# SELF-ORGANIZING SPACECRAFT ATTITUDE CONTROL

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# FOREWORD

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The contributions of Mr. Blatt to the evaluation phase of this program are particularly noteworthy: Mr. Blatt prepared the analog computer simulation and guided the conduct of experiments using the self-organizing controller.

The efforts of the Adaptronics, Inc. staff, particularly Messrs. L. O. Gilstrap, Jr., S. Levine, H. J. Cook, R. J. Brown, J. K. Muse, D. L. Garrison, and N. E. Wilson are gratefully acknowledged, as are the important contributions of R. J. Lee in several antecedent efforts. Miss Julie Hauptli and Miss Peggy Jenkins have been most helpful in their editorial activities involved in this work.

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## ABSTRACT

Results are presented from an investigation of self-organizing attitude control and stabilization for spacecraft. Self-organizing (SOC) control is achieved through high-speed assessments of performance values of successive random experiments with respect to a generalized control criterion, followed by a "reward-punishment" reinforcement process to obtain on-line synthesis of plant actuation signals. The logic is of the Probability State Variable (PSV) type, i.e., reinforcement signals are used to bias the probabilities associated with the SOC experiments. Convergence of SOC output signals to appropriate, time-varying levels generally occurs within several milliseconds, resulting in rapid, well damped, stable control over a very wide range of controller, plant, and disturbance characteristics (including induced artificial failures). A laboratory experimental self-organizing controller has been fabricated. Evaluations of this SOC have been conducted using single-axis analog computer simulations of a representative orbital vehicle. Compared to a conventional controller for this vehicle, the SOC produced superior transient and comparable steady-state performance. The SOC adapted to a range of plant characteristics over which the conventional controller did not provide uniformly satisfactory performance.

# TABLE OF CONTENTS

# LIST OF FIGURES

LIST OF FIGURES, Continued

LIST OF FIGURES, Continued



LIST OF TABLES

# SYMBOLS AND ABBREVIATIONS

## English

| | |
|---|---|
| CGC | Constant Gain Controller |
| $e$ | error |
| $e(0)$ | initial error |
| $\dot{e}$ | error rate |
| $\dot{e}(0)$ | initial error rate |
| $e_p$ | predicted error |
| $\dot{e}_p$ | predicted error rate |
| $\ddot{e}_p$ | predicted error acceleration |
| $G$ | effective gain parameter |
| $G_i$ | PSV output signal (binary) in digital computer simulation |
| $I_v$ | vehicle inertia |
| $I_w$ | momentum-wheel inertia |
| $K$ | PSV output signal (also called u) |
| $K_i$ | system gains |
| $K_m$ | momentum-wheel gain |
| OAO | Orbiting Astronomical Observatory |
| $\dot{P}$ | a defined function for digital computer simulation |
| PSV | Probability State Variable |
| $\overline{RN}$ | pseudo-random number for digital computer simulation |
| $\overline{rp}$ | PSV input signal |
| SOC | Self-Organizing Controller |
| $t$ | time |
| $T$ | prediction interval |

English (Continued)

| | |
|---|---|
| $T_d$ | disturbance torque |
| $T_w$ | momentum-wheel torque |
| u | PSV output signal (also called K) |
| V | a scalar function (Lyapunov function) |
| $\dot{V}$ | first derivative of V with respect to time |
| $\ddot{V}$ | second derivative of V with respect to time |

# SYMBOLS AND ABBREVIATIONS

## Greek

| | |
|---|---|
| $\alpha$ | p-register representation for digital computer simulation |
| $\Delta t$ | sampling time interval |
| $\theta$ | vehicle attitude |
| $\dot{\theta}$ | vehicle attitude rate |
| $\ddot{\theta}$ | vehicle attitude acceleration |
| $\theta_c$ | attitude command signal |
| $\tau_a$ | actuator time constant |
| $\tau_i$ | system time constants |
| $\tau_m$ | momentum-wheel motor time constant |
| $\omega$ | momentum-wheel angular rate |
| $\dot{\omega}$ | momentum-wheel angular acceleration |
| $\dot{\omega}_s$ | momentum-wheel saturation level |

# 1. INTRODUCTION AND SUMMARY

This report summarizes basic design features of a self-organizing adaptive controller for spacecraft attitude control and stabilization. Results of evaluations of laboratory models of the controller, operating on simulated single-axis plants, are presented with recommendations for future applications of these techniques to operational systems.

## 1.1 Program Objectives

The following excerpt from the contractual statement of work is set forth here for background purposes:

> The primary objective of this program is to establish design criteria and techniques for the application of self-organizing theory to attitude control and stabilization systems for space vehicles. In accomplishing this objective an experimental laboratory model shall be designed, fabricated, and evaluated, and the results consolidated such that they may be used in future designs of such controls.

Further elaboration on the above objective is found in Reference 1, pp. 4-5, from which we quote:

> **Test Objectives**
>
> 1. The primary test objective will be to demonstrate the feasibility of applying probability state variable (PSV), self-learning control techniques to a satellite control system.

2. Establish the practicality of high-speed, on-line learning techniques and compare the system performance with a constant gain system.

3. Demonstrate the self-organizing controller hardware within reasonable cost and complexity limits.

4. Analyze the adaptive capability of the control system.

5. Determine the advantages of various PSV network arrangements.

6. Evaluate the performance assessment criteria and the reward-punishment-search logic.

7. Determine the reliability characteristics of the self-organizing control and demonstrate its capability with various component failures or degradation in performance.

## 1.2 Technical Approach

The contractual work statement for this program has required that:

> The single axis controller design shall employ probability state variable devices demonstrating the self-organizing and learning capabilities of such techniques for adapting to a changing environment.

It was further required that:

> The attitude control system design ... shall contain the proper logic to control a simulated "hybrid"

actuator configuration, consisting of cold gas reaction jets for coarse control and inertia wheels for fine control.

In conventional usage, a "hybrid" system consists of two distinct but mutually compatible control systems, viz. the proportional inertia-wheel controller and the on-off reaction-jet system. A systematic approach to the development of self-organizing control for a "hybrid" system must therefore begin with an evaluation of the role which each of these systems is to play in the program. The approach taken in the present effort may be summarized as follows:

(a) The inertia-wheel, fine control system served as the primary means for detailed study of self-organizing control.

(b) Design of the self-organizing inertia-wheel control system was made compatible with operation of on-off reaction jets as customarily used.

(c) Subject to level of effort constraints of the program, self-organizing control techniques were applied to the problem of reaction-jet control in a "hybrid" system.

Topics (a) and (b) above, particularly (a), are taken up in detail in the body of this report. Topic (c) is the subject of Appendix C to this document.

## 1.3 Summary of Work Performed

Theoretical analyses, digital computer simulations, parametric design studies, logic and circuit design, and experimental hardware evaluations (using analog computer simulations of spacecraft dynamics) have been conducted during this program. This report documents all work performed. Detailed schematic and layout drawings of the hardware are omitted, however, in the interest of conciseness; these drawings are maintained on file at the Air Force Flight Dynamics Laboratory and at Adaptronics, Inc.

In the course of this work program, two fundamental developments were realized which are believed to have far-reaching consequences for high-speed, on-line control of dynamic processes. These developments are:

(1) An incremental form of the probability state variable conditioning logic.

(2) A performance assessment criterion (for PSV biasing) which produces extremely rapid convergence of learned signals to their optimal time-varying levels. This criterion has proven to be largely independent of the controlled-plant characteristics.

Two hardware Self-Organizing Controller (SOC) systems were constructed in the course of the program. These systems, termed Mark I and Mark II, have the basic features summarized below.

### 1.3.1 Mark I Self-Organizing Controller*

To permit refinement of basic techniques and to demonstrate feasibility of realizing the desirable characteristics of self-organization in an elementary control application, a laboratory experimental system, termed the Mark I, was fabricated approximately midway in the work program. This system contains a

*See Reference 2

single probability state variable device. The basic purposes which guided development effort for the Mark I system were:

(1) To establish the practicality of applying high-speed, on-line learning techniques to stabilization and control involving direct learning of inertia-wheel excitation signals.

(2) To investigate implementation of a specific performance assessment criterion.

(3) To develop appropriate logic and circuit techniques and demonstrate that self-organizing controller hardware is realized with simple, economical equipment.

A block diagram of the Mark I system, which includes a simulated momentum-wheel actuator and single-axis rotational dynamics of an orbiting satellite, is shown in Figure 1.1. With the switch S1 in position A, the system operates as a conventional, constant-gain, proportional-error controller. In this conventional configuration, the selectable (but fixed) gain $K_1$ and time constants $\tau_1$ and $\tau_2$ are used to obtain desired response characteristics for a chosen plant, i.e., with respect to selected values of the momentum-wheel time-constant $\tau_m$ and the (combined vehicle inertia and actuator gain) factor $K_2$.

With switch S1 in position B, the system operates as a self-organizing controller in a control-computer configuration, i.e., the learned parameter is K(t), the excitation signal to the controlled plant. In this case $K_1$, $\tau_1$, and $\tau_2$ may be used to establish higher order plant dynamics and to study the effects of gain and/or phase changes in the loop.

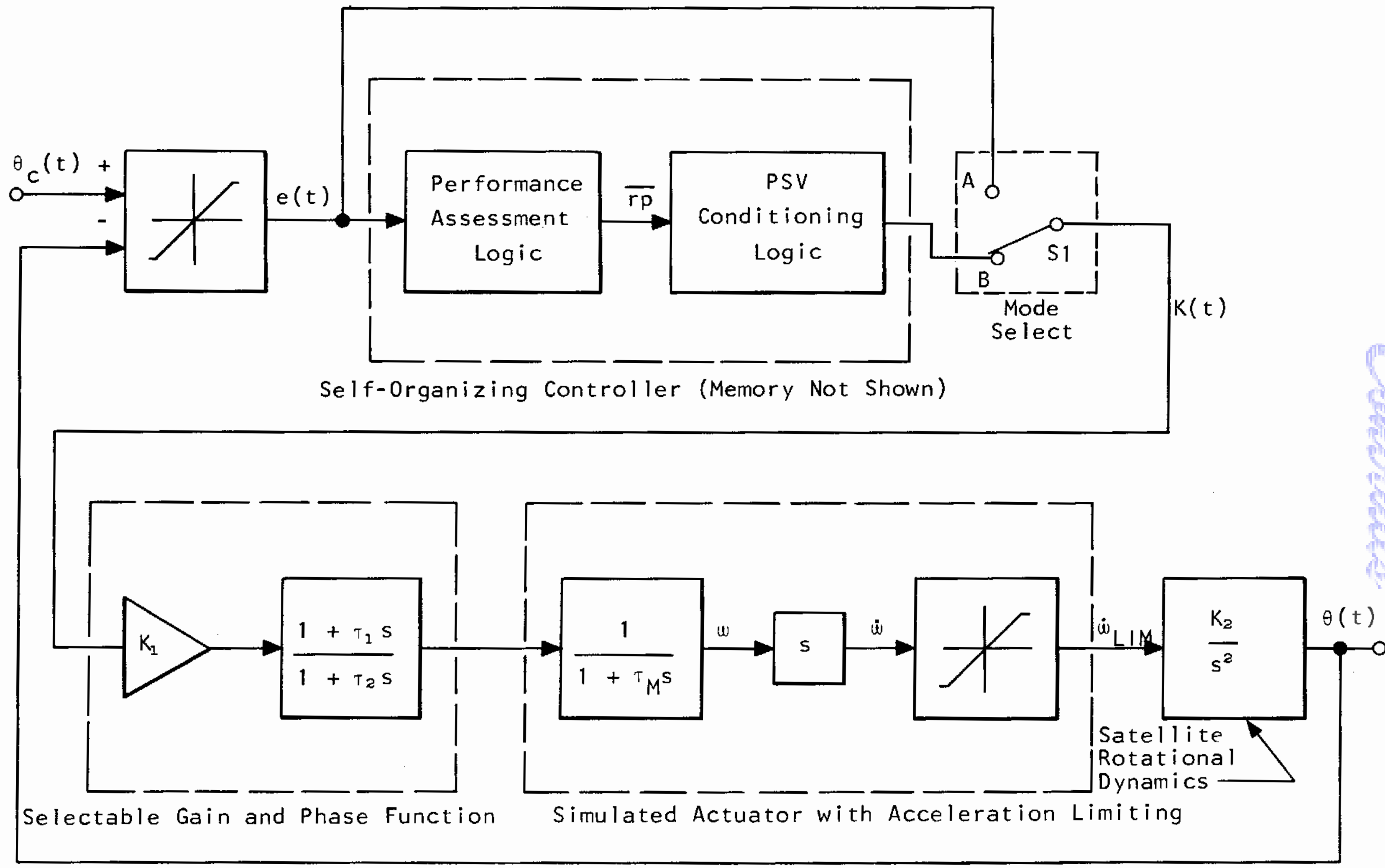


Figure 1.1: Block Diagram of Mark I Self-Organizing Control System

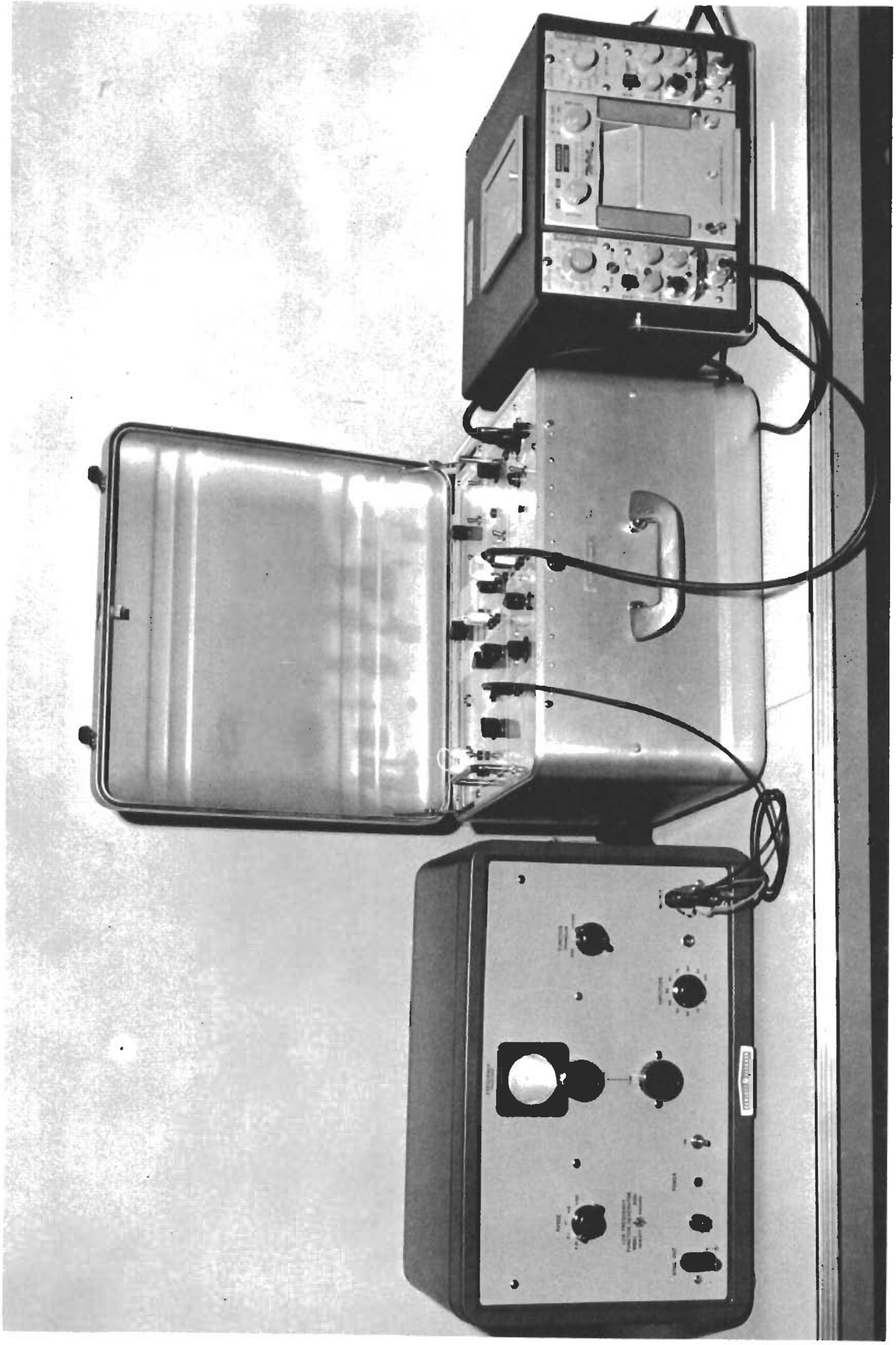

Figure 1.2: Input Function Generator, Mark I SOC, and Recording Oscillograph (Left to Right) as Used in Preliminary Experiments

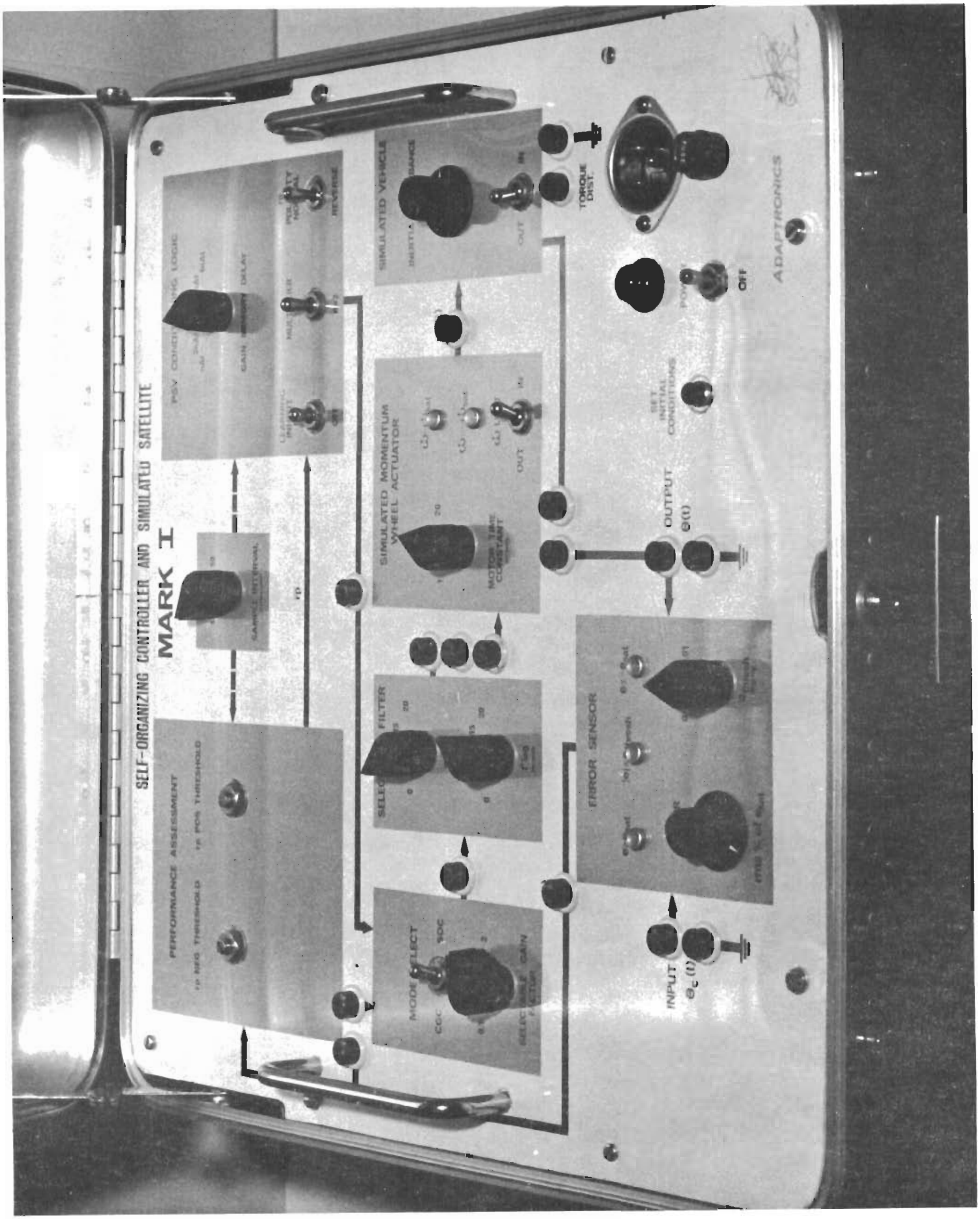


Figure 1.3: Front Panel of Mark I Self-Organizing Controller and Simulated Satellite

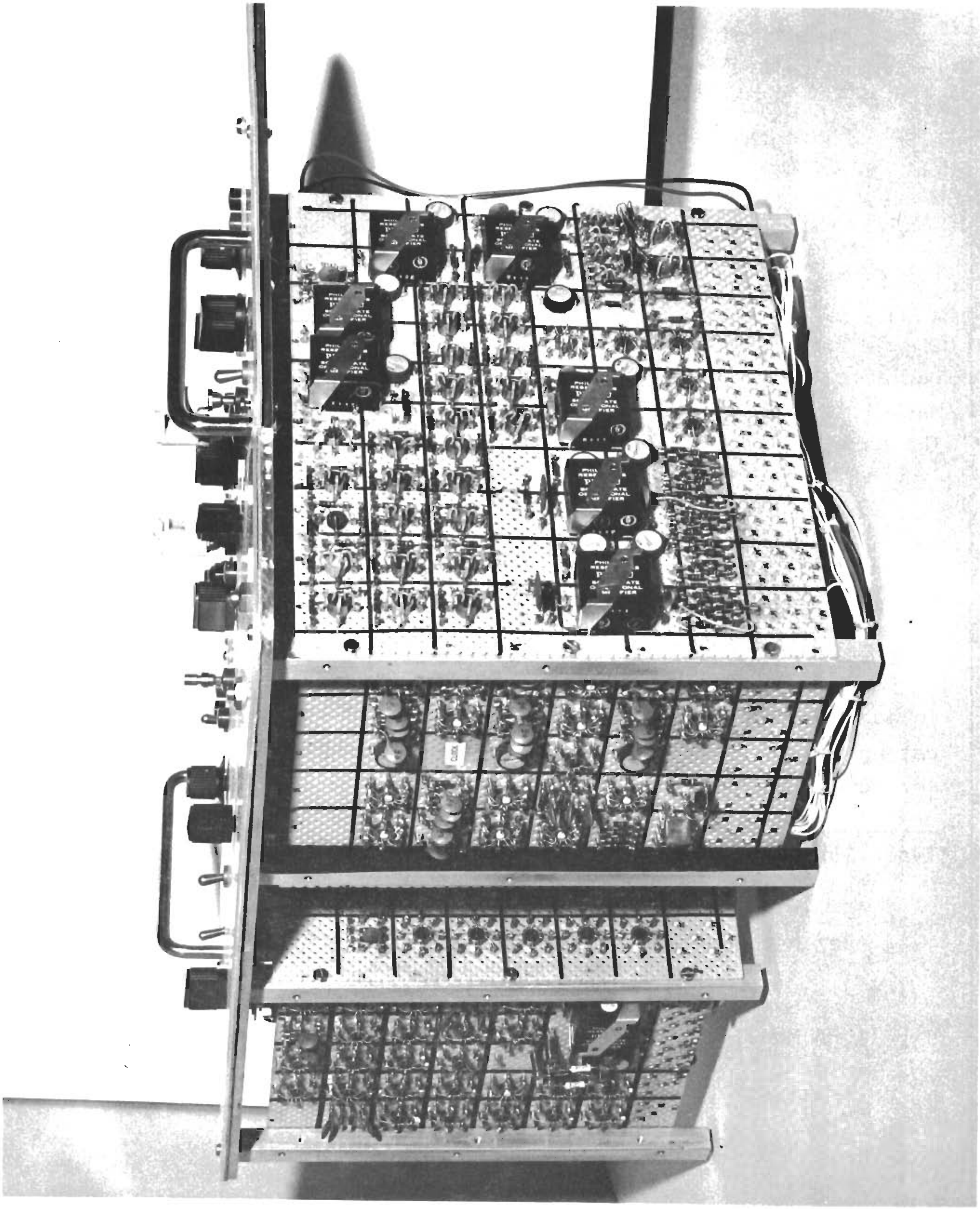

Figure 1.4: Interior of Mark I Self-Organizing Controller and Simulated Satellite

Results of Mark I experiments are presented and discussed in Reference 2.

Photographs of the Mark I system are shown in Figures 1.2, 1.3, and 1.4.

### 1.3.2 Mark II Self-Organizing Controller

Using performance assessment (PA) and probability state variable (PSV) circuits proven in the Mark I evaluations, a Mark II system incorporating five PSV units was constructed. The Mark II system consists of the following elements:*

4 each PSV Modules - Type 1507

1 each PSV Module - Type 0307

1 each PA Module - Type 1

1 each PA Module - experimental (see Appendix C)

In addition, Mark II contains a circuit card providing special gating and threshold logic associated with the simulation of jet actuation.

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| | |
|---|---|
| *Type 1507 PSV Module: | incremental PSV module having 15-level K register and 7-level P register (see Section 3.2). |
| Type 0307 PSV Module: | incremental PSV module having 3-level K register and 7-level P register (see Section 3.2). |
| Type 1 PA Module: | PA module which computes (see Section 3.1) |

$$\overline{rp} = -\text{sgn } e_p \text{ sgn } \ddot{e}_p$$

For evaluation of the Mark II system, the dynamics of representative actuator, sensor, and vehicle combinations were simulated on the EAI 231-R analog computer at the Control Techniques Simulator Facility, Wright-Patterson Air Force Base, Ohio. This simulation provided great latitude in parameter variations and included an on-off reaction-jet system in addition to the momentum wheel shown in Figure 1.1. Pertinent aspects of this analog simulation program are described in Reference 1 and summarized in Appendix B.

Photographs of the Mark II Self-Organizing Controller are shown in Figures 1.5, 1.6, and 1.7.

## 1.4 Application Criteria

Major design criteria evolved in the course of the program may be summarized as follows:

(1) Self Organizing Subsystem Design

The performance assessment criterion and PSV logic as mechanized in this program are of sufficiently wide versatility to be applicable to a broad class of spacecraft attitude control problems. In this program they provided satisfactory performance for a plant gain range of greater than 9,000:1, with a change of one design variable (prediction interval, T) over a range of only 8:1. For fixed SOC parameters, performance was found to be uniform* over a plant gain range of approximately 25:1 and a plant time-constant range of 5:1, while satisfactory performance was obtained over gain and time-constant

*By "uniform" is meant "invariant in transient response shape" (i.e., free from overshoot, etc.) but not "invariant in transient response rise time". Rise time varied inversely with plant gain.

