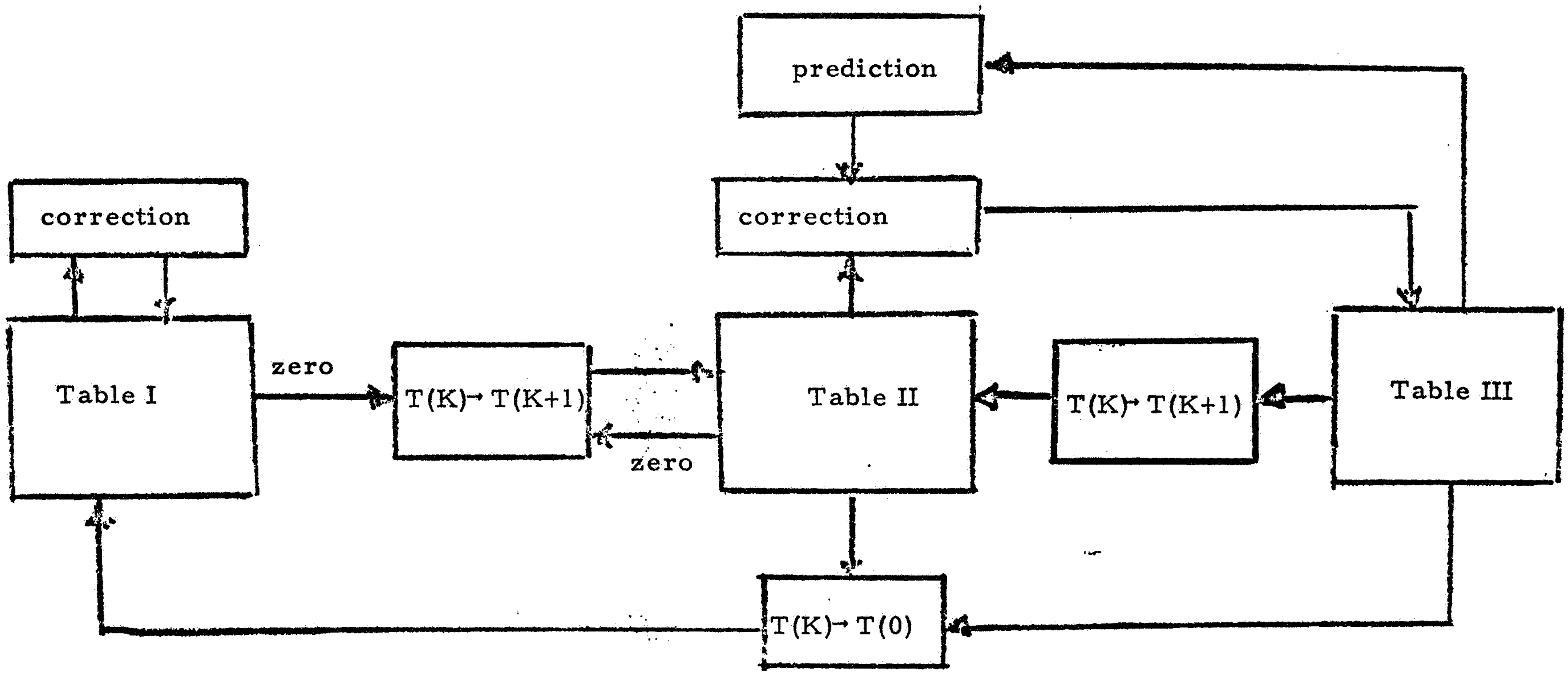


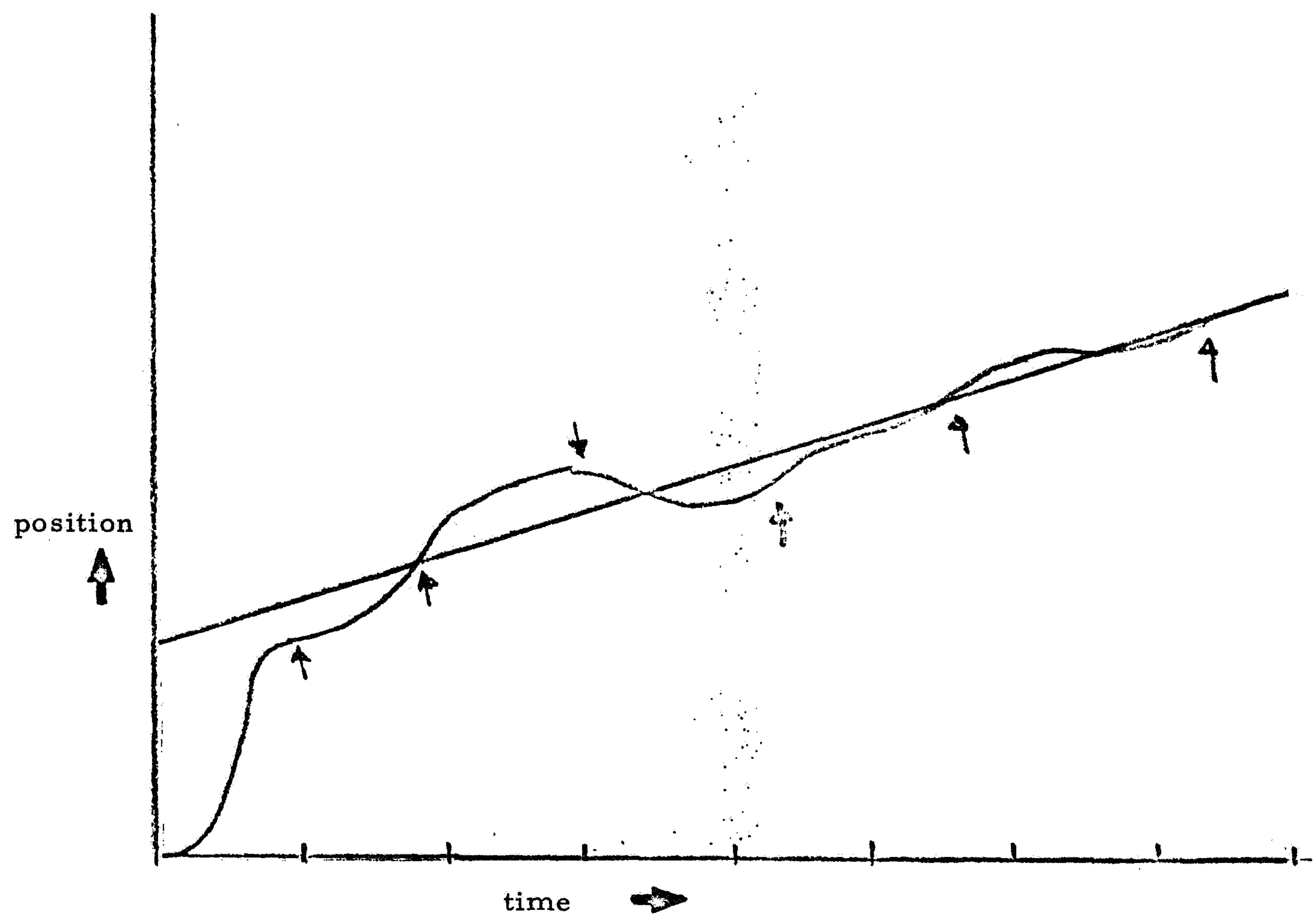
FIGURE 5

POSITION THRESHOLD LEVELS