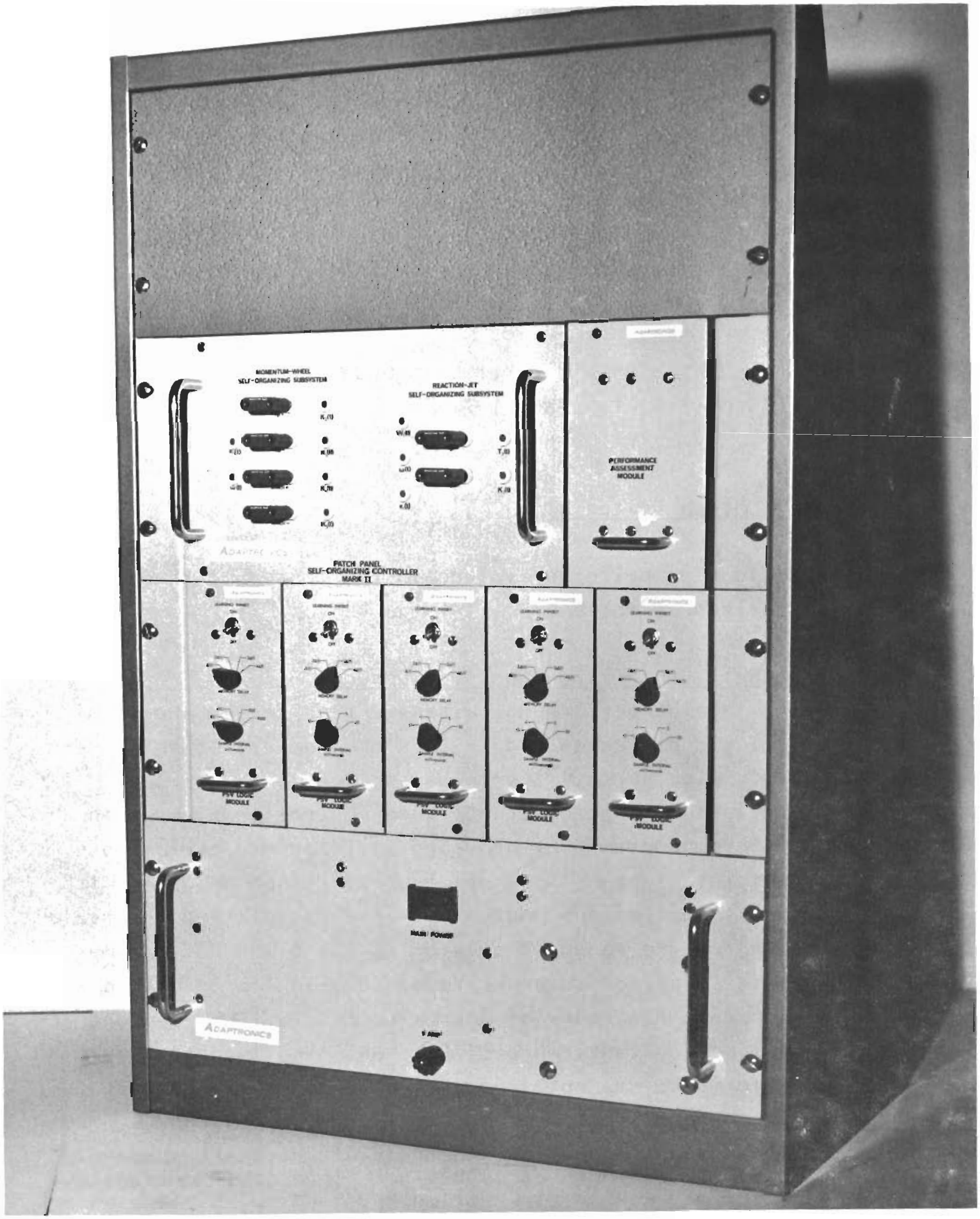


Figure 1.5: Front Panel of Mark II Self-Organizing Controller

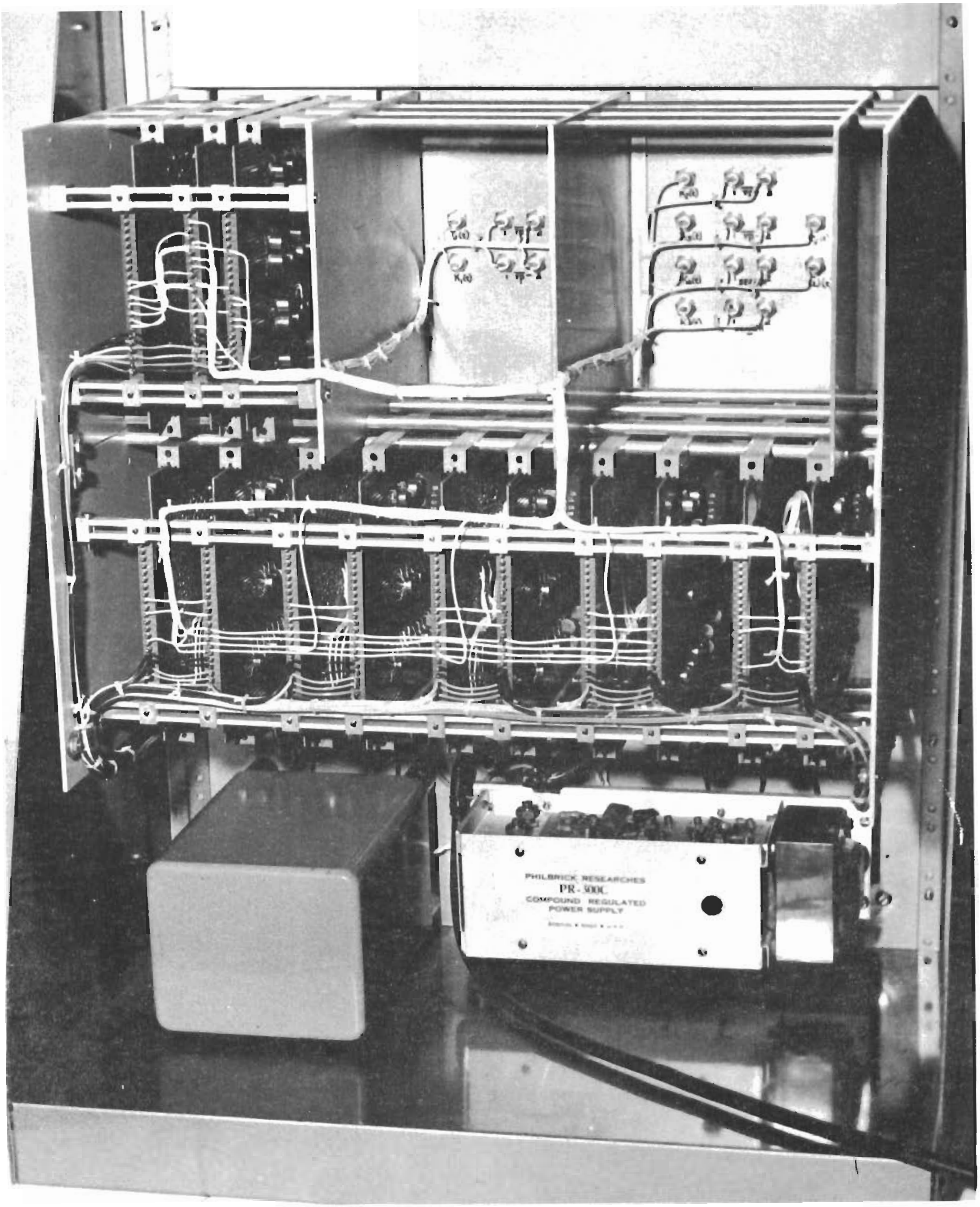


Figure 1.6: Interior of Mark II Self-Organizing Controller (Rear View, Facing Forward)

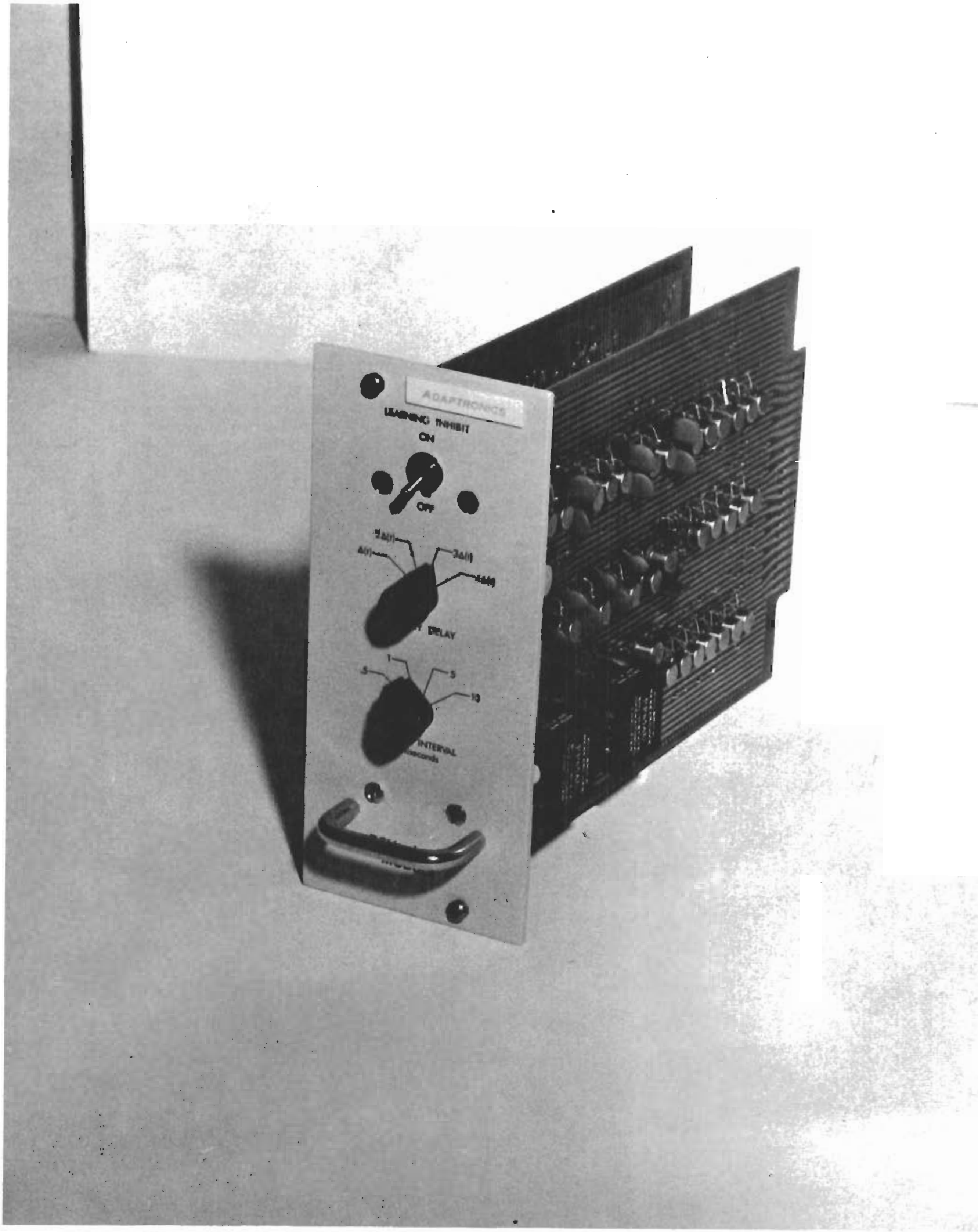


Figure 1.7: Typical Probability State Variable Module
(One of Five from Mark II System)

ranges several times larger than the ranges for uniform performance.

(2) Self Adaptation Range

To obtain maximum adaptation range, design of the SOC would be based on the minimum anticipated plant capabilities, e.g., minimum plant gain and maximum lags associated with torque application. Having been designed for minimum acceptable transient and steady-state performance characteristics for the worst case (viz., minimum plant capability), increased plant capability will lead to improved performance. Alternately, design can be based on the median plant parameter values so as to give more uniform performance in a somewhat reduced but most probable range of plant parameter variation.

(3) Modes of Operation

The basic mode of system operation would utilize the SOC in a control computer capacity, i.e., to learn directly the actuator excitation signals. However, two supplementary modes may be of interest for some applications.

In the additive mode the output of the SOC is added to the error signal (with or without a compensation network in the latter path) and the sum used as actuator excitation. Performance in this mode is not significantly different from the control computer mode; however, the parallel functional paths may offer a reliability advantage.

In the gain multiplication mode the SOC learns a time-varying gain applied to the error signal (with or without a compensation network). Additional (multiplication) hardware is required to implement this mode, yet performance is usually inferior to the control computer or additive modes because at small error values SOC influence is correspondingly reduced.

(4) System Configuration Aspects

Although this program was carried out within the context of single-axis control, a generalization of demonstrated SOC capabilities leads to the conclusion that the conventional procedure of separating a control problem into its single-axis requirements may well be superfluous. Specifically, it is felt that, much in the same way as the SOC now distributes the required excitation signal among multiple PSV units used in its mechanization, the SOC should be permitted similarly to distribute the required control task among a multiple number of actuators with respect to an undivided control objective. This approach can be expected to lead to significant performance and reliability advantages at the control system level.

Detailed design criteria are discussed in the body of this report.

# 2. SELF-ORGANIZING CONTROL: AN INTRODUCTION

Self-organizing control is characterized by the fact that autonomous on-line modification of the control law is accomplished by the use of logic which is independent of a priori knowledge (either in design or operation) of the functional relationship between the actuator and plant inputs and their outputs. Inherent in this characteristic is freedom from a need for explicit mathematical representation of control loop elements and their interaction as a system with the environment. Such freedom becomes more and more desirable as aerospace control requirements become increasingly demanding and as the actuator and plant, through which the controller is expected to yield essentially uniform system performance, become more complex and unpredictable (Ref. 3). In addition, self-organizing control can ultimately lead to increased system reliability, since a large class of controller component failures and actuator malfunctions can be placed in the category of a changing plant, against which adaptation is to be achieved.

## 2.1 General Considerations

Although the ultimate objective in the development of self-organization techniques may be to duplicate the full range of human intelligence capabilities, current emphasis, and certainly present attempts at practical applications, are restricted to learning techniques. Even in this limited aspect of artificial intelligence a further division is necessary. Thus, a distinction must be made between the process of learning and the long-term retention and reuse of results from past learning activities. To implement a meaningful retention and reuse capacity with present instrumentation capabilities has not appeared to be a practical undertaking for flight control systems, whereas the aspect of learning which offers economical mechanization at present is that of the learning process itself.

Based upon our current knowledge, learning is synonymous with self-organization, i.e., the learning goal is taken to have been achieved when the elements of the learning system have organized themselves to produce an output conforming to the specified goal.* A self-organizing control system may contain one or more learning subsystems and these may be arranged to serve a variety of purposes in performing the control function. Thus, a self-organizing control system can be configured so as to learn the control law, or it can employ an explicit control law, using learning to alter the values of parameters within this law.

Self-organizing control systems can properly be viewed as a sub-class of self-adaptive control systems; however, the latter term has, by common usage, become associated with particular types of adaptive system, i.e., the various model-reference systems, high-gain techniques, and error switching techniques evolved in the past decade. Nevertheless, the purpose of self-organization is to provide better adaptation, the distinguishing characteristic of self-organizing control systems being in the manner in which the adaptation is accomplished. Thus, a self-organizing adaptive control system can be defined as one which utilizes learning to carry out the adaptation process. However, for this definition to have meaning, one must also provide a usable definition of "learning".

Thus, within the context of the control problem, adaptation signifies change in the control law which determines the relationship between controller action and controller inputs.

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*In this context, self-organization need not involve autonomous structuring of system elements. Self-organization may consist of changes in the content of registers, provided these changes alter the input-output transformation produced by the system.

In the same context, learning can be defined as a process for instituting control law changes utilizing logic for this purpose which is independent of a priori knowledge, either in design or operation, of the functional relationship between the controlled plant inputs and outputs. (This is an operational definition of learning which is not intended to be all inclusive.)

To facilitate description of its functional elements, a self-organizing system will be referred to as a learning system, i.e., the process of self-organization is considered to be a learning process. As such, one associates with it: (1) a goal circuit (performance assessment logic), which is a means for evaluation of current performance; (2) conditioning logic for computing and effecting suitable changes of the controller parameters and/or output signals; and (3) a memory for storing information concerning past parameter states (Ref. 4). The principal characteristic of the operation of these functional elements is the closed-loop nature of the system, viz., a change in internal parameters is fed back through the (unknown) plant and environment to the performance assessment logic to permit correlation between change and over-all effect: a comparison must be made between current performance relative to stored information regarding recent parameter experiments. This is applicable to learning systems in general, but it is evident that in control system applications the problem is compounded by the fact that the latter are also systems with input, response, and disturbance functions undergoing rapid and abrupt changes. On-line learning in a self-organizing control system must, therefore, exhibit very rapid convergence to appropriate (time-varying) parameter and/or signal levels.

High-speed on-line learning eliminates requirements for both large memory capacity in the controller and pre-training. With fast learning, the controller will cope rapidly with unforeseen environmental and plant changes.

## 2.2 Functional Elements of Learning Systems

A learning system performs continuous or periodic assessments of its own behavior and, by relating these assessments to its past experimentation (experience), alters (adapts) its characteristics so as to increase the likelihood that its future behavior will be brought into or will remain in accordance with its criteria of desirable behavior. A learning system therefore contains the following functional entities in addition to those elements usually found in conventional systems:

(1) Performance Assessment Logic -- a means for assessment of the system behavior in terms of a criterion or criteria of desirable behavior. In general, the performance assessment requires processing of patterns present in the controller input information and comparison of these patterns with an appropriate standard. However, the comparison need not be explicit.

(2) Memory -- a means for storing information concerning past experiments. The memory can take the form of explicit arithmetic data or of implicit probability distributions.

(3) Conditioning Logic -- a means for computing and effecting suitable experiments, i.e., alterations of the system characteristics. The conditioning logic implements the strategy of learning.

These functional entities, taken in combination, constitute what may be called the conditioning subsystem. The conditioning subsystem generates changes to parameter or signal values within the performance subsystem, the latter usually consisting of the more conventional system functions.

Figure 2.1 illustrates the relationships between conditioning and performance subsystems in a learning system. The performance assessment function shown in the figure has been referred to historically as a "goal circuit". The conditioning logic/memory/performance subsystem combination is often viewed in the form of a generalized network of trainable devices.*

The equation

$$y = f(s, x, y, z)$$

where x and y are the input and output vectors, respectively, and z is a vector comprised of measures of plant and environment parameters, emphasizes the basic characteristic of trainable devices; viz, outputs are a function of a (variable) state, s.

Figure 2.1 justifies the restricted definition of learning previously used in the control system context. Thus, conditioning subsystem will generally require measures of x, y, and z to generate changes in the performance subsystem state, i.e., to change the control law by changing s. However, to qualify as a learning system process, the conditioning must not require _a priori_ knowledge of either the form or numerical characteristics of f(s, x, y, z). Furthermore, this independence of _a priori_ information must apply both to the operation and the design of the performance assessment and conditioning logics.

In SOC applications, the performance assessment logic computes three discrete performance values (denoted by $\overline{rp}$): +1 for reward (or positive reinforcement), -1 for punishment (or negative reinforcement), and 0 for zero reinforcement. The

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*Extremely simple networks have sufficed for the self-organizing control system applications considered to date. It is recognized, however, that only relatively elementary SOC applications have thus far been treated.

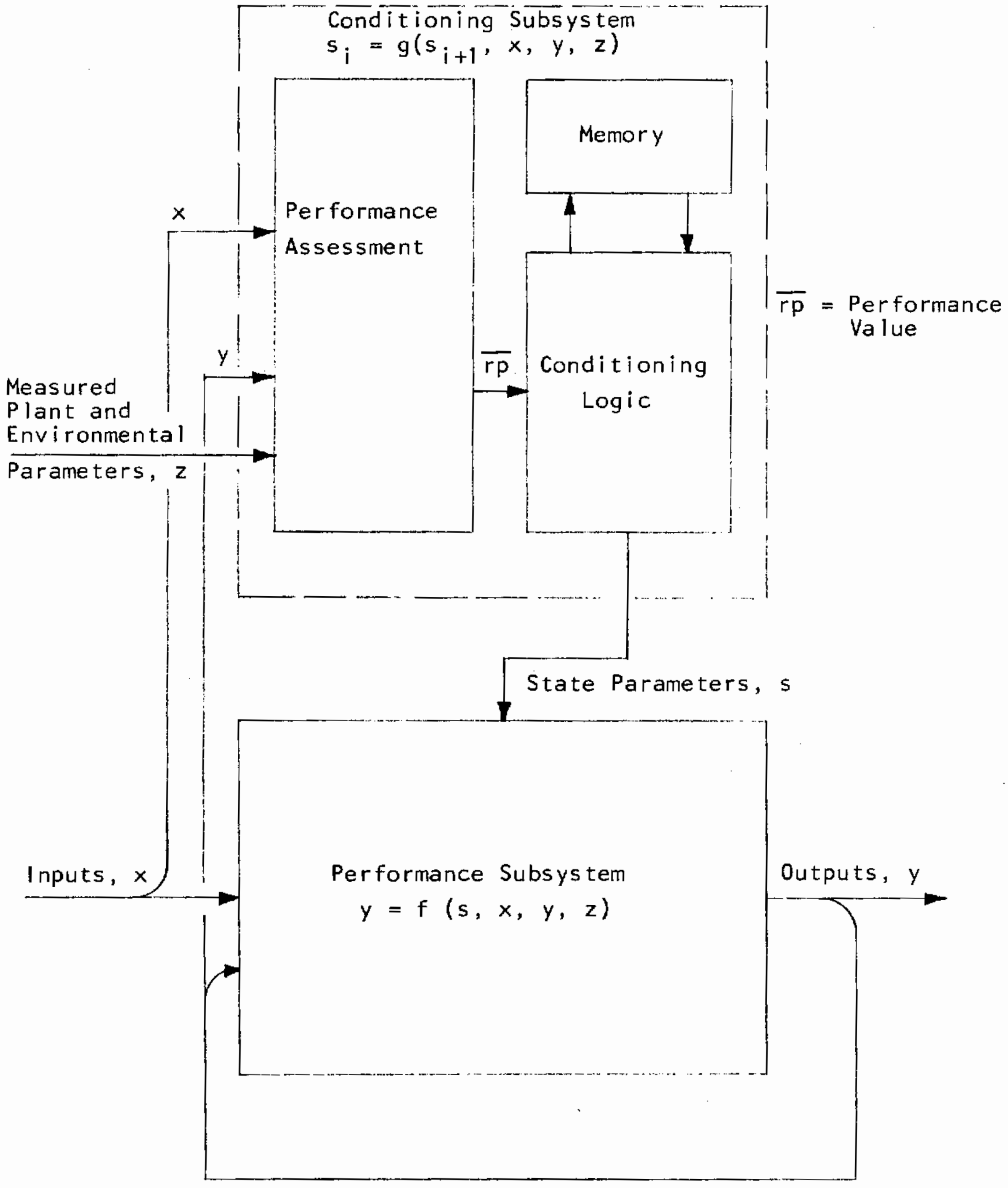



Figure 2.1: Functional Diagram of Learning System

performance assessment criteria are, of necessity, problem specific. Selection of the criterion for a specific requirement is a critical area in learning system design, since it requires formalizing the requirements on system performance. However, certain basic principles are emerging from investigations in this area, as discussed more fully in Section 3.1.

The conditioning logic mechanizes the strategy of learning. Strategies of learning usually embody a form of parameter space search, often likened to hill climbing. However, to be of practical utility in learning applications for dynamic processes, the hill climbing must be performed within a time-varying environment and often in a multi-parameter environment. The basic requirements are: (i) high speed of search, (ii) provision for the probable degradation of information by noise, and (iii) simplicity of mechanization despite multiple parameters. In addition, these systems are sometimes required to perform a search involving multi-modal (multiple-hill) performance response surfaces.

Since conventional hill-climbing techniques (gradient methods of steepest ascent and descent) generally do not satisfactorily meet all of the above requirements, new search strategies have been evolved. One of these strategies relates to a small number of parameters (in the order of ten) in a rapidly time-varying environment, while the other strategy is intended for a large number of parameters (in the order of several hundred) in a relatively static environment. The latter strategy, termed the Random State Variable (RSV) strategy (Ref. 4), has proven very useful in parameter identification processes. The former, termed the Probability State Variable (PSV) strategy (Ref. 4) is fundamental to self-organizing control.

As a PSV system learns, changes occur in probability distributions associated with the values of internal parameters.

PSV These changes are the result of actions on the environment of successive random trials, where each new trial is generated relative to parameter values produced by the trial immediately preceding. The outcome of each trial is evaluated in terms of the performance assessment criterion, and the statistics of future trials (the probability distributions) are biased so as to reinforce desirable performance trends. Thus, new trials are based on accumulated evidence concerning the present or predicted results of previous actions.

An incremental type of PSV strategy has been developed with particular reference to control system applications. With the incremental strategy, the system learns the rates of change of internal parameter values. The advantages of the incremental PSV strategy over PSV algorithms previously used are:

(1) The self-organizing system experiments with a changed internal parameter set at each successive sample instant, thereby maximizing rate of information return and minimizing convergence time.

(2) The magnitude of each parameter change is fixed, providing important hardware simplifications, yet the system remains capable of performing multimodal searches (probability of change in a prescribed direction can never equal either zero or unity).

Generally speaking, the PSV strategy is found to provide convergence times sufficiently small to permit the compensation of dynamic environments and time-varying plants without major restrictions. This is partly because, with prediction, the periodic performance assessments can be made over intervals of time which are a small fraction of the transient response time. To take full advantage of high learning speed, the performance criterion should therefore be designed to shape the transient response in an optimum manner.

$10^5$ slower

Both "predictive" and "historical" performance assessment criteria can be used in self-organizing control system synthesis. The former class of criteria is applicable whenever actuator and plant operation are sufficiently continuous to permit prediction of response trends by the usual extrapolation procedures. When usable, predictive criteria yield very fast learning: the organization time may be as little as one ten-thousandth of the dominant plant time constant. By way of comparison, historical (smoothed) measures of performance require an organization period equal to approximately ten times the dominant plant time constant, i.e., learning is as much as $10^5$ times slower than with the predictive criteria. Other drawbacks of historical performance measures are their usual reliance on repeated identical system inputs, their increased memory requirements, and difficulties in achieving successful organization when plant dynamics are changing very rapidly.*

## 2.3 Definition

A number of investigations related to SOC techniques are in progress elsewhere in this country and in the U.S.S.R. In a review of a number of papers published during 1963, Ref. 7 presented the following summary concerning the topic "Adaptive and Self-Optimizing Control":

> In the adaptive literature the stress is on the direct identification of unknown parameters. In the self-optimizing (optimization, extremal control, automatic optimization) literature the stress is on search techniques (methods of steepest descent, etc.) for an experimental determination of an optimal, but unknown,

*Gibson et al.(Ref. 5) base learning on a sequence of identical trials and even use this as an operational definition of control system learning. The authors tested the idea of identical trials in an earlier program (Ref. 6), but presently downgrade this approach for the reasons given above.

operating point. The former point of view dominates the American literature while the latter point of view dominates the Soviet literature.

Suitable performance assessment techniques, coupled with the incremental PSV search strategy, can provide experimental determination not only of an optimal operating point but also of unknown optimal paths or loci traced by an operating point which, in general, moves rapidly and often discontinuously within the pertinent parameter or signal space. To sharpen the semantics of future work in this field, the authors wish to suggest the following operational definition of "self-organizing control". This definition is predicated on the apparently unique realization of optimal path searches available with this type of control.

Self-organizing control is a form of adaptive control which provides experimental determination of unknown optimal paths as traced by the system operating point moving rapidly within the parameter or signal space relevant to organization.

In this context, the operating point is defined by the control state vector, i.e., the state of the various signals applied to the plant. Optimal paths achieve this property in relation to criteria embodied in the performance assessment function(s). However, these criteria do not contain explicit formulations of desired paths and the latter are therefore termed unknown. Experimental determination emphasizes the absence of explicit mathematical and detailed quantitative formulations of the plant input-output relationships. In defining self-organizing control as a form of adaptive control attention is focused on the fact that adaptive features need not be explicitly mechanized in the performance assessment criteria. This is predicated upon the observed ability of self-organizing control to provide desired transient and steady-state performance that is largely invariant over wide ranges of plant parameters.

# 3. SOC DESIGN AND MECHANIZATION

This section presents the design approach and mechanization employed for the Mark I and Mark II self-organizing controllers.

## 3.1 Performance Assessment

### 3.1.1 PA Design Approach

On-line processes in self-organizing control require that, unlike conventional design procedures, the desired performance characteristics be made a part of the performance assessment criterion. The criterion must therefore:

(1) lead to a steady-state in which the error and error-rate are simultaneously zero ? second order system ?

(2) provide for stable convergence toward the steady-state

(3) incorporate desired control qualities, e.g., shape the convergence process over and above stability considerations.

Control quality requires consideration of two distinct regions of operation. Thus, in terms of response to a disturbance, the initial phase of returning to the desired equilibrium state should, in general, call for a high degree of utilization of available control capabilities. During the terminal phase, however, emphasis changes to shaping attitude response so as to prevent large overshoots and/or oscillatory convergence to

$e = \dot{e} = 0$. The criterion to be described here distinguishes between the above requirements and provides a means for adjusting their relative effects on performance. This criterion is most conveniently described in terms of extensions of the concepts of Lyapunov's Direct Method (Refs. 8 and 9) for stability analysis.

In general, Lyapunov's Direct Method requires that for a system to have a stable equilibrium state, some scalar function, $V$, of its variables must be positive definite while $\dot{V}$ must be negative definite. The trivial solution, $V = 0$, is then asymptotically stable in the sense that the state vector will converge toward the trivial solution as $t \rightarrow \infty$. For the control problem considered here, if the basic variables are $e$ and $\dot{e}$, and $V = f(e, \dot{e})$, the trivial solution, and hence the equilibrium state for which asymptotic stability is sought, corresponds to $e$ and $\dot{e}$ becoming zero simultaneously. This is, of course, a general statement of the control problem. A geometric interpretation of the above would consist of a plot of the surface defined by $V = f(e, \dot{e})$. Because of the conditions imposed on $V$ and $\dot{V}$, this surface is in the form of a cup which is always above the $e$, $\dot{e}$ plane, touching it only at the origin which, in this case, represents the desired equilibrium state $e = \dot{e} = 0$.

Since the definition of $V$ is at the designer's discretion, it can be chosen to be positive definite. Thus, one possibility might be to mechanize $\dot{V}$ in the performance assessment unit and generate the reinforcement signal $\overline{rp}$, on the basis of the sign of $\dot{V}$, viz.

$$\dot{V} \underset{->}{\overset{<+}{}} 0 \qquad \text{3:1}$$

Where <+ 0 signifies a reward (positive reinforcement) when $\dot{V}$ is negative. This criterion would seek stable convergence; however, it does not go far enough, since it says nothing about the desired quality of control, i.e., no requirements are imposed on the manner in which the equilibrium state is to be approached. An improvement on the above is obtained by basing the performance assessment criterion on $\ddot{V}$, requiring that it be negative, viz.

$$\ddot{V} \; \substack{<+ \\ ->} \; 0 \quad \ldots\ldots\ldots\ldots \quad 3:2$$

Equation 3:2 achieves two objectives. First, if $\dot{V}$ is positive, the organization process will be directed to make $\dot{V}$ negative, so as to assure stable convergence. Second, because V may be viewed as a measure of the "distance" from the desired state (Ref. 10), the requirement $\ddot{V} < 0$ leads to optimizing the rate with which this distance is reduced, i.e., the system strives to accelerate convergence toward the equilibrium state.

Recalling that accelerated "motion" to the phase plane origin is desirable only during the initial phase of response, the function V is chosen to be

$$V = |e + T\dot{e}| \quad \ldots\ldots\ldots\ldots \quad 3:3$$

where T is a design constant, to be referred to as the prediction interval. Equation 3:3 does not comply with the general requirements for a Lyapunov function, since it is not positive definite, i.e., $e + T\dot{e} = 0$ is a line in the phase plane passing through the origin. This, however, is the desired form, since anywhere on the line the solution of $e = -T\dot{e}$ yields

$$e = e(0) \exp(-t/T) \quad \ldots\ldots\ldots\ldots \quad 3:4$$

where e(0) is the initial attitude error and t denotes time. Thus, once on the line given by $e + T\dot{e} = 0$, system error convergence tends to take place exponentially and T may be viewed as the nominal time constant for the terminal region of response.

In summary, the performance assessment criterion may be based on the second derivative of V as defined by Equation 3:3, and since only sign information is sought in simpler self-organization processes, this yields

$$-\overline{rp} = \text{sgn}\ \ddot{V} = \text{sgn}\ e_p\ \text{sgn}\ \ddot{e}_p \overset{<+}{->} 0 \quad \ldots\ldots\ldots\ldots\ 3{:}5$$

where

$$e_p = e + T\dot{e} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 3{:}6$$

$$V = |e_p| \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 3{:}7$$

The criterion of Equation 3:7 will call for accelerated convergence to the $e = -T\dot{e}$ line and constrained (exponential) convergence along this line to the origin. This is illustrated in Figure 3.1, where the surface defined by Equation 3:3 now takes the form of a trough touching the phase plane along the $e = -T\dot{e}$ line.

The above approach has proven satisfactory for systems which exhibit sufficient continuity to validate the process of tangential extrapolation used to compute $e_p$ and $\ddot{e}_p$. Inertia-wheel control loops, treated either individually or as parts of hybrid-actuator systems, are organized successfully using Equation 3:5. Performance assessment within an on-off control loop, however, usually cannot be performed adequately via Equation 3:5. An approach to performance assessment design for such cases is discussed in Appendix C.

### 3.1.2 PA Mechanization

The specific performance assessment relationship mechanized in the engineering models may be written as

$$\overline{rp} = -\text{sgn}\ e_p\ \text{sgn}\ \ddot{e}_p \quad \ldots\ldots\ldots\ldots\ldots\ldots\ 3{:}8$$

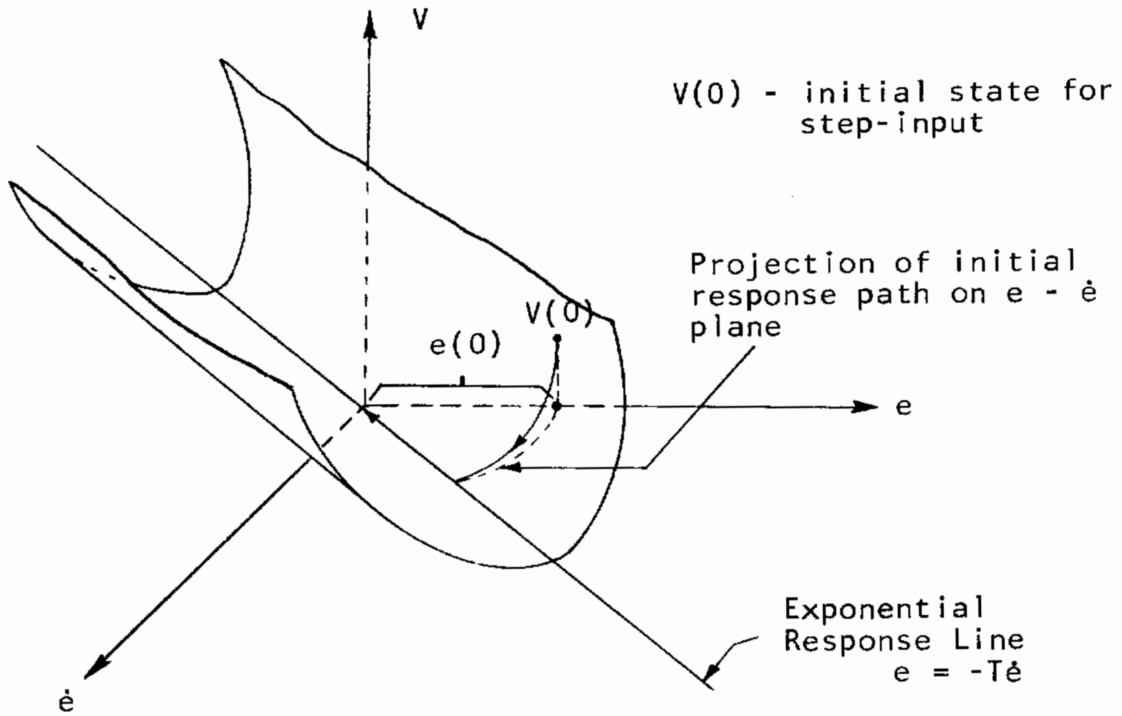



Figure 3.1: Performance Criterion Geometry

The computation of this function is separated into three parts: the analog computation of $e_p$ and $\ddot{e}_p$, the determination of the algebraic sign of these functions, and the logical multiplication of the two signs. A block diagram of the hardware implementation of the performance assessment is shown in Figure 3.2.

The computation of $\ddot{e}_p$, where

$$\ddot{e}_p = \ddot{e} + T\dddot{e} \quad \ldots\ldots\ldots\ldots \quad 3{:}9$$

presented the usual problems inherent in analog differentiation, particularly aggravated by the requirement for a third derivative. There are a variety of approaches to analog differentiation, all of them depending upon the technique of band-limiting the differentiator such that the derivative is accurate only up to a certain cutoff frequency, $f_c$, above which the circuit response either flattens out or falls at -6 db per octave, depending on the order of the band-limiting. This effect is shown in Figure 3.3(a), and the circuit chosen for differentiation is shown in simplified form in Figure 3.3(b). This circuit employs second-order limiting above $f_c$. In the SOC, the frequencies of interest in $\ddot{e}_p$ are the result of the PSV unit K-register activity which falls primarily into the 10 cps to 100 cps frequency range. Limiting has been applied above this range, and the resultant computation of $\ddot{e}_p$ proves satisfactory.

The threshold-detection process and logical multiplication are implemented using straightforward level-detection and logic techniques. A "dead band" is used in determination of sgn $\ddot{e}_p$ to reduce noise susceptibility, resulting in a three-valued output from the sgn $\ddot{e}_p$ threshold circuit. This introduces the possibility of a zero $\overline{rp}$; controller action under this condition is discussed in Section 3.2.

The circuitry used in mechanization of the performance assessment unit consists of inexpensive computing amplifiers for

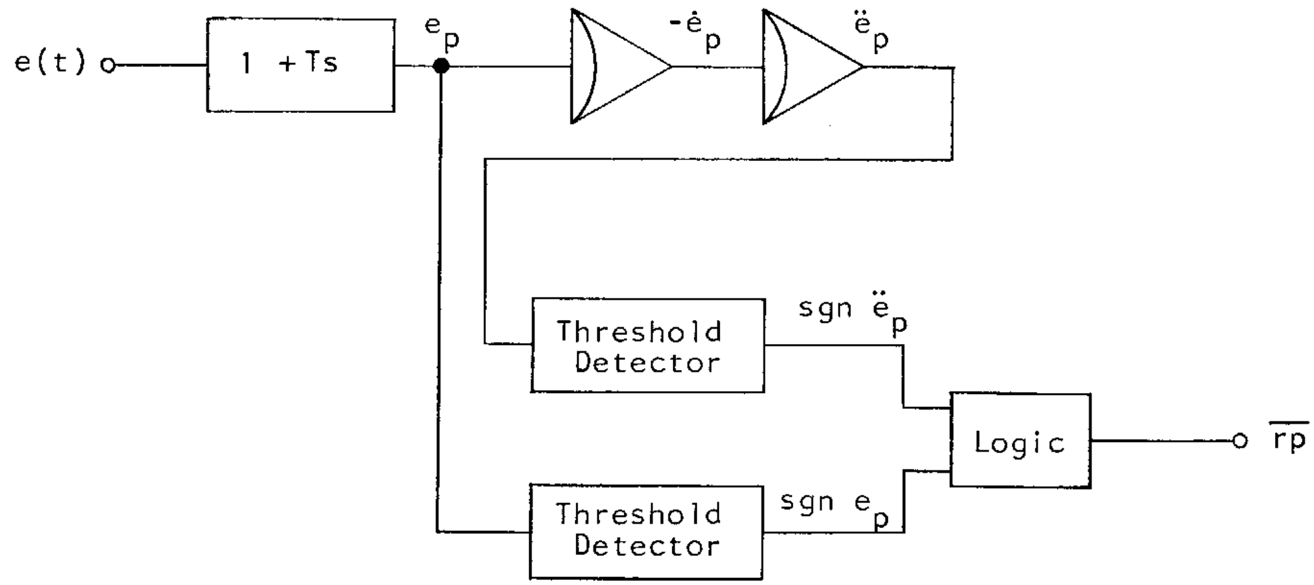



Figure 3.2: Block Diagram, Performance Assessment Mechanization

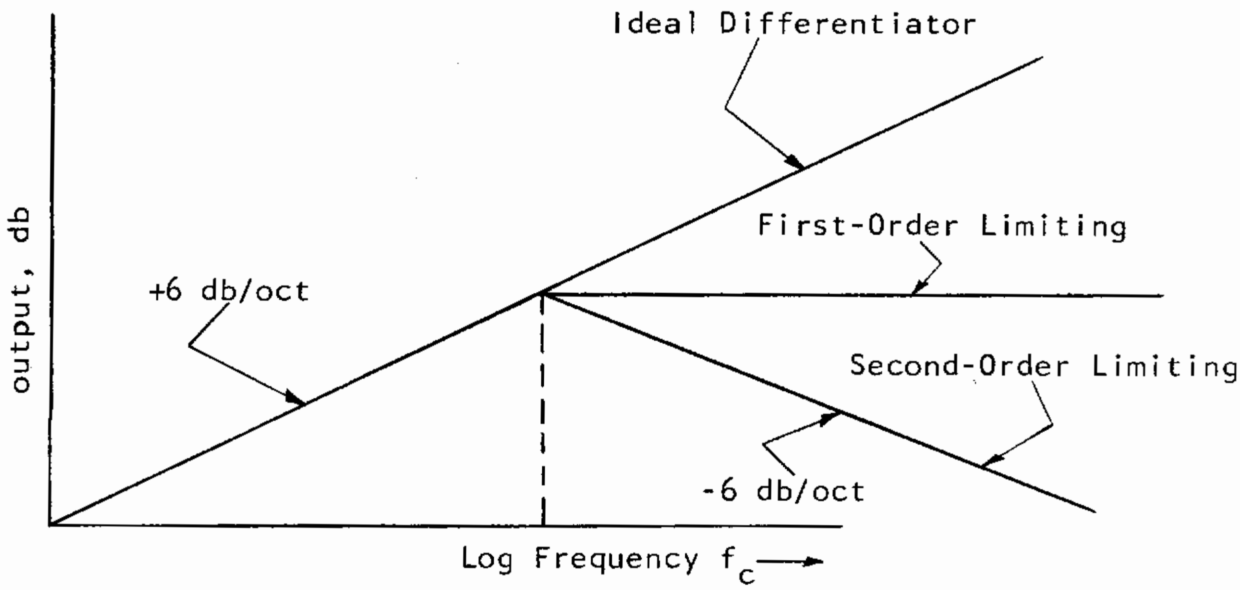



Figure 3.3(a):Differentiator Responses

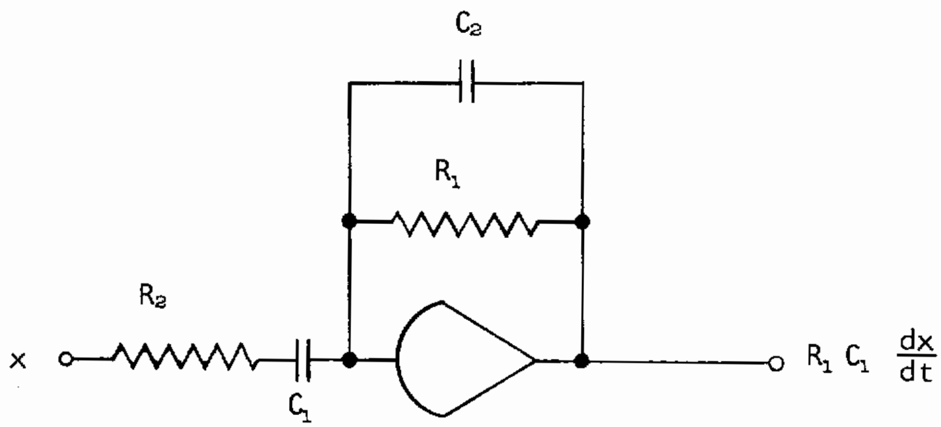



Figure 3.3(b):Practical Differentiator

the analog section and silicon monolithic micrologic for the digital circuitry.

### 3.1.3 Summary Remarks

Because of its general applicability to control of continuous and quasi-continuous plants, the performance assessment unit described above is termed the Type 1 PA Module. With the Type 1 PA, it is not necessary, in general, to have a priori information regarding the polarity of actuator elements in the plant. This is because all inputs to the Type 1 PA are obtained from system sensors, and no underlying assumptions as to plant polarity are made. The ability of the Type 1 PA to adapt to plant polarity reversals, which adaptation is virtually instantaneous, can be sacrificed (on a design trade-off basis) in favor of extremely high SOC performance assessment sampling frequencies to achieve equally rapid experiment generation and resulting very high-speed convergence of the learned quantities. This option is discussed further, taking a systems viewpoint, in Section 3.3.

## 3.2 PSV Conditioning Logic

### 3.2.1 PSV Approach

The probability state variable concept, originated by R. J. Lee in the 1950's (see discussion in Ref. 3) has been applied to adaptive control in the form of both analog transfer function learning (Ref. 6) and Boolean logic learning (Refs. 6 and 11). The PSV strategy of learning employed in Ref. 6 was modified, however, during the present program to achieve faster convergence and simplifications in the hardware.

The experimental processes in a self-organizing control system must exhibit rapid convergence to appropriate time-varying parameter and/or signal levels. To achieve this rapid convergence, it is desirable to use extremely fast performance assessment sampling and conditioning logic experiment generation.*

The general functions to be performed by the conditioning logic section of the self-organizing controller are:

(1) to make experimental changes in its own output state

(2) to retain a record, or memory, of recent output state changes

(3) to associate the contents of its memory with a performance assessment signal, $\overline{rp}$ (for reward-punishment), and consequently increase the probability of making future output state changes producing desirable results.

Consideration of the functions listed above leads to a subdivision of the PSV logic into three functional sections. The first of these sections is a source of experimentation having controllable statistics, the second is a means for storing the results of previous experiments, and the third is a means for logically combining the memory contents with the $\overline{rp}$ signal so as to obtain a valid correlation between cause and effect.

With an incremental PSV strategy, the output state variable,* here denoted K(t), is periodically incremented one step either up or down from its prior-existing level. The step size, $\Delta K$, is predetermined, and the time interval between state changes,

*As shown in Section 4, good results are achieved with SOC sampling frequencies as high as $10^4$ and $10^5$ times the natural frequency of the closed-loop system (natural frequency calculated for a nominal, constant-gain controller).

* System control input

termed $\Delta t$, is fixed. The direction of incrementation of K(t) is probabilistic, and is determined by the instantaneous state of a statistical source, which generates a random binary sequence having a duty cycle, or probability of being in one state, which is continuously controllable. The control of the statistics of the source is exerted by a variable, termed p(t), which is integral to the PSV logic. This variable is also incremental and, like K(t), can be incremented one step per $\Delta t$, although, unlike K(t), p(t) need not be incremented every $\Delta t$. The direction of incrementation of p(t) is not probabilistic, however, but is determined by the memory state (sgn $\Delta K$) and the instantaneous value of $\overline{rp}$. Thus, the combination of cause (as reflected in the memory state) and effect ($\overline{rp}$) acts, by incrementing p(t), to change the probability associated with a particular direction of change of K(t), and, in particular, acts to increase the probability that K(t) will change in a direction that will produce a positive $\overline{rp}$. A diagram showing the interrelationship of these basic functions is shown in Figure 3.4.

Within the framework of basic functions described above, detailed design studies, placing particular emphasis on digital computer simulation, have been conducted to determine the specific characteristics of each function that best satisfy the requirements of the spacecraft attitude control problem. Design parameters determined included:

(1) number of incremental levels and maximum limits for for K(t)

(2) number of incremental levels and maximum limits for p(t)

(3) transfer function of statistical source output statistics versus the p(t) control voltage

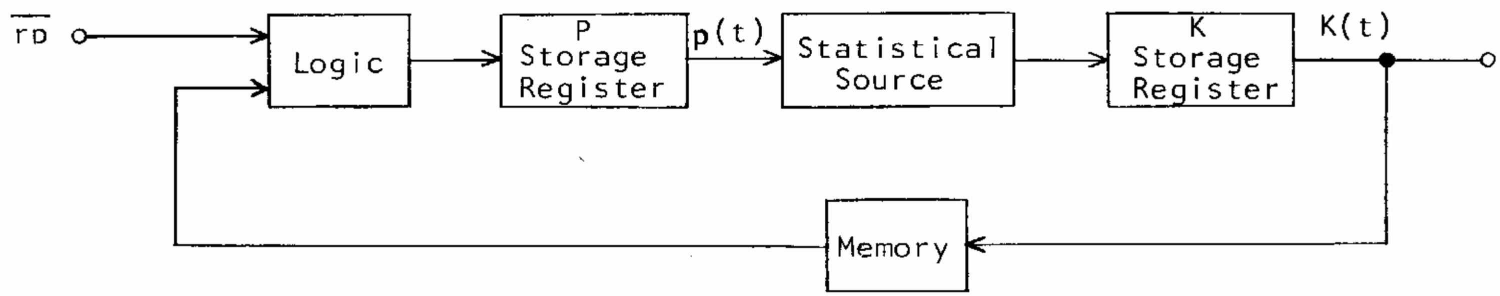



Figure 3.4: Basic Diagram, PSV Conditioning Logic

(4) required memory characteristics and memory length

(5) basic system clock rate

A discussion of the design process for the PSV system begins most logically with a consideration of the transfer function of the statistical source. Although it has been observed that the control system as a whole is relatively insensitive to the quantitative shape of this transfer function, its qualitative aspects are of considerable importance.

p(t) is a variable which is permitted to assume a fixed number of discrete values, and which may, but need not, step one increment up or down at time intervals of $\Delta t$. Associated with each value of p(t) is a specific probability that the statistical source output random binary sequence will be a zero or a one. A value of p(t) at the midpoint of its range corresponds to a probability of 50% that the source output will be a one or a zero. An excursion of p(t) away from its midpoint will increase the probability of a one (e.g.), while an excursion in the other direction will increase the probability of a zero. Qualitatively, an important consideration in selection of the statistical source transfer function is that minimum and maximum attainable values of the p(t) input voltage produce output duty cycles (output statistics) different from the limiting cases of 0% and 100% duty cycle associated with alternative outputs from the source. In brief, the source must never be driven into a deterministic mode of operation. Furthermore, between the actual output duty cycle limits, nominally set at 5% and 95%, a smooth variation of output statistics with input voltage is desirable.

Reference 4, pp. 223-246, presents detailed design, mechanization, and performance data for a statistical source identical to the type employed in the Mark I and Mark II PSV units.

Considering K(t), it is seen that a p(t) value at midpoint results in equal probability of a positive or negative increment, while an excursion of p(t) away from its midpoint results in increased or decreased probability associated with a given sign of $\Delta K$, the question of increase vs. decrease being determined by logical convention. Another way of stating this relationship is to say that K(t) will probably step in a direction determined by the algebraic sign of p(t) (assuming a zero midpoint), with this probability increasing as p(t) moves farther from its midpoint.

The remaining functions within the PSV conditioning logic are the memory and the correlation network. The latter consists of gating, by means of which the memory contents are associated with $\overline{rp}$ information received from the performance assessment unit. The approach taken for this part of the synthesis task was to proceed on the basis that the incremental (on the average) performance assessment has validity, that is, that the individual effect of a recent $\Delta K$ whether positive or negative has been correctly discerned by the performance assessment in its determination of $\overline{rp}$. It is therefore necessary only to store information as to the direction of each K(t) increment (this storage is for a length of time approximately equal to the propagation time of the effects of this increment through the system), and then to associate this memory information with the resulting $\overline{rp}$ so as to determine the desirability of increasing or decreasing the probability of continuing in that particular $\Delta K$ direction. Experimental results confirm that this relatively simple approach to cause and effect correlation is indeed highly effective for a large class of control system problems.

When K(t) has reached its physical upper or lower limit, a zero $\Delta K$ will occur whenever the statistical source output attempts to drive K(t) past its limit. However, the "intent" of the statistical source remains manifest despite the inability of K(t) to change, and this "intent" is used in memory as though it signified an actual K(t) change.

In the mechanization of the PSV unit, the capability of varying the memory delay time over the range of $\Delta t$ to $4\Delta t$ was included to permit study of the relationship between plant characteristics and memory delay. Likewise, a variation capability was deemed desirable for the sample interval, $\Delta t$, nominally equal to one millisecond for spacecraft attitude control applications, because it appears that this time interval is related to plant characteristics (see Section 3.3).

The digital computer simulation program used in selection of basic PSV conditioning logic design parameters is described in Appendix A.