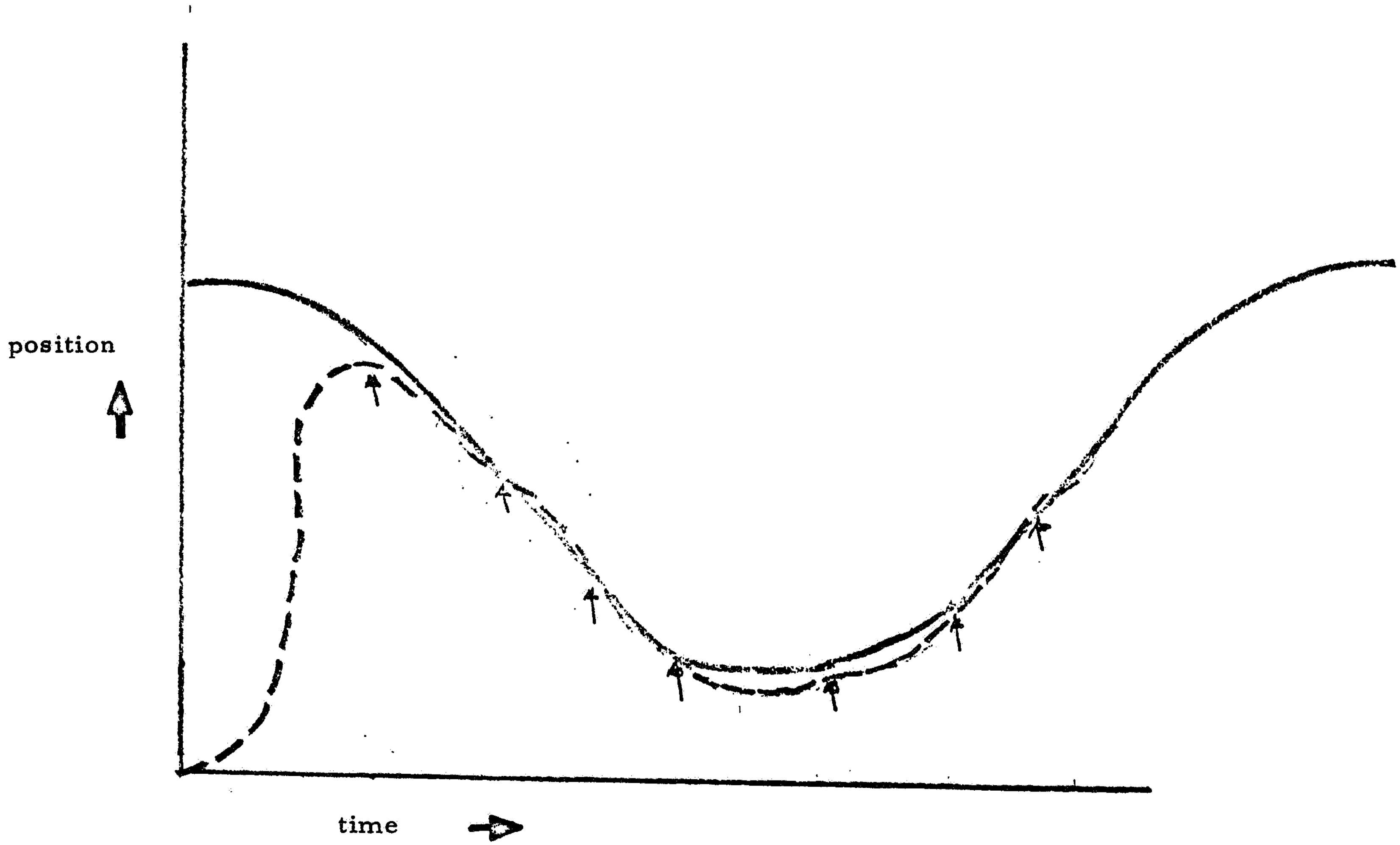
LEVEL ADJUSTMENT SCHEME

FIGURE 6



RESPONSE TO RAMP

FIGURE 7



RESPONSE TO SINE WAVE

FIGURE 8