### 3.2.2 PSV Mechanization

A block diagram of the hardware realization of the PSV conditioning logic, referred to as the PSV Module, is shown in Figure 3.5. The functions in the PSV Module are implemented using primarily digital circuitry. The output parameter, K(t), which is the directly-controlled variable, is contained in a four-stage reversible binary counter, called the K register, and is converted to an analog voltage by a simple resistive network. The K register is permitted to assume fifteen of the sixteen possible combinations of a four-stage register. When the register count reaches fifteen, add pulses are inhibited; likewise, subtract pulses are inhibited at a count of one. Once each sample period, as determined by the clock repetition rate (which is selectable by front panel control) the K register is incremented one count either up or down. The direction of incrementation is determined by the state of the statistical source at the time of occurrence of the clock pulse. As described in Section 3.2.1, the statistical source is a signal generator producing an output which is a random sequence of zeros and ones. The unique feature of the statistical source is that its duty cycle, or the <u>probability</u> of its being in one state or the other,

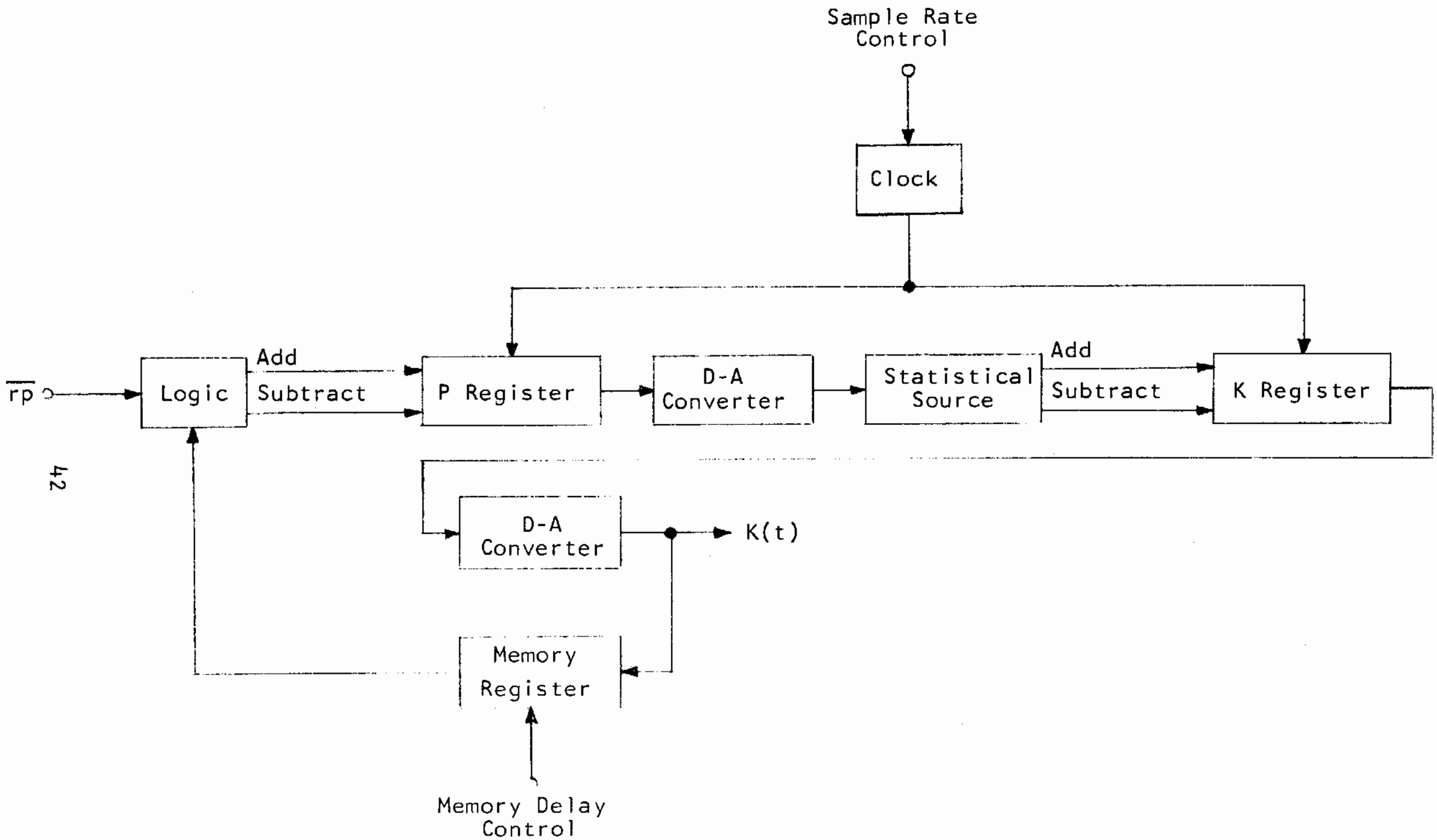



Figure 3.5: Probability State Variable Conditioning Logic

is continuously controllable by means of an analog voltage, p(t). When this probability control voltage is at its nominal center value, the output state has a 50% probability of being in either state, whereas changing the probability control voltage to its extreme positive or negative value biases the probability to about 95% in favor of a one or a zero, depending upon the polarity of the probability control voltage. The direction of incrementation of the K register at any clock pulse time is therefore probabilistic, with a bias depending on the instantaneous state of the statistical source, i.e., the probability of a positive or negative K register increment is governed by the probability control voltage applied to the statistical source.

The probability control voltage applied to the statistical source is proportional to the contents of a three-stage binary reversible counter called the P register, and is derived directly from the P register through a resistive digital-analog converter. Like the K register, the P register is clocked once each sample period and may, in general, be incremented either up or down. Unlike the K register, the P register can also remain unchanged. The direction of incrementation of the P register is governed by two factors: the state of the $\overline{rp}$ conditioning signal and the state of the Memory register. The P register is permitted to take on seven of its eight possible values; add and subtract pulses are inhibited at counts of seven and one, respectively.

Each time the K register is incremented, the direction of incrementation is stored in the first stage of a four-stage shift register. This Memory register contains, therefore, a record of the direction of the previous four trials (increments). The Memory register is tapped, and any one of the four register stages may be selected to govern the incrementation of the P register. The second signal that is used to determine the direction of P register incrementation is $\overline{rp}$, which is combined with the output of the Memory register in a simple gating network to derive the correct add or subtract signal to the P register. The logic of this gating network is such that if $\overline{rp}$ is positive, the P register is counted in a direction that increases the probability that the K register will be incremented in the <u>same</u> direction as it was incremented one, two, three, or four time intervals previously, the number of time intervals being determined by the Memory register stage that is tapped. If $\overline{rp}$ is negative, the P register is counted in a direction to increase the probability of a K register step in the <u>opposite</u> direction to that of the memory register contents. If $\overline{rp}$ is zero, the P register remains unchanged.

Thus, the operation of the PSV Module is such that the probabilities associated with alternative directions of change of the module output variable are biased in favor of changes which have recently produced desirable results, as indicated by the $\overline{rp}$ signal.

The sequence of events at each clock pulse is:

(1) the P register is incremented, thus changing the output statistics of the statistical source,

(2) the K register is incremented in accordance with the new probabilities, and

(3) the direction of K register change is shifted into the Memory register.

As in the realization of the performance assessment unit, the circuitry and electrical techniques used are quite routine, involving no state-of-the-art components or circuits. Industrial grade silicon monolithic micrologic is used extensively.

### 3.2.3 Summary Remarks

The PSV unit appears to possess inherent flexibility in use as a modular building block for control system applications.

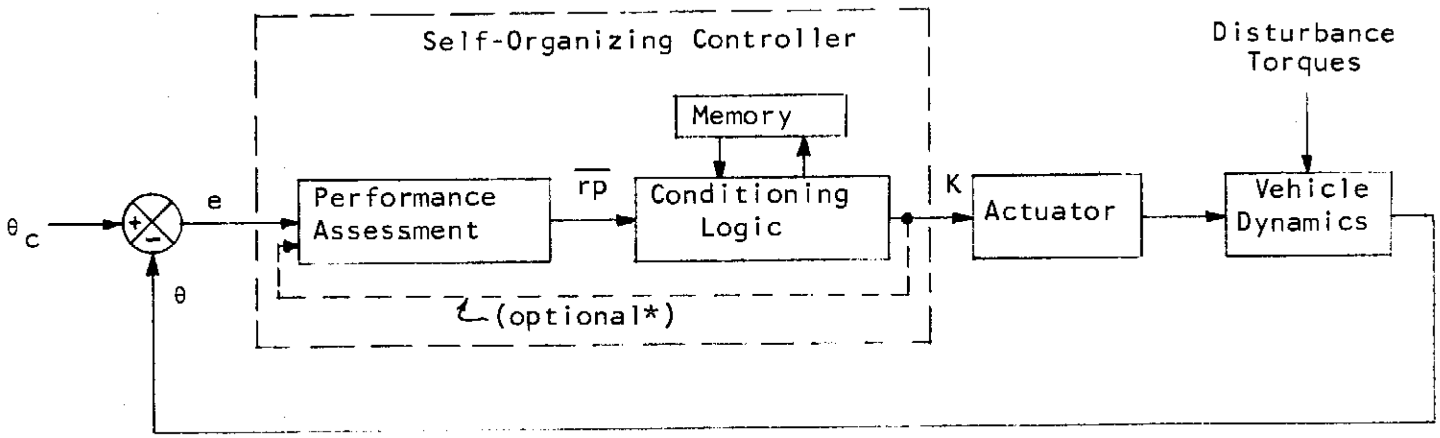
The final PSV unit design, used in the momentum-wheel loops of the Mark I and Mark II systems, is termed the Type 1507 PSV Conditioning Logic Module. This designation indicates the number of levels used in registers for K(t) and p(t), respectively.

For experimentation with reaction-jet self-organizing control, the Mark II system also includes a Type 0307 PSV Module, as discussed more fully in Appendix C.

## 3.3 SOC System Considerations

The configuration of a typical system using a PSV self-organizing controller (SOC) is shown in Figure 3.6. There are a number of other possible controller configurations, some of which are discussed in Sections 1.4 and 4.5; however, this configuration serves as a basis for a discussion of the operating features of a self-organizing controller.

The learned control signal K(t), computed by the SOC, is governed by an $\overline{rp}$ signal which is a function of two components: $e_p$ and $\ddot{e}_p$. To clarify the general theory of operation of this system, these two components can be thought of as carrying information concerning the current activity of different parts of the control loop. In brief, $e_p$ carries primarily information concerning the macroscopic behavior of the plant, and $\ddot{e}_p$ contains primarily information concerning the microscopic level of operation, viz., outputs of the PSV unit(s). The high-speed experimentation of K(t) therefore shows up in $\ddot{e}_p$, while being unobservable in $e_p$, except for long-term effects. Indeed, it has




$\theta_c$ - command attitude

$\theta$ - vehicle attitude

e - attitude error

$\overline{rp}$ - reward-punish signal

K - learned actuator excitation signal

* see discussion

Figure 3.6: Basic Elements of Single-Axis Self-Organizing Control System

$\ddot{e}_p$ p. 32

been found in laboratory experimentation that, while it is indispensible that $e_p$ be an actual prediction of plant performance as measured in e(t), it is not always necessary that the information contained in $\ddot{e}_p$ be transmitted through the plant; it has been shown experimentally that the information contained in $\ddot{e}_p$ can be computed directly from K(t) by adding a very small fraction of K(t) to e(t) at the input of the performance assessment unit. This optional feedback of K(t) to the performance assessment unit is shown in Figure 3.6. Since the computation of $\ddot{e}_p$ by direct differentiation of $e_p$ requires that the plant transmit the high frequencies contained in K(t) at sufficiently high amplitudes to be detectable by the performance assessment unit, the possibility that $\ddot{e}_p$ or equivalent, may, in certain cases, be derived from K(t) directly is extremely attractive. Such a capability increases the independence of controller operation from plant characteristics, particularly high-frequency response, actuator saturation, and nonlinearities. It is therefore recommended that this line of development be actively pursued in future SOC investigations.

In the mode of operation where $\ddot{e}_p$ is computed by direct differentiation of sensor feedback information, the possibility exists that at various times the value of $\ddot{e}_p$ may fall in the "dead band" (see Section 3.1.2), resulting in $\overline{rp}$ of zero. Under this condition, the performance assessment unit sends a signal to the PSV logic which causes the latter to enter a "search mode". In the search mode, the PSV Module P registers are set to their midpoints for as long as the $\overline{rp}$ remains zero. If *a priori* knowledge of the plant and actuator polarities is available, one has the option of performing the search with the P registers set one step above or below their midpoints, depending on plant polarity (if known), resulting in a slight bias of successive $\Delta K$ steps in what is most often the correct direction. This search mode operation can also be used in the case of actuator and/or sensor saturation, for which cases high-frequency information transmission through the plant is interrupted. The control

N.B.

quality obtained in using the search mode is inferior to that obtained in the "reinforcement mode" (normal PSV operation), due to the loss of full use of the P register. Reinforcement modes in which high-frequency information concerning K(t) activity need not be transmitted through the plant are thus very useful, as suggested in the previous paragraph.

A factor of importance in the realization of a practical self-organizing controller is the selection of an optimum sample interval for increments of p(t) and K(t). The exact relationship between sample interval and plant characteristics is still not entirely clear; this relationship appears to be dependent on the dominant time constant of the plant and on plant gain. It has been observed experimentally that a ratio of plant time constant to sample rate of at least $10^4$ gives best results, and that these results are relatively unaffected by considerable increases (i.e., two-to-one) in this ratio. Apparently requires apriori knowledge of the dominant time constant.

The memory delay time is also related to plant gain and lag characteristics. A two-stage shift register has been found to be satisfactory over a very wide range of plant parameter variations, however. Further studies should focus on advanced memory techniques, perhaps utilizing information averaged over several time intervals.

During the course of the investigations of practical SOC systems, consideration was given to techniques for halting experimentation when the plant was in the steady-state with negligible e and ė levels. Such techniques are referred to as "stop rules". One general method evaluated was to detect conditions where both predicted error and predicted error rate were below selected threshold levels, with inhibition of further changes in the K(t) output invoked under such circumstances. This approach was not successful, since K(t) varies so rapidly over its full range that, in general, an instantaneous value of K(t) is not the correct value to maintain a given steady-state

NOTE

condition. A preferable approach is to make use of the additive system configuration (see Section 4.5). Using this configuration, detection of steady-state conditions can be used to remove the SOC component of the actuator excitation signal, leaving the plant controlled by a fixed-gain controller in the steady-state. This last approach makes use of the best features of both types of controller.

## 3.4 SOC Size, Weight, and Power Consumption

Although miniaturization was not a major goal in the development of the SOC breadboard engineering models fabricated in this program, the circuits and packaging used are considered sufficiently representative of PSV controller devices that the physical characteristics of these models serve as a basis for projecting future possibilities. Table 3.1 lists the key properties for each module type.

| | Power Consumption, Watts | Weight, Lbs. | Volume In.$^3$ |
|---|---|---|---|
| Performance Assessment | 1.0 | 0.5 | 35 |
| PSV Logic | 1.9 | 1.1 | 70 |

Table 3.1: Mark II SOC Module Size, Weight, and Power Consumption

The total circuitry required for a Mark II controller of the type constructed for this study (i.e., one Performance Assessment Module and five PSV Modules) weighs about five pounds, consumes approximately eight watts, and occupies about 300 in.$^3$

The above figures for size and weight include all circuit components and printed circuit boards, but do not include connectors, mounting chassis, chassis wiring, or power supplies.

In this program, no particular attempts at achieving miniature size or economies in weight and power were made, therefore it is to be expected that design efforts directed toward building a self-organizing controller for space applications would result in a significant reduction in all three categories. A very conservative projection for a flightworthy SOC electronics package (less power supplies) consisting of one Performance Assessment and three PSV Logic Modules appears to be:

Size: 100 $in.^3$

Weight: 4 lbs.

Power: 5 watts

# 4. SYSTEM EVALUATION TESTS

This section emphasizes the results of system evaluation tests performed using the Mark II self-organizing momentum-wheel controller, integrated with the dynamics of a representative orbiting satellite vehicle simulated on an analog computer.*

## 4.1 Objectives

Performance assessment and conditioning logic subsystems described in the preceding section were evolved during the program via theoretical methods coupled with simulation activities. Digital simulation was predominant during the early phases, prior to and during the construction of the self-organizing controller subsystems. System evaluation tests were performed during the later phases of the program and used analog simulation techniques to model the single-axis attitude control dynamics of a representative orbiting satellite vehicle.

The test program objectives for the Mark II SOC evaluations for the momentum-wheel loop may be summarized as follows:

(1) Performance Characteristics

From a control system point of view, the SOC employs many basic concepts bearing little

*Mark II SOC evaluations were performed at the Control Techniques Simulator Facility, Wright-Patterson Air Force Base, Ohio. Mr. Paul E. Blatt, Air Force Project Engineer, prepared the analog simulation program, conducted supporting studies (Ref. 1) on the plants to be tested with the SOC, and actively participated in the evaluation program reported here. The authors wish to express their appreciation to Mr. Blatt for his contributions to this study.

resemblance to established and well-understood methods for relating a system design to desired performance. It was therefore necessary to gain understanding of SOC performance characteristics and of their relationships to design parameters in the performance assessment and conditioning logics.

(2) Self-Adaptive Capabilities

The preceding objectives could be achieved in large measure by considering a plant with fixed parameters. An important attribute of self-organizing control is its self-adaptive capability relative to changing environmental and plant parameters. A major objective of the test program was, therefore, to establish the effects of abrupt and gradual changes in such SOC performance.

(3) Modes of Operation

The performance assessment criterion implemented in this program is sufficiently general to permit use of the self-organizing controller in a number of different modes, viz., direct computation of actuator-excitation signals, varying the gain of an otherwise conventional controller, or operating the self-organizing controller in parallel with a constant-gain circuit. Evaluation of these alternate modes of operation was an additional objective of the test plan.

A test program centered around the above objectives was expected to lead to suitable criteria for the design of self-organizing momentum-wheel attitude control systems.

## 4.2 Test Configurations

Since a large variety of configurations were used in the course of the program, it is desirable to establish a basic configuration to which the others can be referred. Such a configuration is shown in Figure 4.1.

The basic configuration, (Figure 4.1), uses the SOC directly to compute excitation signals to the momentum-wheel motor. This approach is referred to as the control computer mode of operation. The momentum wheel is represented as a first order lag, and acceleration limiting ($\dot{\omega}$ saturation) has been included to permit the study of nonlinear effects present in actual equipment.

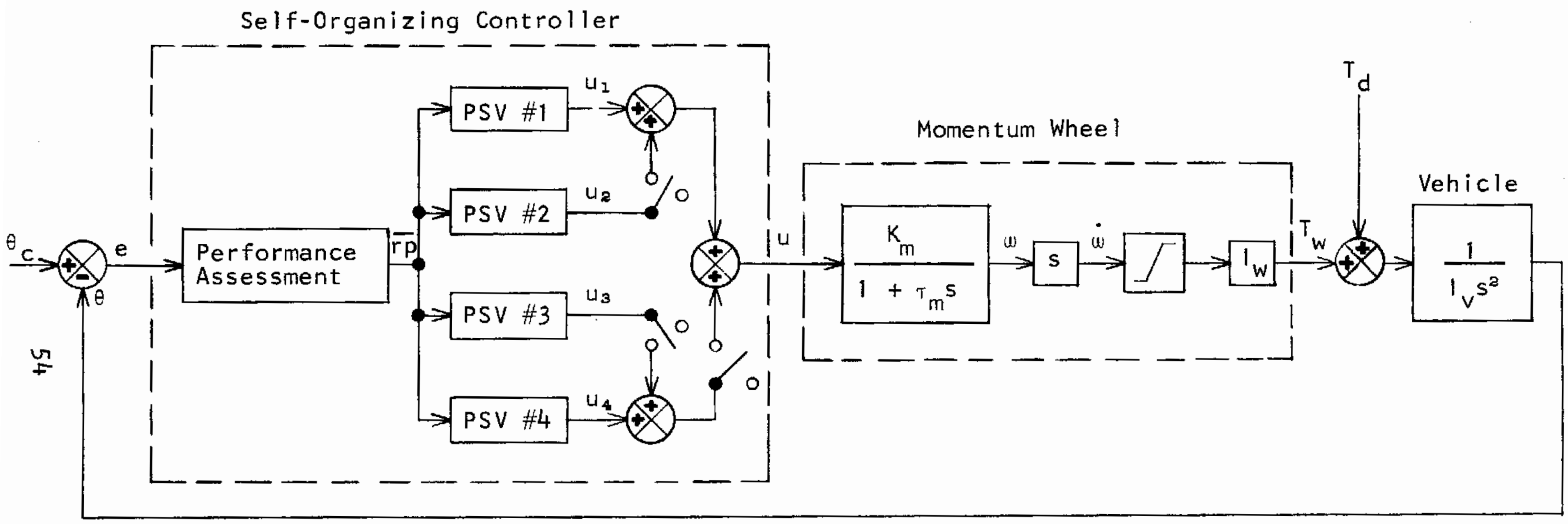
The voltage u applied to the momentum wheel is limited by the level set at the PSV Module K register. For one PSV unit, this voltage is ± 10 volts. When more than one PSV unit is used, their output is summed, with the result that

$$-10n \leq u \leq +10n$$

where

n denotes the number of PSV Modules used. In actual application, using the control computer configuration, the limits on u would be set to the rated motor voltages. In the data to be presented, therefore, a change in the number of PSV units can be viewed as a change in gain, e.g., if 40 volts is taken as the rated motor voltage, n = 4 would give the appropriate setting and n = 2 is equivalent to reducing the gain by one-half while maintaining rated voltage at ± 40.

In selecting plant parameter values, it first appeared desirable to simulate a specific space vehicle control problem and the Orbiting Astronomical Observatory (OAO) system was selected (Ref. 12). Thus, vehicle inertia was set at




$$\frac{K_m I_w}{I_v} = G$$

Figure 4.1: Basic Self-Organizing Controller Test Configuration

$$I_v = 685 \text{ slug-ft}^2$$

It soon became apparent, however, that the OAO is too restrictive a problem for the purposes of this study. The fine momentum wheel, for example, which is the primary OAO actuator, is hardly representative of torque levels and time constants associated with many space vehicle control devices. For this reason, nominal values used in the simulation for wheel inertia, $I_w$, and the motor time constant, $\tau_m$, were taken from the OAO coarse wheel, viz.

$$I_w = 0.0328 \text{ slug-ft}^2$$

$$\tau_m = 20 \text{ seconds}$$

To permit the study of system performance with controllers of higher torque capability, e.g., control-moment gyros, the value of the gain factor $K_m$ was varied above the limits normally associated with momentum-wheel usage.

## 4.3 Basic Performance Data

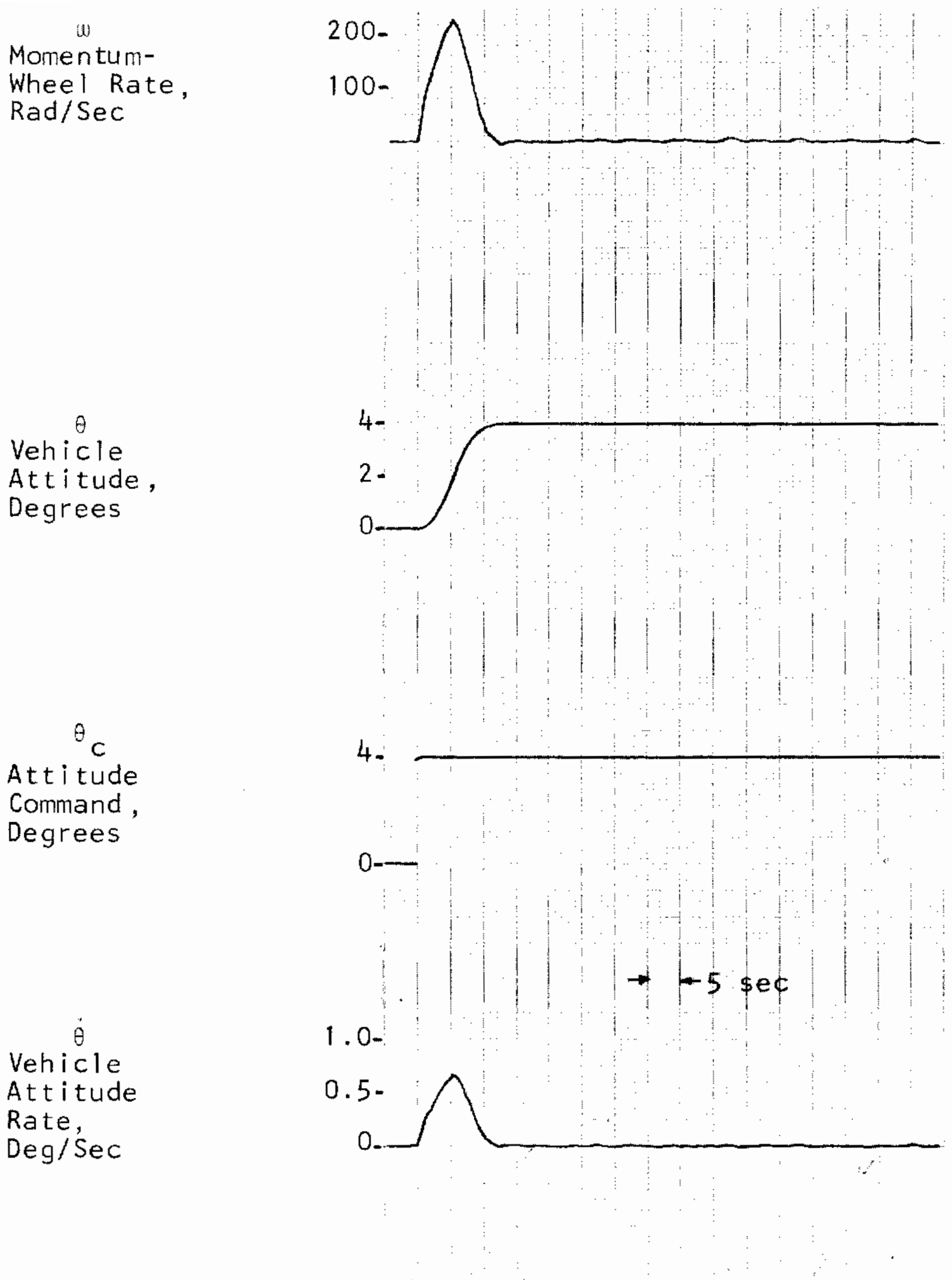
Self-organizing control circuitry implemented in this program allows for the change of three parameters: the prediction interval, T, in the Performance Assessment Module; the sample intervals, $\Delta t$, in the PSV Modules; and the memory delays in the PSV Modules. In general, performance characteristics were not found to be highly sensitive to variations in the sample intervals, provided they were one millisecond or smaller. Likewise, the memory delays were not critical, although performance exhibited degradation if the delays were changed from the value of $2\Delta t$ used in obtaining all the data presented here. The principal design parameter proved to be the prediction interval, T.

Figures 4.2 through 4.6 show typical response data for, respectively: (1) a step input; (2) initial conditions involving attitude and rate errors; (3) a constant disturbance torque, $T_d$; (4) a ramp input; and (5) a sinusoidal input. All of these data were obtained with T = 3.2 seconds and using four PSV Modules operating in the control computer mode of Figure 4.1.

Both transient and steady-state performance appear to exhibit desirable characteristics, with the exception of the steady-state errors following an initial $\dot{\theta}(0)$ in Figures 4.3(a) and 4.3(c). However, these steady-state errors cannot be reconciled with the criterion used in the controller for, as shown, in the ramp-input response of Figure 4.5, the error appears only for the positive slope of $\theta_c$ but not in the negative slope portion. These errors are therefore attributed to a null offset in the circuitry, a condition which was on other occasions removed by suitable adjustments.

It is of major interest to investigate system behavior relative to the theoretical requirements of the performance assessment criterion. Attention is therefore invited to the discontinuities in the $\omega$ and $\dot{\theta}$ traces of Figure 4.2. To show their relevance better, a phase-plane plot of this step-input response is provided in Figure 4.7 and it is seen that the discontinuity occurs at the $e = -T\dot{e}$ line corresponding to the design value of T = 3.2 seconds.

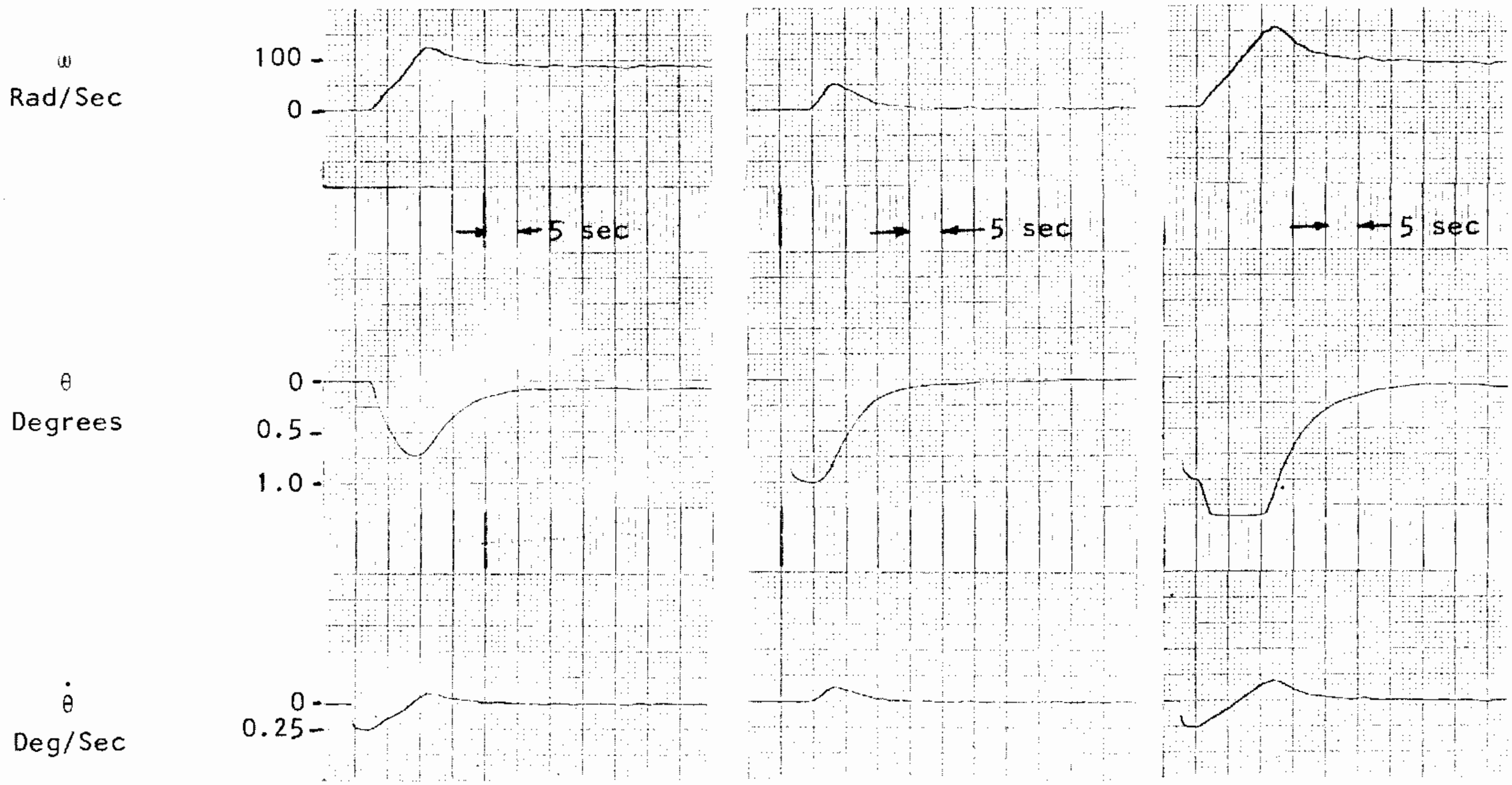
During the initial response phase, i.e., from $e = e(0)$ until the $e = -T\dot{e}$ line is reached, the system moves along the $V = f(e, \dot{e})$ surface seeking a preferred path toward the switching line. To illustrate this, Figure 4.7 contains a curve from e(0) to the $e = -3.2\dot{e}$ line which would have been followed if a step input of the maximum PSV voltage were applied to the momentum wheel and maintained during this phase. As may be seen from Figure 4.7, this maximum voltage is indeed called for by the self-organizing controller for some initial portion of the




$G = 1.644 \times 10^{-2}$ Deg/Sec/Volt

$n = 4$ $\tau_m = 20$ Sec

Figure 4.2: Typical Step-Input Response, Control Computer Mode



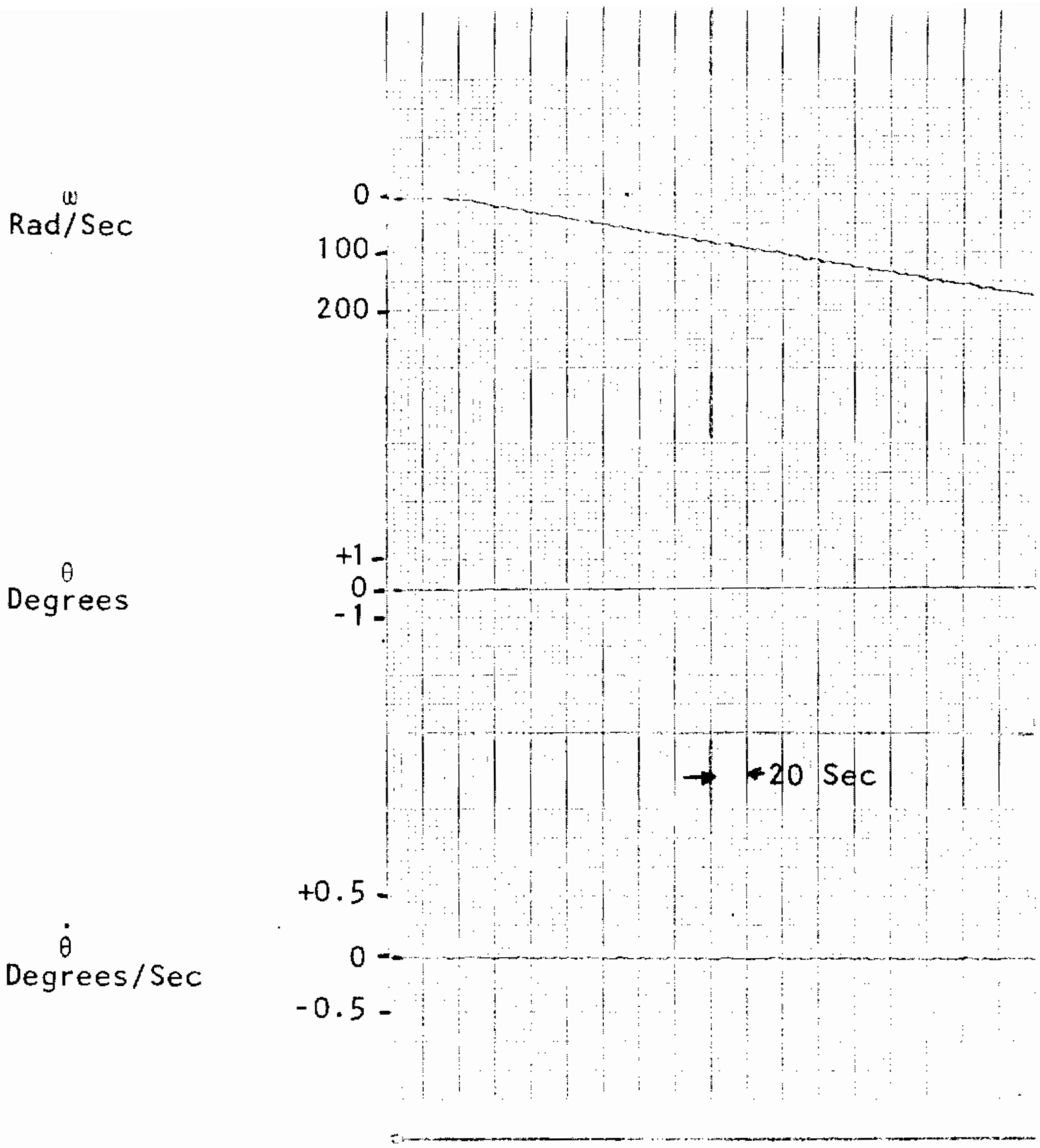

(a) Initial Rate Only
$\dot{\theta}(0) = 0.25$ Deg/Sec

(b) Initial Attitude Error Only
$\theta(0) = 1$ Degree

(c) Combined Initial Attitude and Rate Errors: $\theta(0) = 1°$, $\dot{\theta}(o) = 0.25\ °/\text{Sec}$

$G = 8.22 \times 10^{-3}$ Deg/Sec/Volt
$n = 4$; $\tau_m = 20$ sec

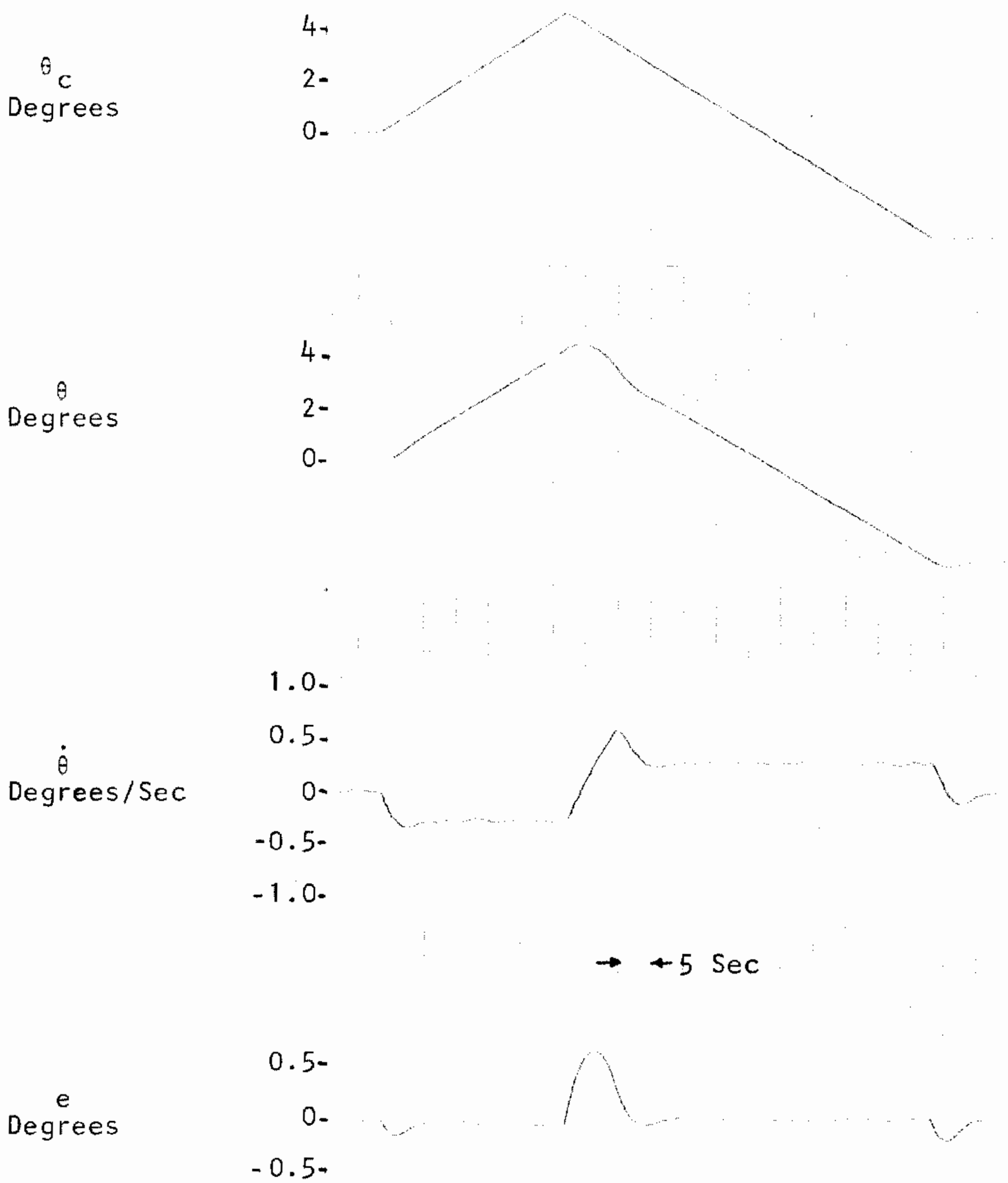
Figure 4.3: Response to Initial Attitude and Rate Errors




$T_d$ = 250,000 Dyne-Cm

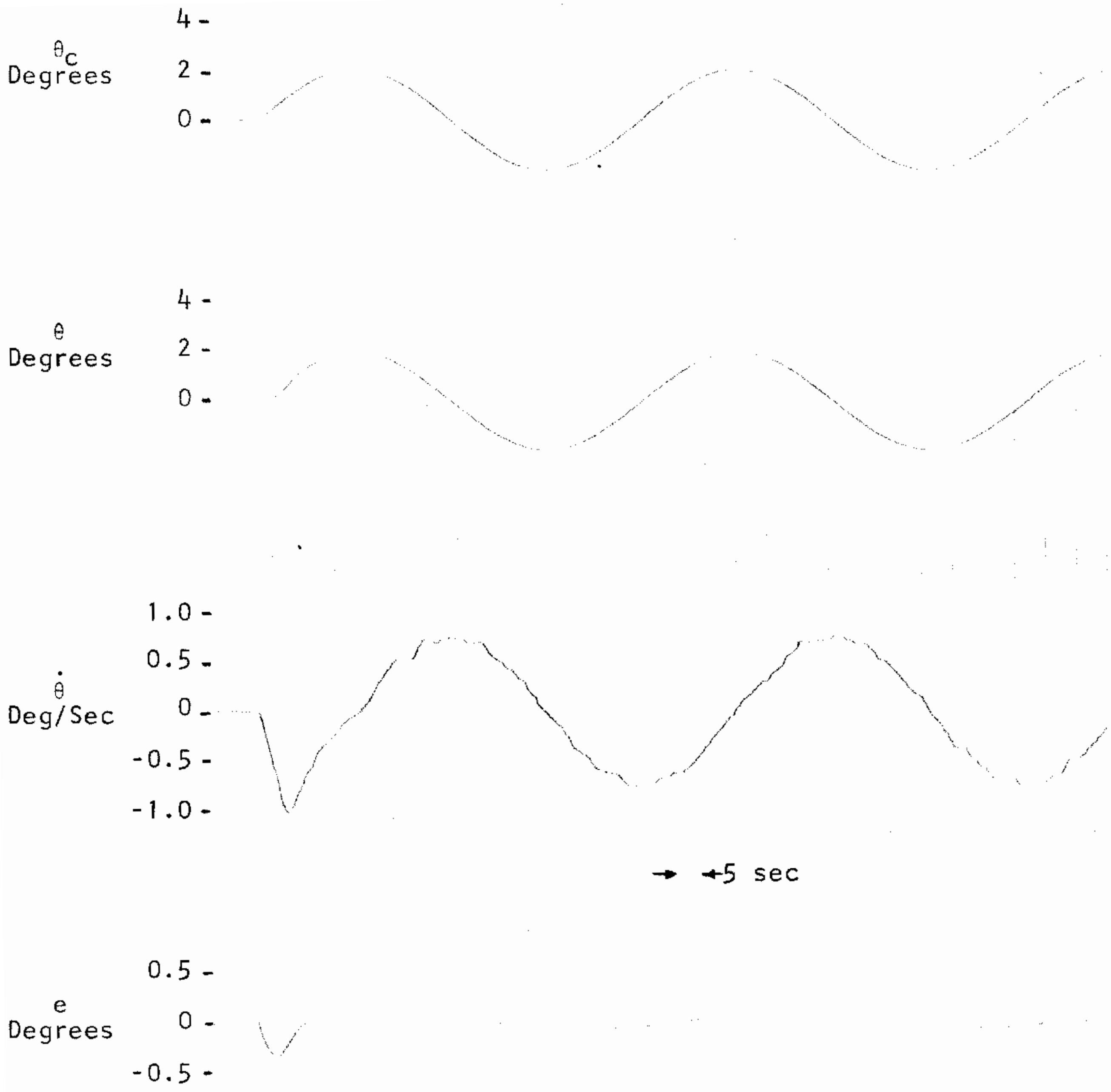
G = 8.22 x $10^{-3}$ Deg/Sec/Volt
n = 4; $\tau_m$ = 20 Sec

Figure 4.4: Response to Constant Disturbance Torque



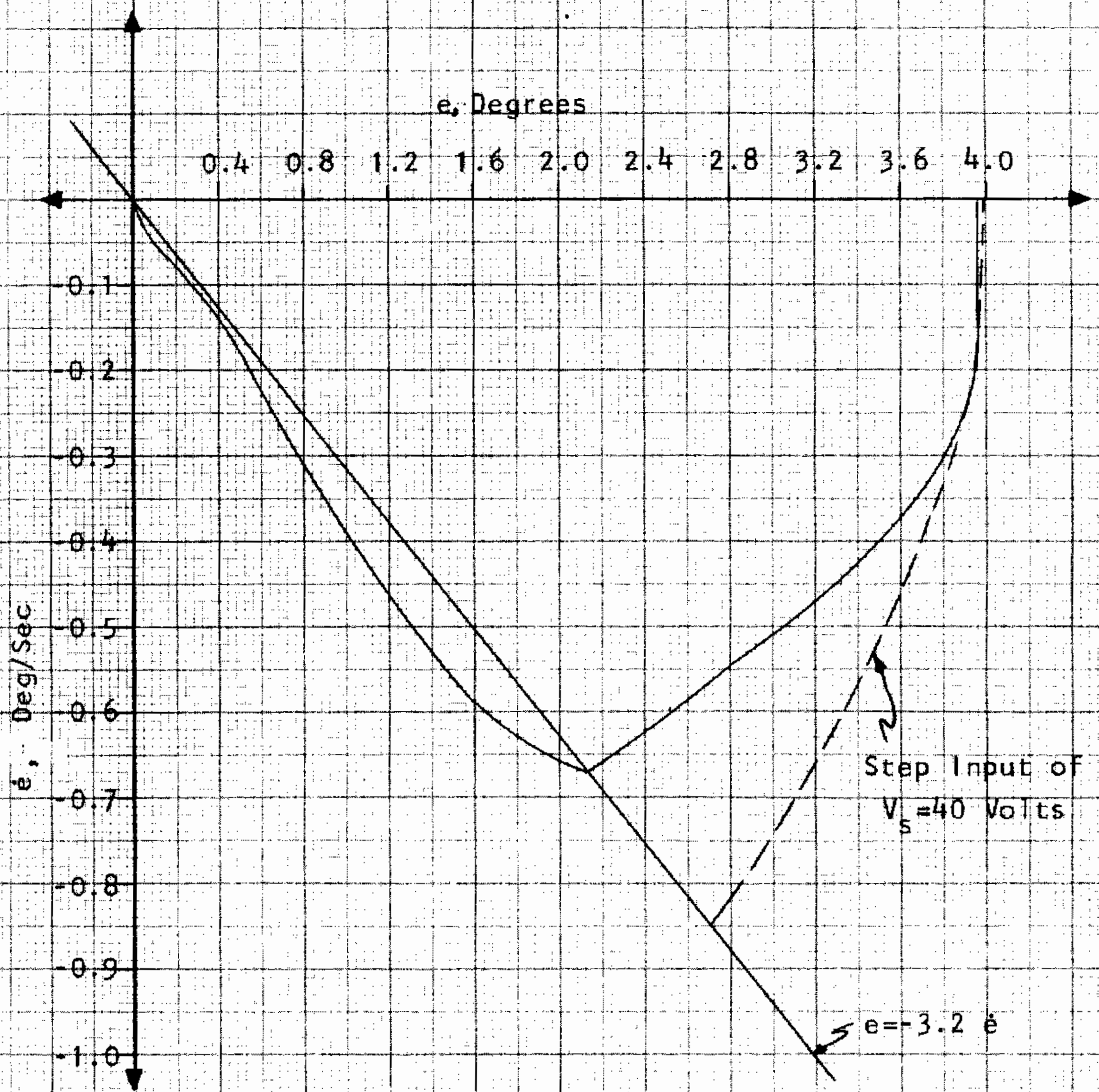

$G = 8.2 \times 10^{-3}$ Deg/Sec/Volt; $\tau_m = 20$ Sec; $n = 4$

Figure 4.5: Response to Ramp Input




$G = 8.2 \times 10^{-3}$ Deg/Sec/Volt; $\tau_m = 20$ Sec; $n = 4$

Figure 4.6: Response to Sinusoidal Input




$G = 1.644 \times 10^{-2}$ Deg/Sec/Volt

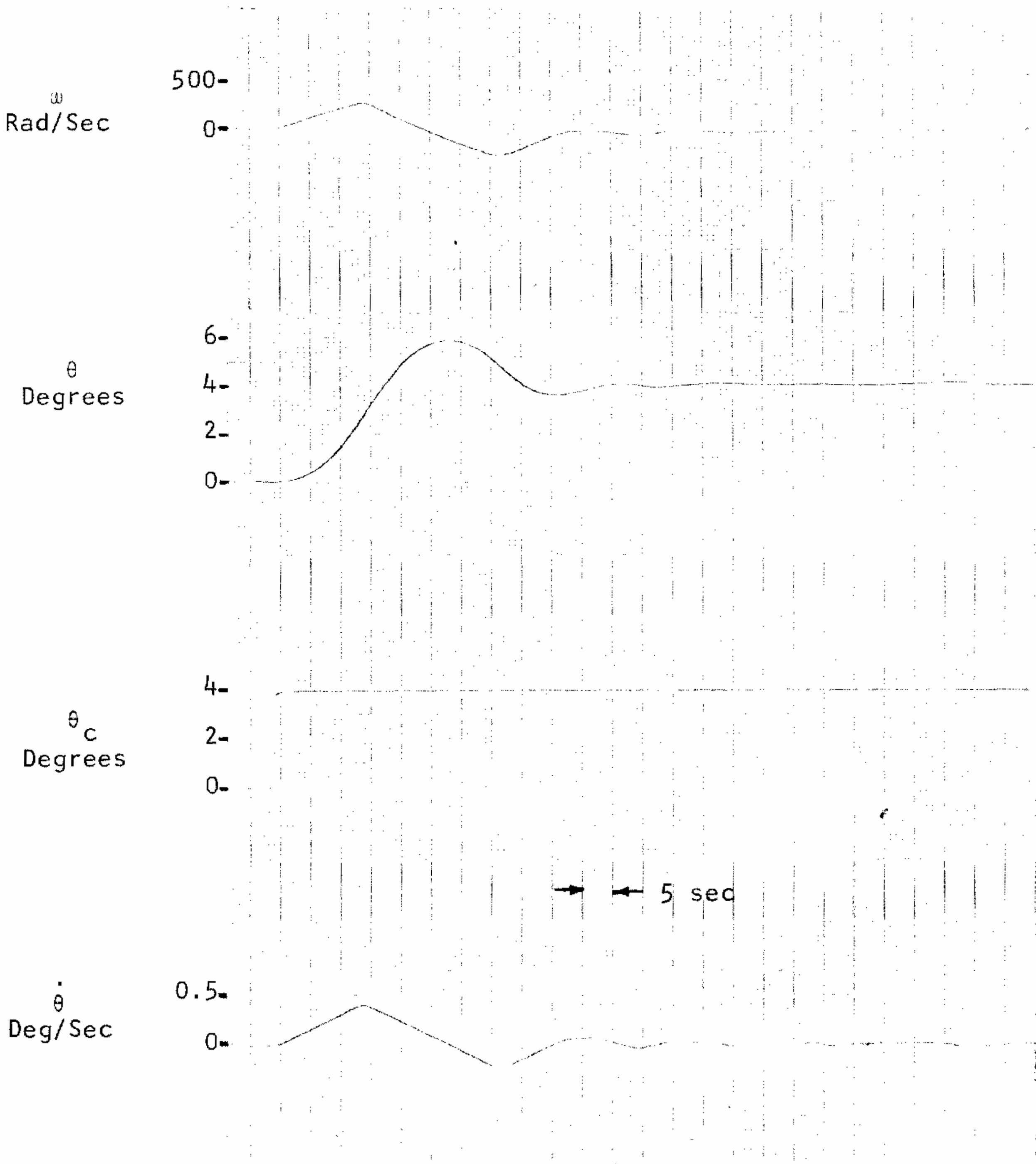
$\tau_m = 20$ Sec

Figure 4.7: Phase Plane Diagram of Step-Input Response

transient, but is then reduced so as to change the path toward the terminal exponential-response line.

During the terminal phase of SOC response, the theoretical path is along the $e = -T\dot{e}$ line (see discussion in Section 3.1.1). However, since the momentum-wheel acceleration cannot be reduced to zero instantaneously, it is possible for the system to overshoot. If this occurs, the criterion is again called upon to guide the response toward the $e = -T\dot{e}$ line by reversing the polarity of the voltage applied to the motor. Deviations from the theoretical path are a function of plant characteristics, i.e., its torque capabilities and the lags associated with torque application. To illustrate this, Figure 4.8 shows the step-input response with a plant for which gain has been reduced by a factor of two, the motor time constant $\tau_m$ has been increased by a factor of two (thereby increasing the lag in torque application) and in which a limit of ± 10 rad/sec² has been imposed on wheel angular acceleration, $\dot{\omega}$. The latter is particularly severe on the self-organizing controller, since the SOC makes use of maximum angular acceleration of the momentum wheel during a large part of the transient and the acceleration limit amounts to a reduction by a factor of three of the maximum acceleration capability of the already-degraded actuator. Degradation in response is clearly evident in Figure 4.8, i.e., there is a large overshoot and some oscillation.

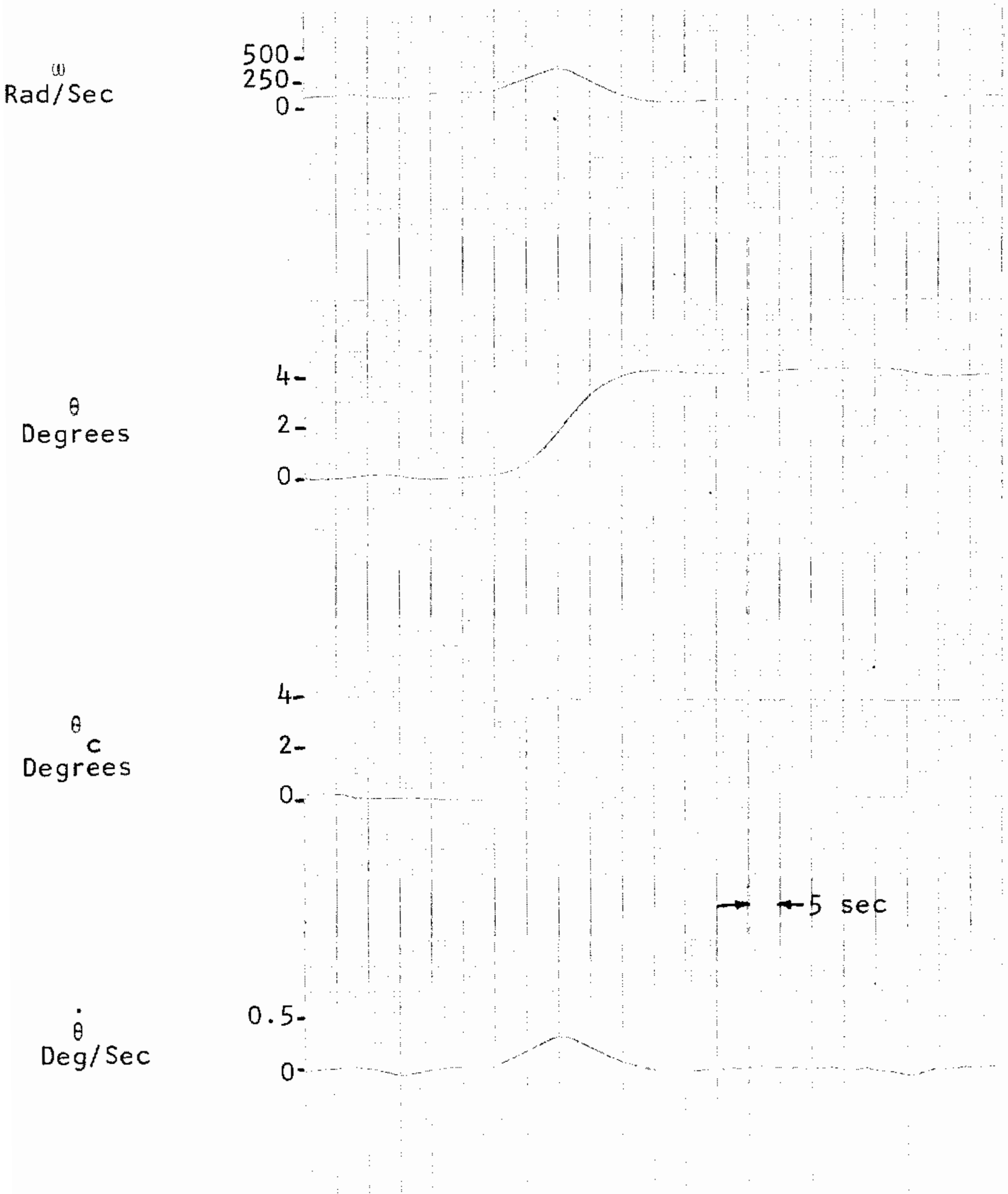
Figure 4.9 shows the improvement obtained by changing the prediction interval, T, from 3.2 seconds to 6.4 seconds for the same plant characteristics used in obtaining Figure 4.8. To highlight further the improvement in performance, a phase-plane plot of the above two responses is provided in Figure 4.10. Referring to the latter, it is to be noted that increasing the prediction interval, and hence changing location of the $e = -T\dot{e}$ line, results in larger error values and lower angular rates at the point of entering the terminal exponential response. Changing the prediction interval thus permits attainment of desired terminal response characteristics.




$G = 8.22 \times 10^{-3}$ Deg/Sec/Volt; $\dot{\omega}_s = \pm\ 10$ Rad/Sec$^2$

$\tau_m = 40$; $n = 4$; $K_m = 30$

Figure 4.8: Step-Input Response With Acceleration Limiting - 3.2 Second Prediction Interval




$G = 8.22 \times 10^{-3}$ Deg/Sec/Volt; $\dot{\omega}_s = \pm 10$ Rad/Sec²

$\tau_m = 40$; $n = 4$; $K_m = 30$

Figure 4.9: Step-Input Response With Acceleration Limiting -- 6.4 Second Prediction Interval

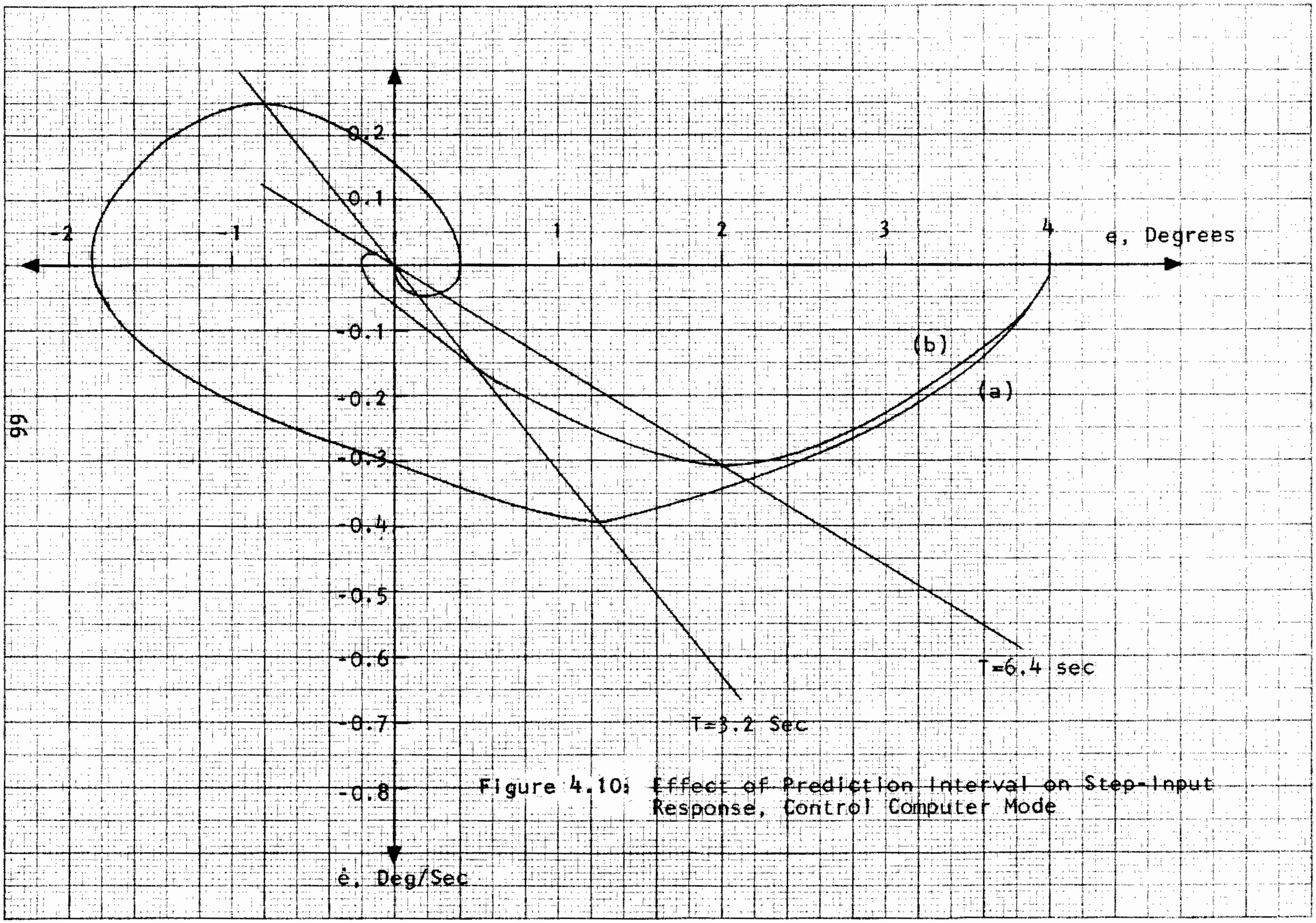


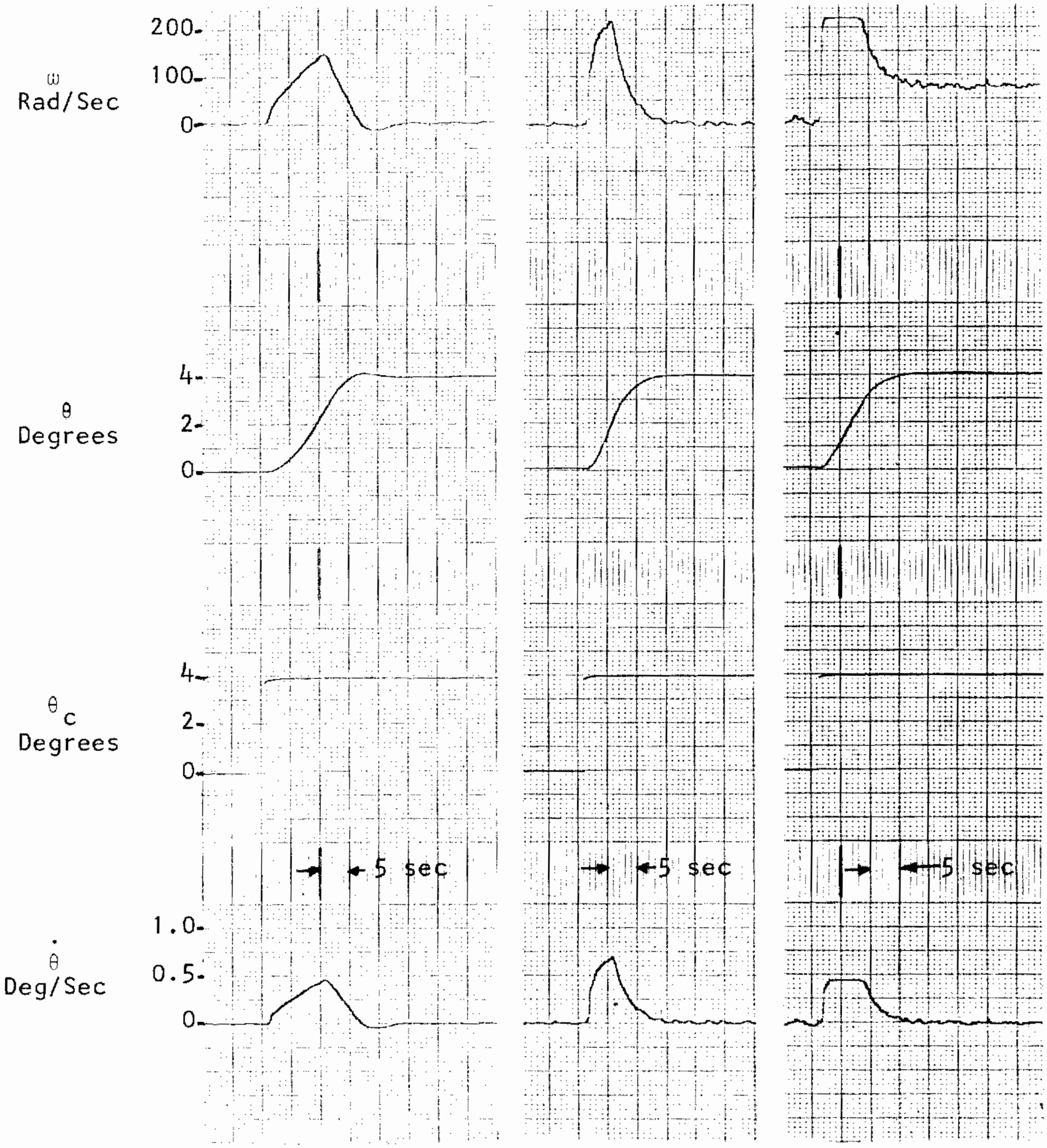

Figure 4.10: Effect of Prediction Interval on Step-Input Response, Control Computer Mode

## 4.4 Self-Adaptation Tests

Figure 4.11 shows the effects on step-input response of changes in plant parameters. Figure 4.11(a) serves as a reference, with gain and $\tau_m$ values as noted. Without changing the prediction interval (T = 3.2 seconds), Figures 4.11(b) and (c) were obtained to show the response with increased plant capabilities. The motor time constant has been reduced in (b) from 20 to 5 seconds. The motor gain has been increased in (c) by a factor of 6.6. (In the latter case an amplifier in the simulation equipment saturated, producing an effect comparable to wheel-speed saturation.) Figures 4.11(d) and (e) show changes in response with reduced plant capabilities, i.e., lowered gain and increased actuator lag. Response of the system appears to be generally satisfactory over the range of parameter variations shown.

The above data indicate that transient response characteristics are more sensitive to actuator lag than they are to gain changes. This is shown more clearly in Figure 4.12, which is a phase-plane plot of the data in Figure 4.11. In general, the greatest range of adaptation would be achieved by selecting the prediction interval with respect to the lowest anticipated plant capabilities for, as shown above, higher plant capabilities will improve transient performance.

For comparison purposes, Figure 4.13 has been prepared to show the response of a constant-gain system when plant parameters are changed over the range used in the adaptation tests of Figure 4.11. The constant-gain configuration included a lead-lag network (corresponding to Figure 4.17 with switch S3 closed). Values of lead and lag time constants were chosen to produce the reference response of Figure 4.13(a) at nominal gain $G_n$ and $\tau_m$ = 20 seconds. Increasing the gain, as in Figure 4.13(b), produced an oscillatory response; reduction of $\tau_m$, as in Figure 4.13(c), caused considerably slower convergence toward the steady-state.




(a) $G=G_n$; $\tau_m=20$ Sec (b) $G=G_n$; $\tau_m=5$ Sec (c) $G=6.6\ G_n$; $\tau_m=20$
Wheel-Speed Saturation

$G_n = 8.2 \times 10^{-3}$ Deg/Sec/Volt; $n = 4$

Figure 4.11: Effect of Changes in Gain and Motor Time Constant

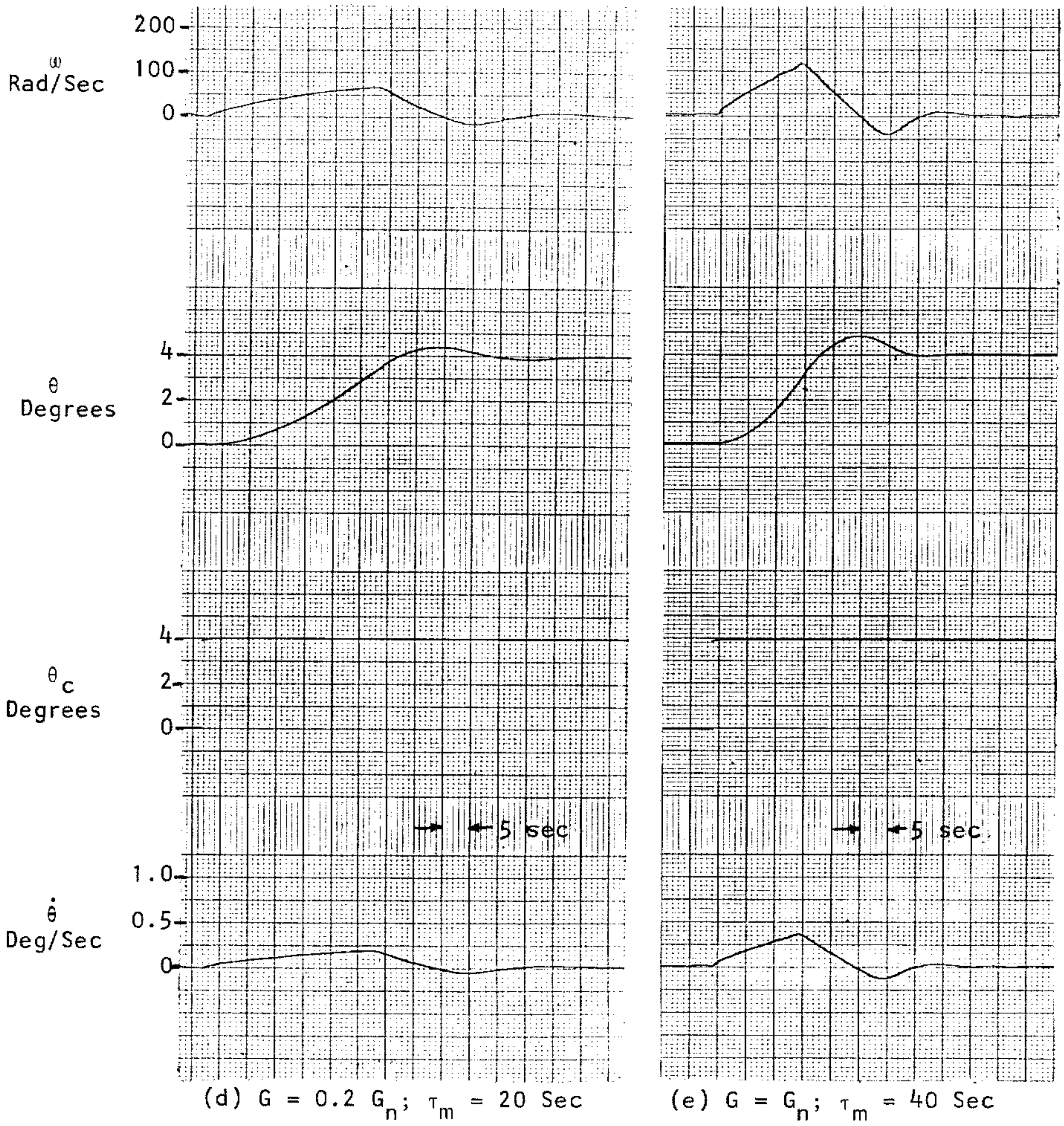



Figure 4.11: Effect of Changes in Gain and Motor Time Constant (Concluded)

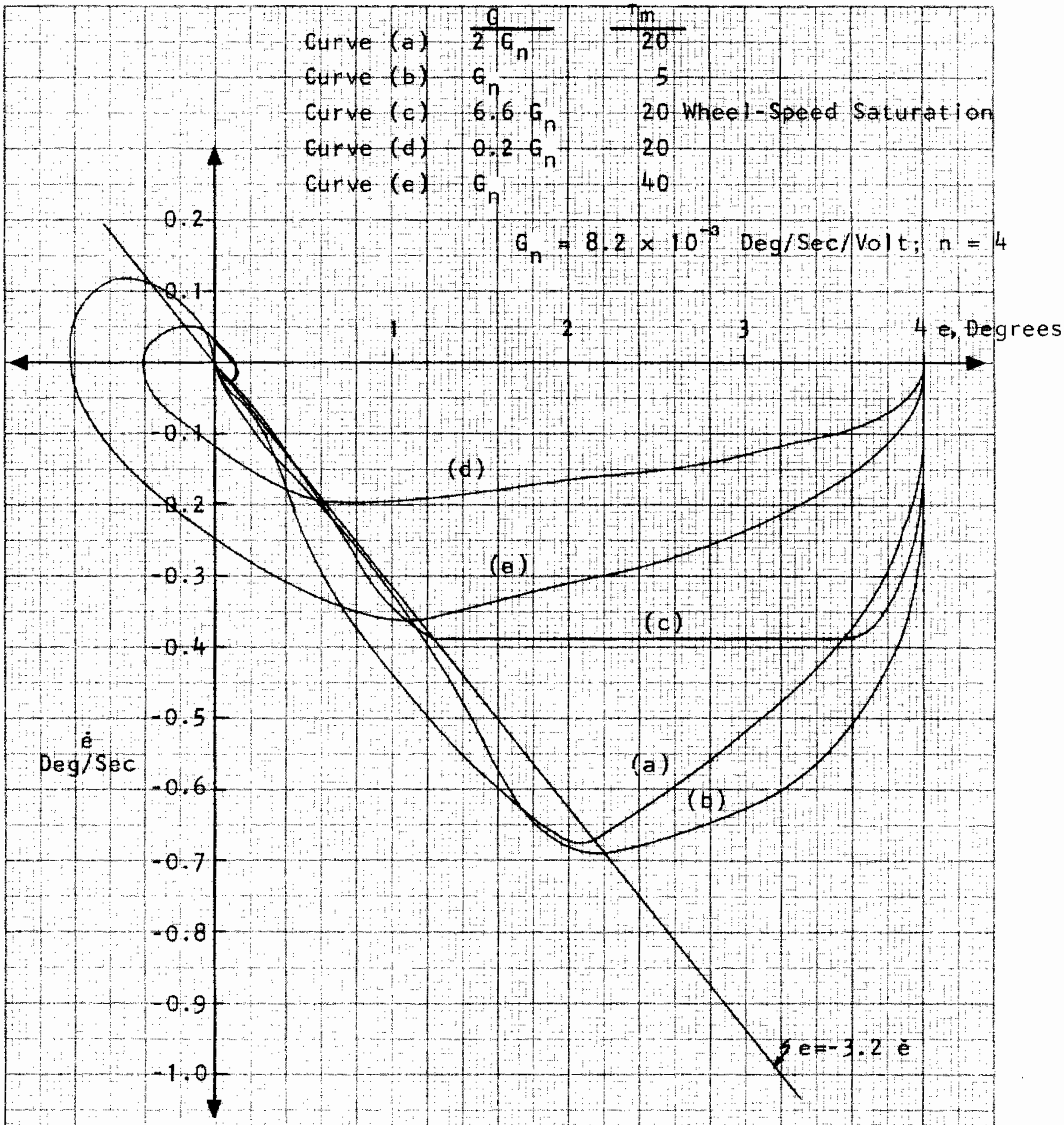
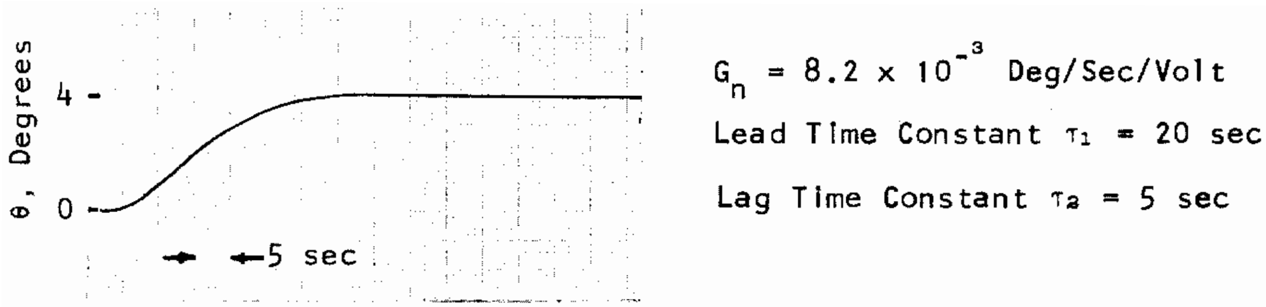
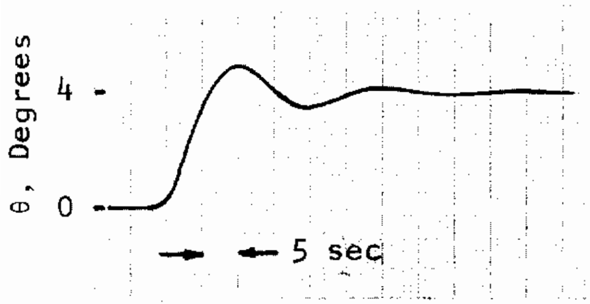


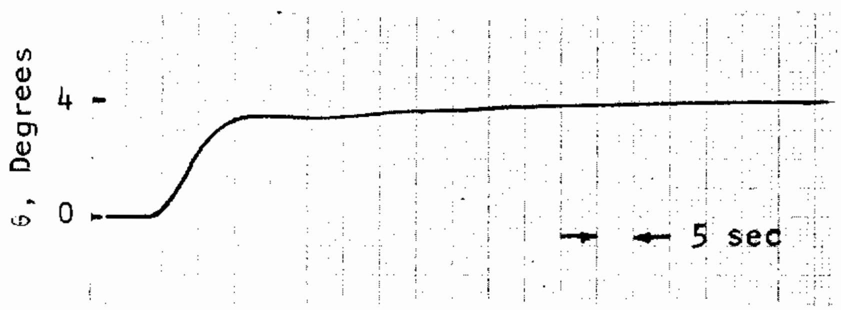

Figure 4.12: Phase-Plane Response for a Range of Gain and Motor Time-Constant Values



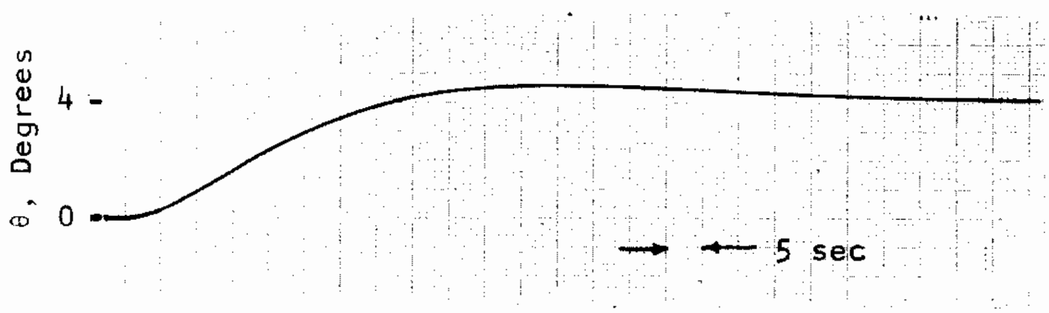

(a) $G = G_n$, $\tau_m$ = 20 sec, Constant Gain




(b) $G = 6.6\ G_n$, $\tau_m$ = 20 sec, Constant Gain

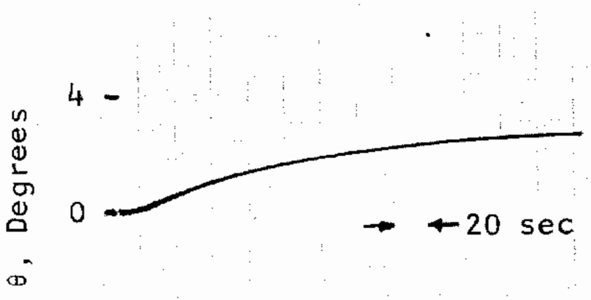



(c) $G = G_n$, $\tau_m$ = 5 sec, Constant Gain



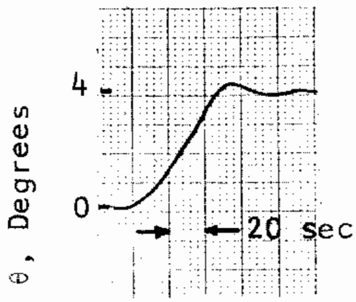

(d) $G = G_n$, $\tau_m$ = 40 sec, Constant Gain

Figure 4.13: Constant Gain and Self-Organizing Control System Response to a 4-Degree Step Input




(e) G = 0.1 $G_n$, $\tau_m$ = 20 sec

Constant Gain




(e*) Self-Organizing Controller:
$G = 0.1 G_n$, $\tau_m$ = 20 sec, n = 4

$G_n = 8.2 \times 10^{-3}$ Deg/Sec/Volt

Lead Time Constant $\tau_1$ = 20 sec

Lag Time Constant $\tau_2$ = 5 sec

Figure 4.13: Constant Gain and Self-Organizing Control System Response to a 4-Degree Step Input (Concluded)

These changes are in the category of increased actuator capability, and further increases would only aggravate the situation in the case of constant-gain control. In contrast to this, self-organizing controller response improves with increased actuator capability, as illustrated in Figure 4.11(b) and (c).

The effect of reducing actuator capabilities for constant-gain control is illustrated in Figure 4.13(d) and (e), where the motor lag $\tau_m$ has been increased to 40 seconds and gain reduced by a factor of 10, respectively. (Note the changed time scale in Figure 4.13(e).) Figure 4.13(e*) shows the response of the self-organizing controller for the same conditions as the constant-gain controller of Figure 4.13(e). The contrast is self-evident.

Figure 4.14 shows adaptation to changes in vehicle inertia during the transient response, intended to simulate conditions similar to those associated with stage separation. Since a change in inertia is equivalent to a gain change, the ability of the controller to handle an inertia change can be readily anticipated. The significance of Figure 4.13 is therefore the demonstration that plant changes can occur during the transient without major effects on performance.

All of the data presented here are based on the use of four PSV Modules, whose outputs are summed before application to the momentum wheel. As previously noted, changing the number of PSV units is equivalent to changing gain in the plant. This is confirmed in the phase-plane plot of Figure 4.15. Thus, when a multiple number of PSV units is used, the complete loss of one unit, (having its output go to zero) causes a reduction in effective gain.

When all PSV units are operating, the SOC response exhibits minimum "granularity", since increasing the number of PSV units is roughly comparable to increasing the number of levels available in the K register of the individual PSV units.

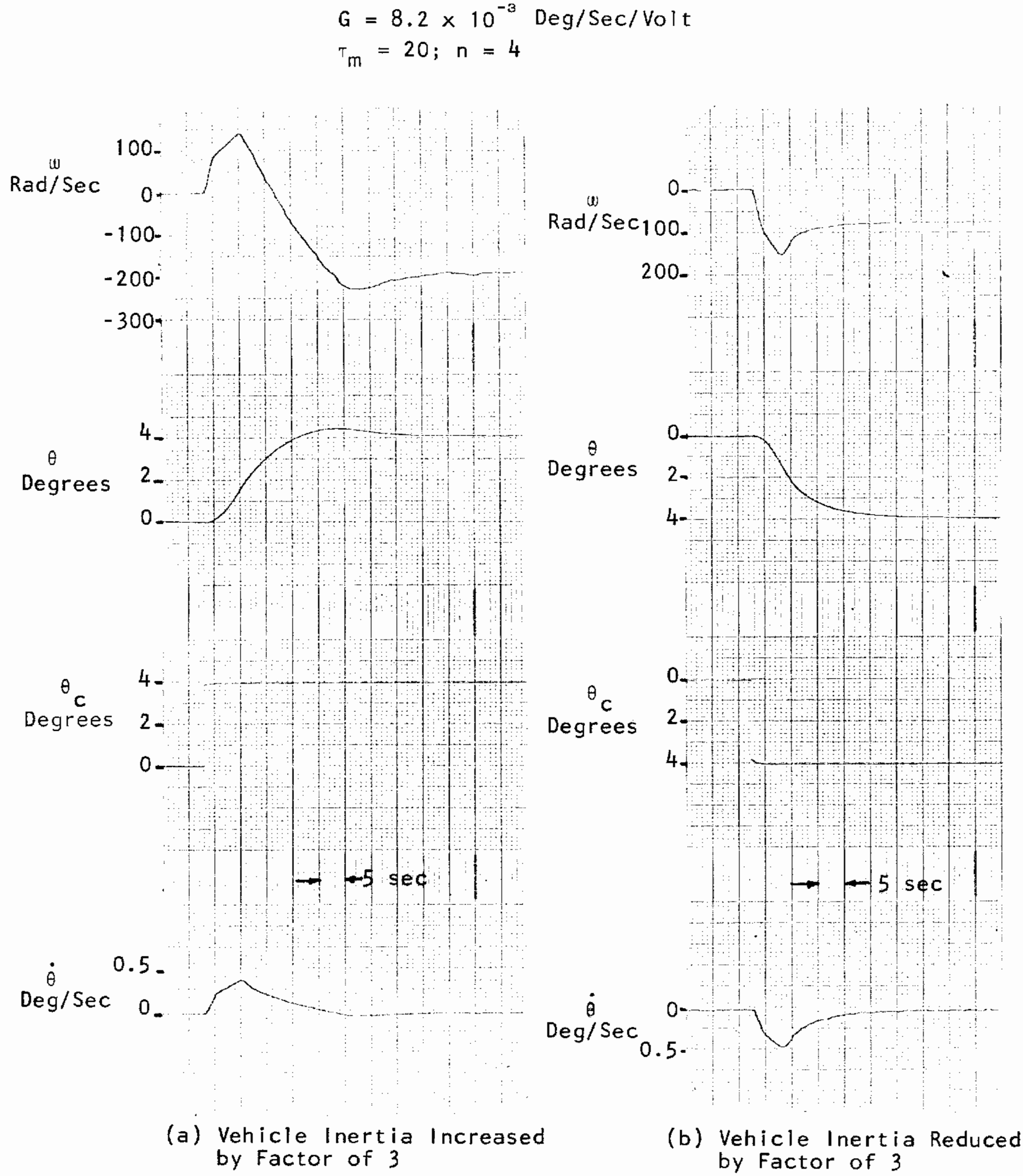



Figure 4.14: Step-Input Response with Vehicle Inertia Change During Transient

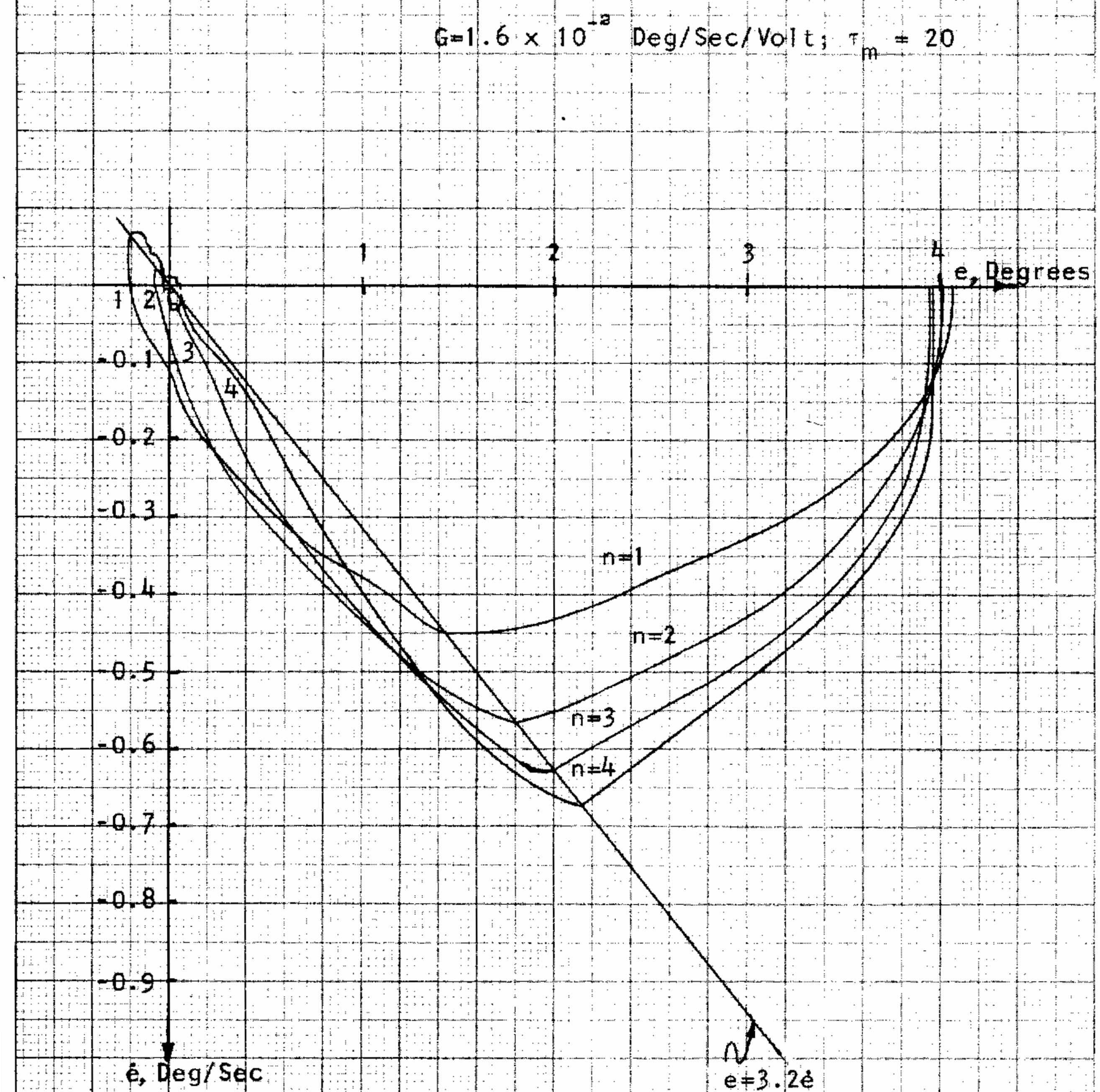
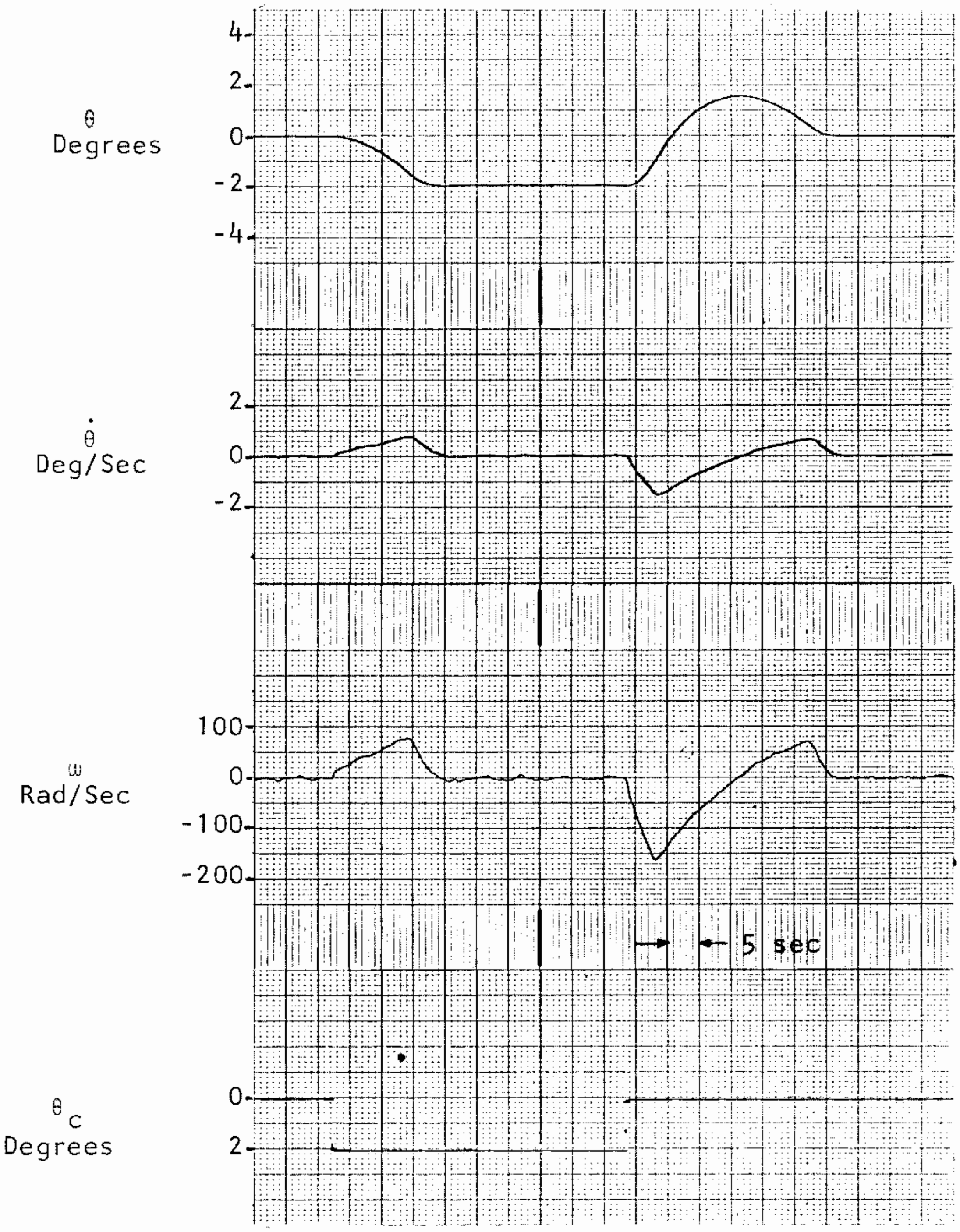



Figure 4.15: Effect of Number of PSV'S Used on Performance

A PSV unit can, of course, also fail such that its output performs either a random walk (with or without bias) or is locked at a constant non-zero level. The worst case is the hard-over failure with a PSV unit producing maximum output. The effect of a hard-over failure is shown in Figure 4.16. The maximum voltage produced at the motor terminals is now unbalanced. Thus, considering the first step input of Figure 4.16, there is the equivalent of a lowered gain, producing a lower $\theta(t)$ transient slope. However, during the terminal response phase, the opposite polarity is called for by the performance criterion, and, since full voltage is available, there is no significant effect on response in this phase. The opposite situation exists during the second step input of Figure 4.16. Here, the initial response phase is unaffected relative to normal performance. However, the terminal phase, operating at a lower effective gain value, produces a substantial overshoot. The overshoot cannot be oscillatory, however, for as soon as the error rate changes polarity, full plant capacity becomes available.

An index of self-adaptation capability is the range of plant parameter values to which the performance assessment criterion can be applied with a suitable (fixed) choice of the prediction interval, T. Although the full range of this "design adaptability" has not been established, an indication is available from the data accumulated in the course of evaluation of the Mark I and Mark II systems. Thus, the ratio of highest to lowest loop gain values for which SOC systems were tested is more than 9,000:1, and the corresponding ratio of prediction intervals needed to provide comparable transient response over this range was about 8:1. These figures are felt to be indicative of the design versatility of the control criterion.




$G = 8.2 \times 10^{-3}$ Deg/Sec/Volt; $\tau_m = 20$

-20 volts ≤ $v$ ≤ +40 volts

Figure 4.16: Effect of Hard-Over PSV Module Failure

## 4.5 System Configuration Test

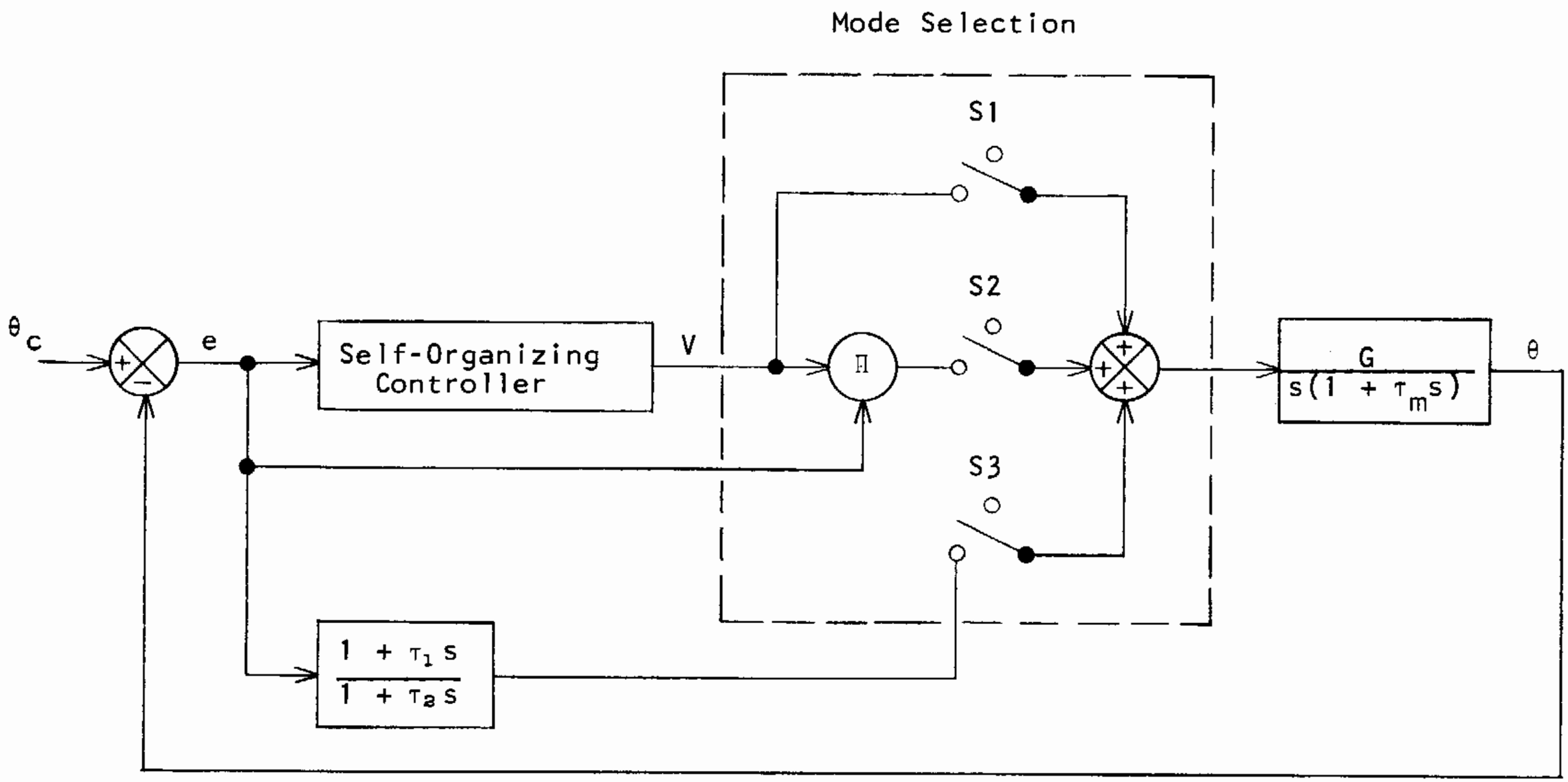
In addition to the control computer mode used for basic performance and adaptation testing, two alternate system configurations are of interest. These are shown in the block diagram of Figure 4.17.

In the gain multiplication mode, the output of the self-organizing controller is used to multiply the error, and this product is applied to the plant. A representative response obtained using this mode is shown in Figure 4.18(a). Figure 4.18(b) shows the improved performance obtainable in the control computer mode with identical plant and controller parameter values.

The SOC is handicapped in the gain multiplication mode by the fact that at small error values its authority is correspondingly reduced. Increasing or decreasing the relative authority of the self-organizing controller in this mode, by changing its maximum output voltage, will influence response as shown in Figures 4.19 and 4.20, respectively. Utility of the gain multiplication mode thus appears to be restricted cases where the terminal responses are shaped by suitable compensating networks in the error path, with self-organizing control used primarily to influence the initial response phase.

In the additive mode of operation, the output of the self-organizing controller is added to that from a conventional control circuit. Comparative performance data in this mode is shown in Figures 4.21 and 4.22.

The SOC is dominant in the additive mode because it can negate the output from the conventional circuit. It can do this most efficiently at small error values. However, the additive mode SOC can also take advantage of beneficial contributions from the conventional path, as judged by its performance

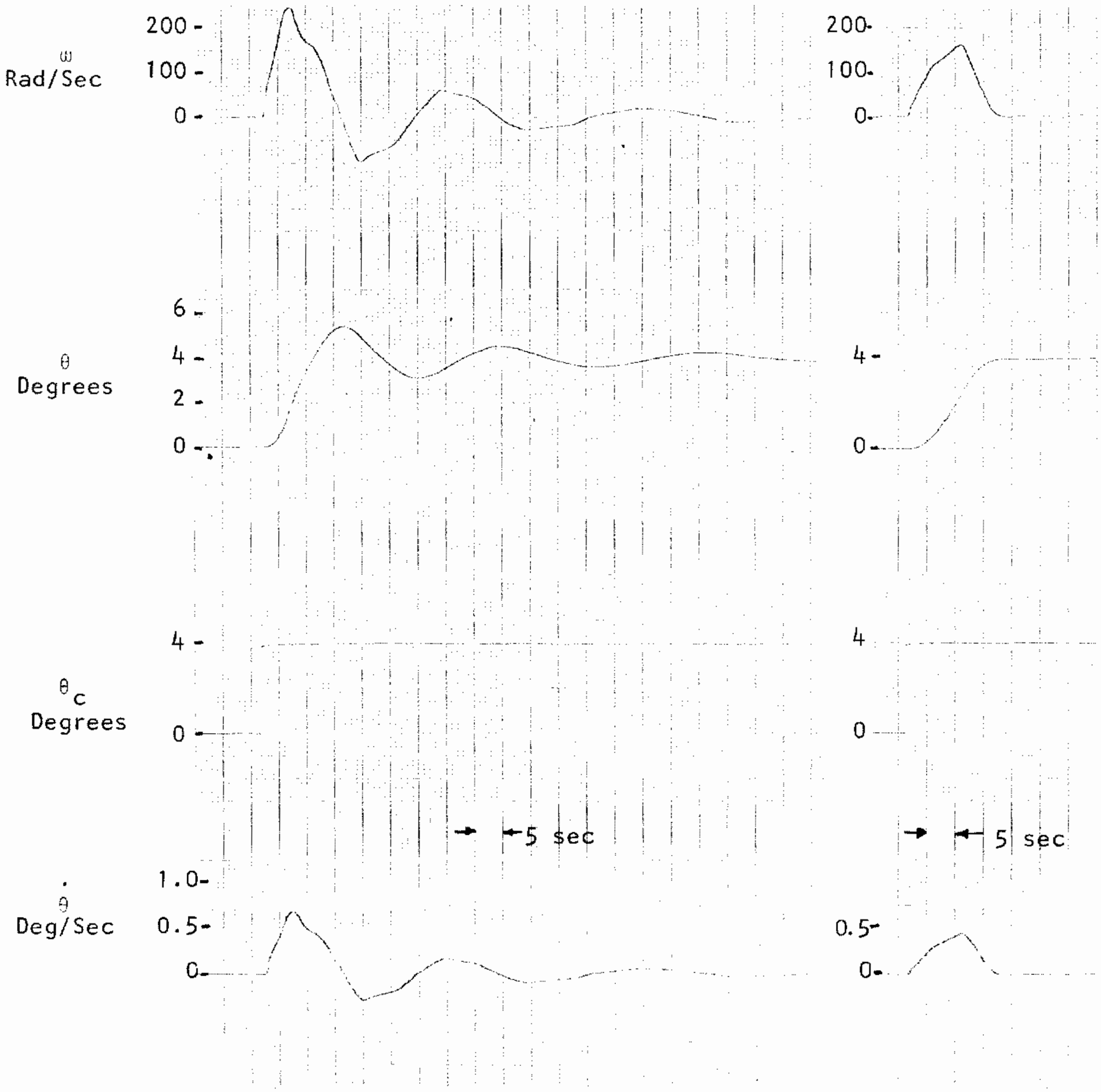



S1 closed - control computer mode

S2 closed - gain multiplication mode

S3 and S1 closed - additive mode

Figure 4.17: Block Diagram of System Configuration Tests




(a) Gain Multiplication Mode

n = 2

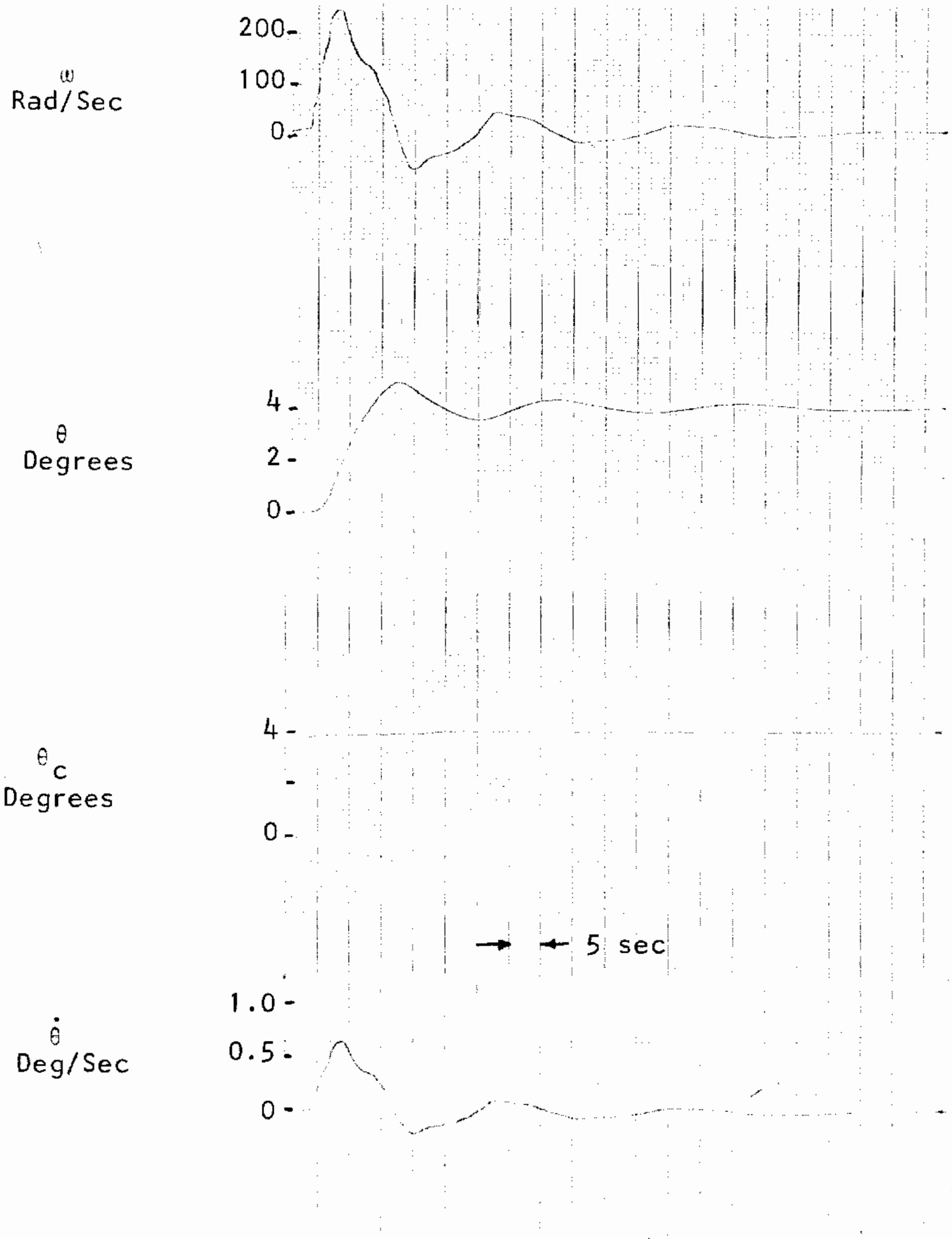
(b) Control Computer Mode

n = 2

$G = 1.64 \times 10^{-2}$ Deg/Sec/Volt

$\tau_m$ = 20 Sec

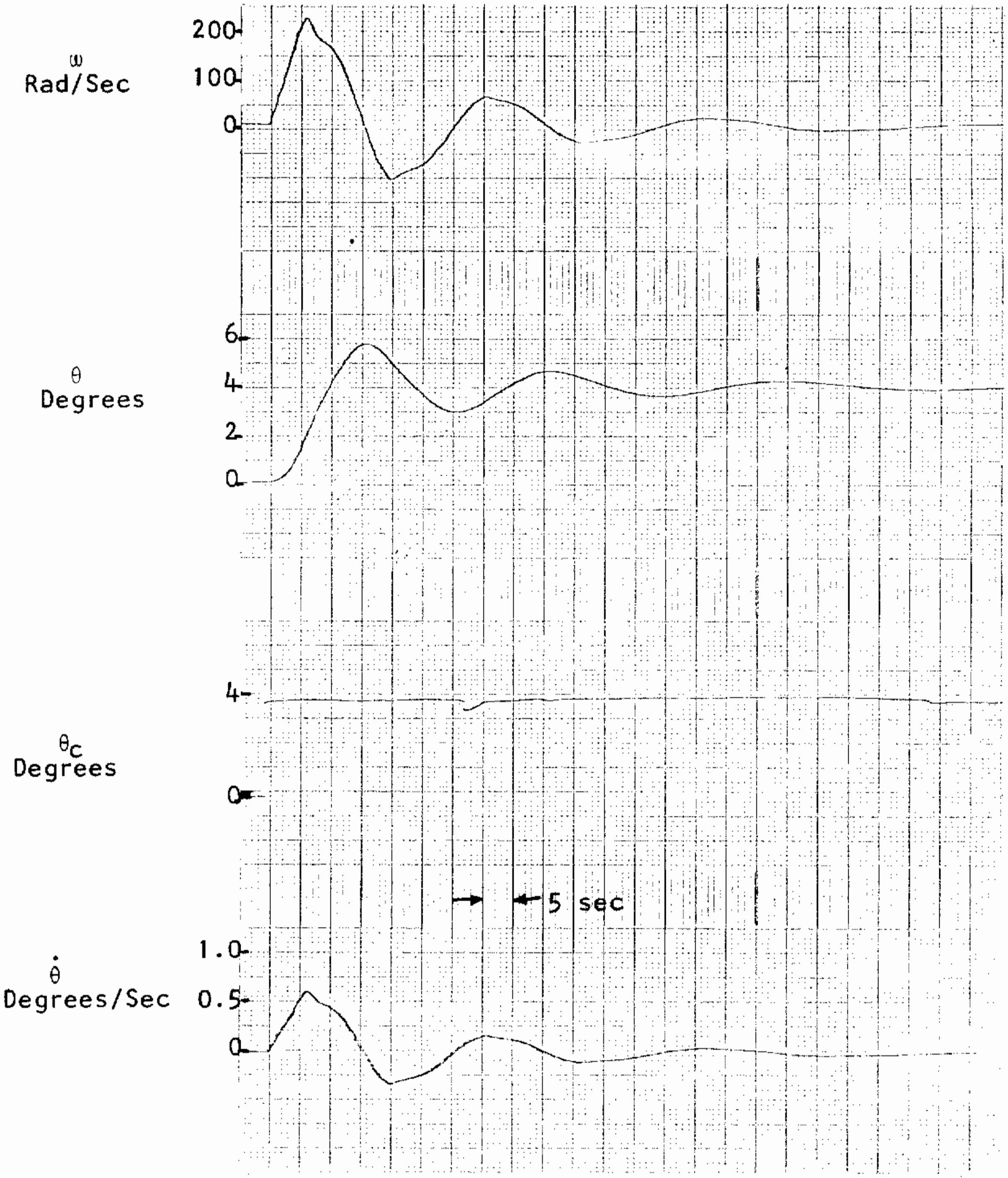
Figure 4.18: Comparative Data - Gain Multiplication Mode




n = 4

G = 1.64 x $10^{-2}$ Deg/Sec/Volt; $\tau_m$ = 20 Sec

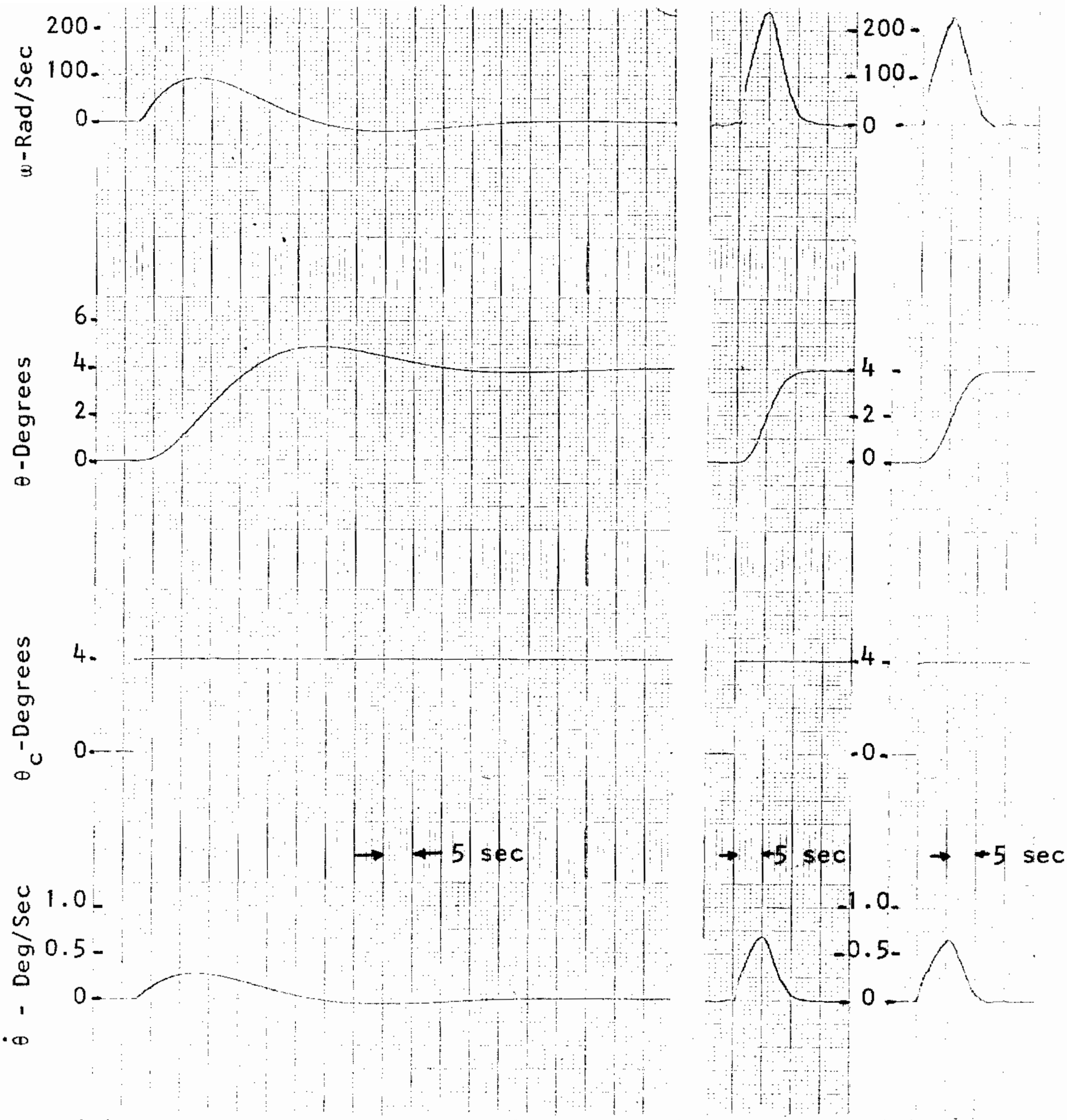
Figure 4.19: Gain Multiplication Mode with Increased SOC Authority




n = 1

G = 1.64 x $10^{-3}$ Deg/Sec/Volt; $\tau_m$ = 20 Sec

Figure 4.20: Gain Multiplication Mode with Reduced SOC Authority




(a) Constant Gain Control (CGC) Only $\tau_1$ = 10 Sec; $\tau_2$ = 5 Sec.

(b) CGC and SOC

(c) SOC Only n = 4

G = 1.64 x $10^{-2}$ Deg/Sec/Volt; $\tau_m$ = 20 Sec

Figure 4.21: Comparative Data - Additive Mode

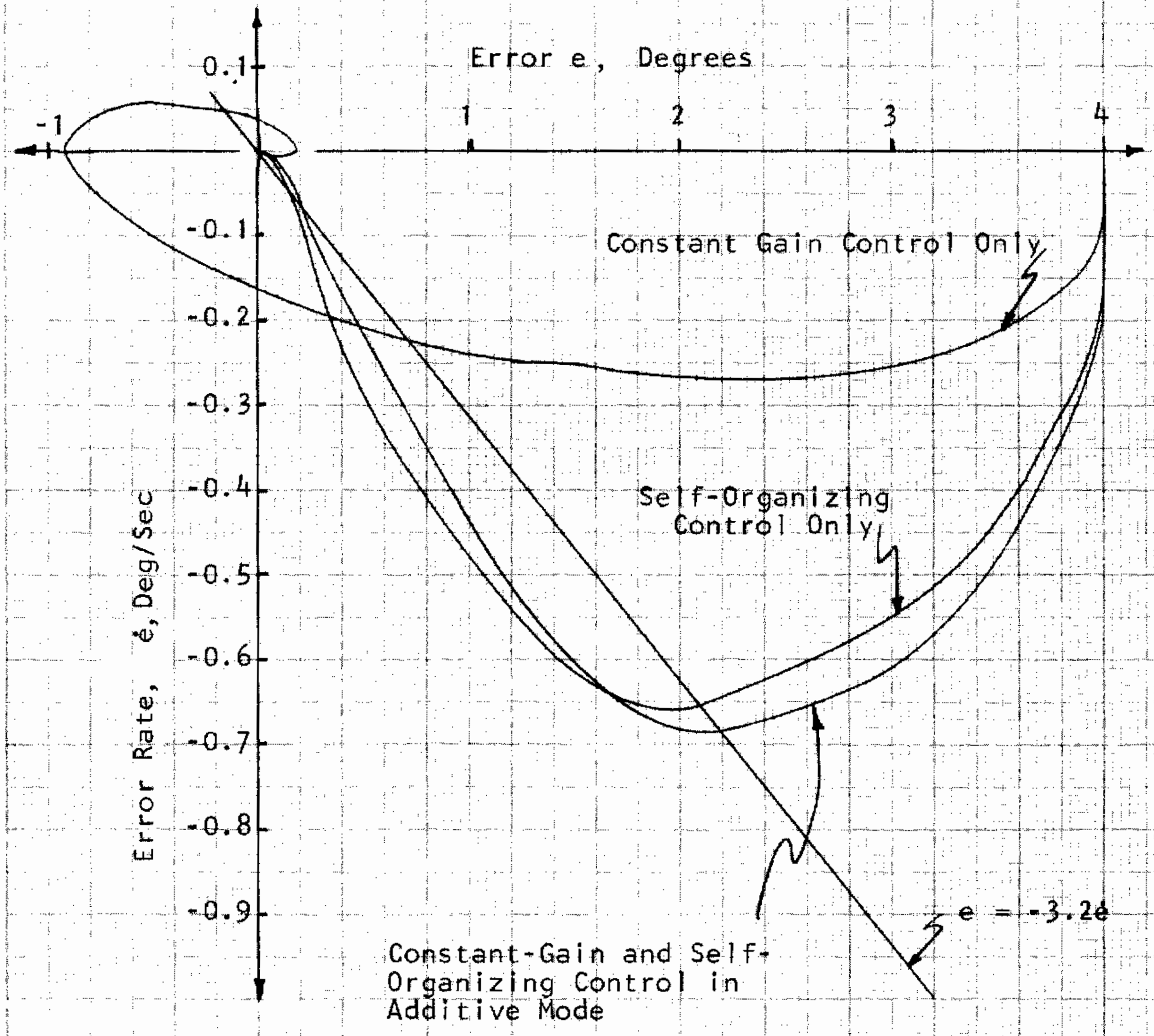



Figure 4.22: Phase-Plane Plot of Additive Mode Performance Data

assessment criterion. Although the performance in the additive mode of operation is not significantly different from that in the basic control computer mode, the additive mode offers a reliability advantage due to the parallel functional paths, plus convenience in implementation of an SOC "stop rule" (automatic learning inhibit and/or SOC disengage) if such is desired.

## 4.6 Hybrid System Tests

The self-organizing control system, operating with the simulated momentum wheel in the control computer mode, was combined with simulated on-off cold gas jet reaction systems as described in Appendix B. The purpose of this combination was to check for possible incompatibilities in hybrid system operation. However, no basic incompatibilities can be visualized and none were noted in these tests. The self-organizing controller, unless excluded by suitable logic, merely notes the effects of actuations within the jet reaction system and supplements the jet operation, both during the initial response phase, where the wheel contribution is minor, and during the terminal phase, where its effects are dominant.

Appendix C describes approaches to self-organization within the on-off actuator loops.

## 5. CONCLUSIONS

The development and evaluation efforts described in this report were concerned with both self-organizing systems and space vehicle attitude control. In assessing the major results of this effort, it is therefore desirable to consider these areas separately as well as together.

With regard to self-organizing systems, it is concluded that high-speed organization using probability state variable logic is feasible with current mechanization techniques to permit practical application in dynamic environments.

The space vehicle attitude control concept which has resulted from the application of self-organization techniques is concluded to be of practical utility with significant advantages in a large class of applications.

Noting that mechanization of these self-organizing spacecraft control concepts in actual application need not require significantly greater controller complexity than is required by conventional approaches, the principal merits of the new technique may be summarized as follows:

(1) Uniformly satisfactory transient and steady-state performance are obtained over a wide range of variation of spacecraft external and internal environmental parameters.

(2) Optimum utilization of momentum-storage actuators, in design as well as operation, is possible, permitting the most efficient use of their torque capabilities.

(3) Very high system reliability can be obtained through the use of "functional" redundancy, i.e., through design concepts which make full functional (as opposed to voting) use of available capability, whether this capability is in excess of the minimum required (so as to enhance performance) or is the minimum dictated by reliability specifications.

(4) Self-organization techniques can be used to reduce dependence on critical or precision control system components, either through elimination of such components or by the reduction of stringent component functional requirements.

The program reported in this document emphasized development and evaluation of a particular performance assessment criterion which, although highly effective and readily mechanized, is only one of a great many possible alternatives. To take full advantage of the high-speed self-organization capability demonstrated in this program, more encompassing performance goals can, and should, receive future attention.

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# APPENDIX A

# DIGITAL SIMULATION

# APPENDIX A: DIGITAL SIMULATION

This appendix presents flow charts and a summary of instructions for self-organizing controller simulation on digital computers. Much of the development work in designing the Mark I SOC and, to a lesser extent, the Mark II SOC was accomplished via digital simulations, and it is believed that the basic program described here provides a useful tool for further development efforts.

The simulations were accomplished on a G-15D computer. The Intercom 500X single-address programming system was used. This system performs arithmetic operations in a floating point mode using slightly more than five significant (decimal) digits. Subroutines written in machine language are callable by the Intercom 500X system as well as routines.

The flow charts and discussions that follow are not the detailed flow charts used in coding the program for the G-15D computer. Rather they have been generalized so as to be usable with any digital computer and any convenient programming language. The equations for the plant dynamics are included as well as the mathematical model of the Performance Assessment Module and the detailed logic of the PSV Module.

A block diagram of the system to be simulated is shown in Figure A1. A master flow chart for the computer program is shown in Figure A2. Both show a single PSV Module; however, the number of modules can be increased to any desired number by summing or otherwise combining the multiple outputs so as to present a single excitation signal (voltage) to the plant. Multiple PSVs are conditioned sequentially with the same $\overline{rp}$ input signal applied to each. The actuator and plant can also be enlarged by appropriate changes in the transfer functions and

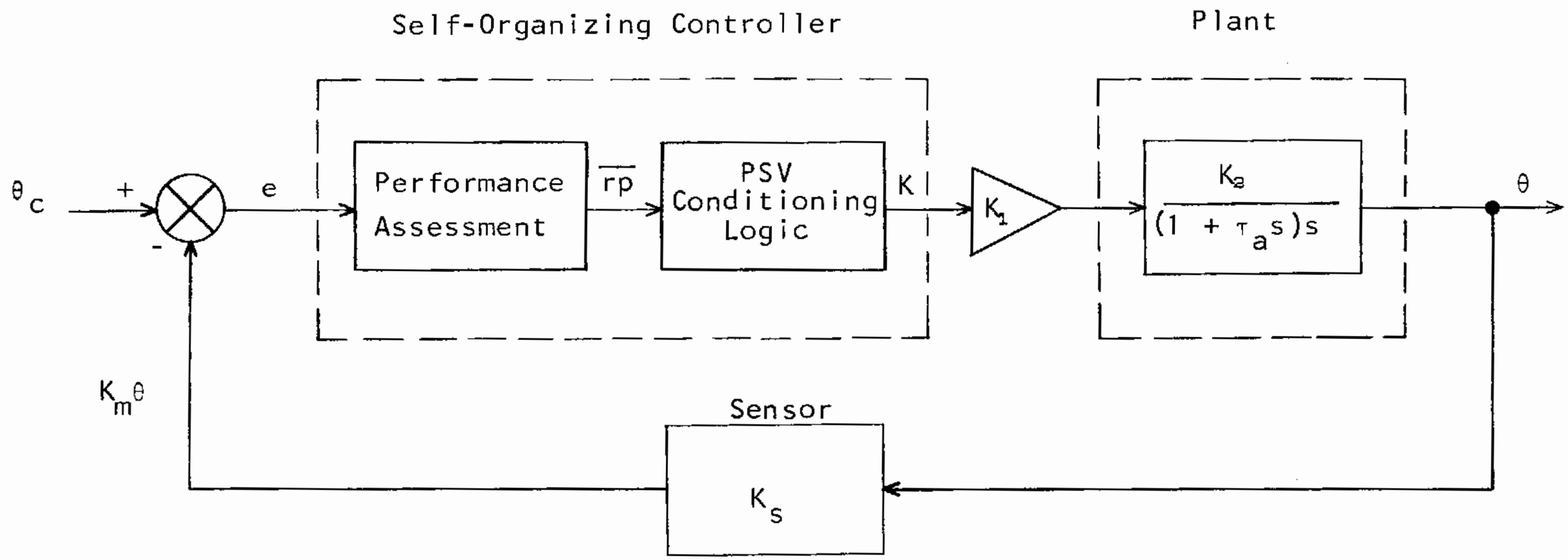


Figure A1: Self-Organizing Control System

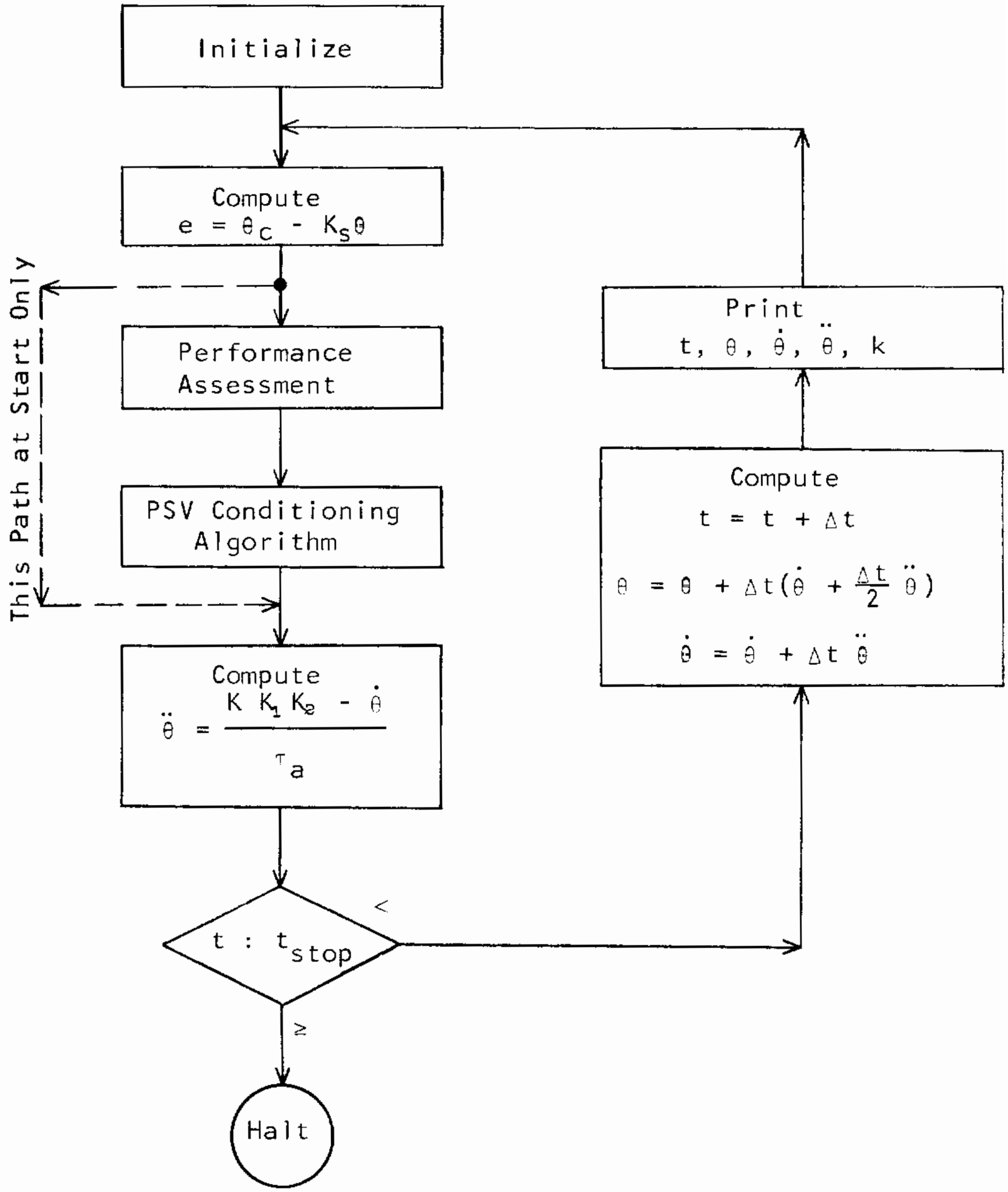


Figure A2: Flow Chart for Digital Computer Simulation of Self-Organizing Control System corresponding changes in the representative equations.

The performance assessment criterion implemented in the Mark I and Mark II SOC systems employs a first-order prediction function of error. The predicted error, tangentially extrapolated, is

$$e_p(t) = e(t) + T\dot{e}(e) \quad \ldots\ldots\ldots\ldots \quad A{:}1$$

where T is the prediction interval, taken as a constant. The $\overline{rp}$ conditioning signal, computed by the performance assessment logic, is

$$\overline{rp} = -\text{sgn}\ e_p\ \text{sgn}\ \ddot{e}_p \quad \ldots\ldots\ldots\ldots \quad A{:}2$$

This conditioning signal rewards a performance trend which <u>accelerates</u> the predicted error toward zero (convergent error trend) and punishes a divergent error trend represented by an acceleration of predicted error away from zero. This performance criterion is simple but has been found to give satisfactory results in the spacecraft attitude control application.

Figure A3 is a flow chart for realizing a performance assessment criterion equivalent to that of Equation A:2 in the digital simulation. To obtain the equivalent criterion, one may begin with Equation A:1 and differentiate, whence

$$\dot{e}_p = \dot{e} + T\ddot{e} \quad \ldots\ldots\ldots\ldots \quad A{:}2$$

Let us now introduce a function $\dot{P}$, such that

$$\left.\begin{aligned} \dot{P} &= -\frac{c}{T}\dot{e}_p, \quad e_p > 0 \\ \dot{P} &= \frac{c}{T}\dot{e}_p, \quad e_p < 0 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots \quad A{:}3$$

where c is an arbitrary positive constant. Equation A:3 may be

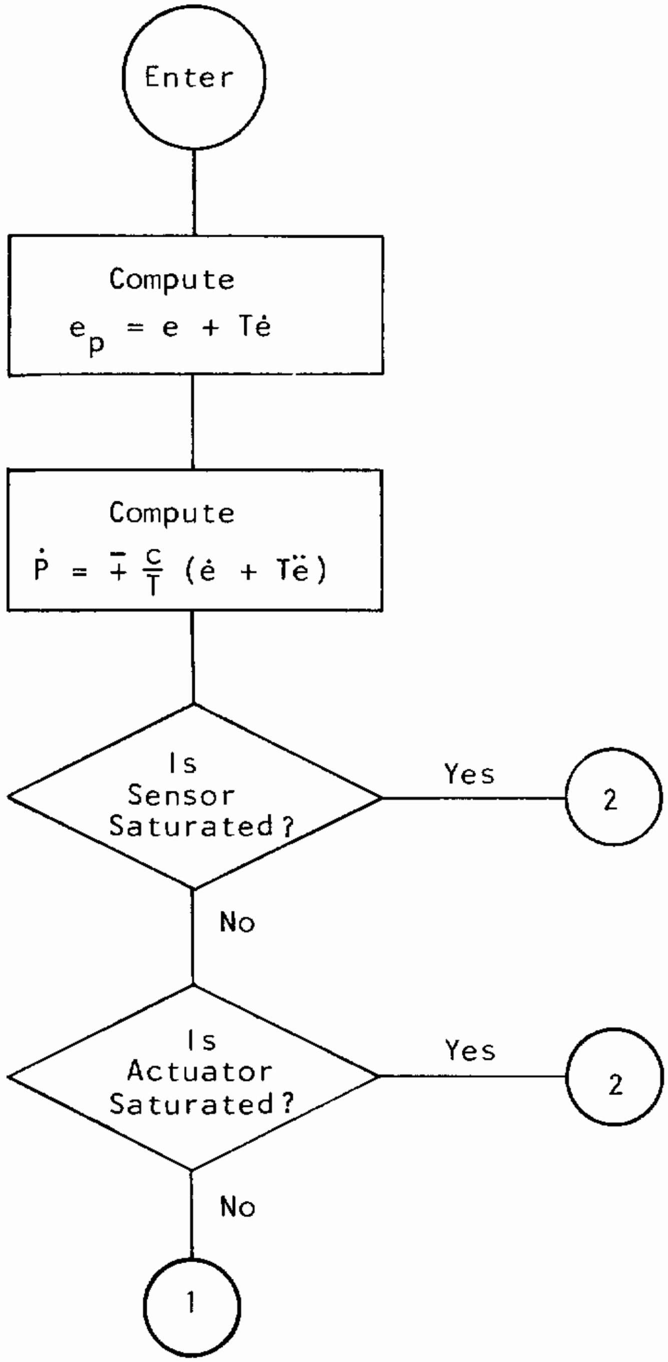


Figure A3: Performance Assessment

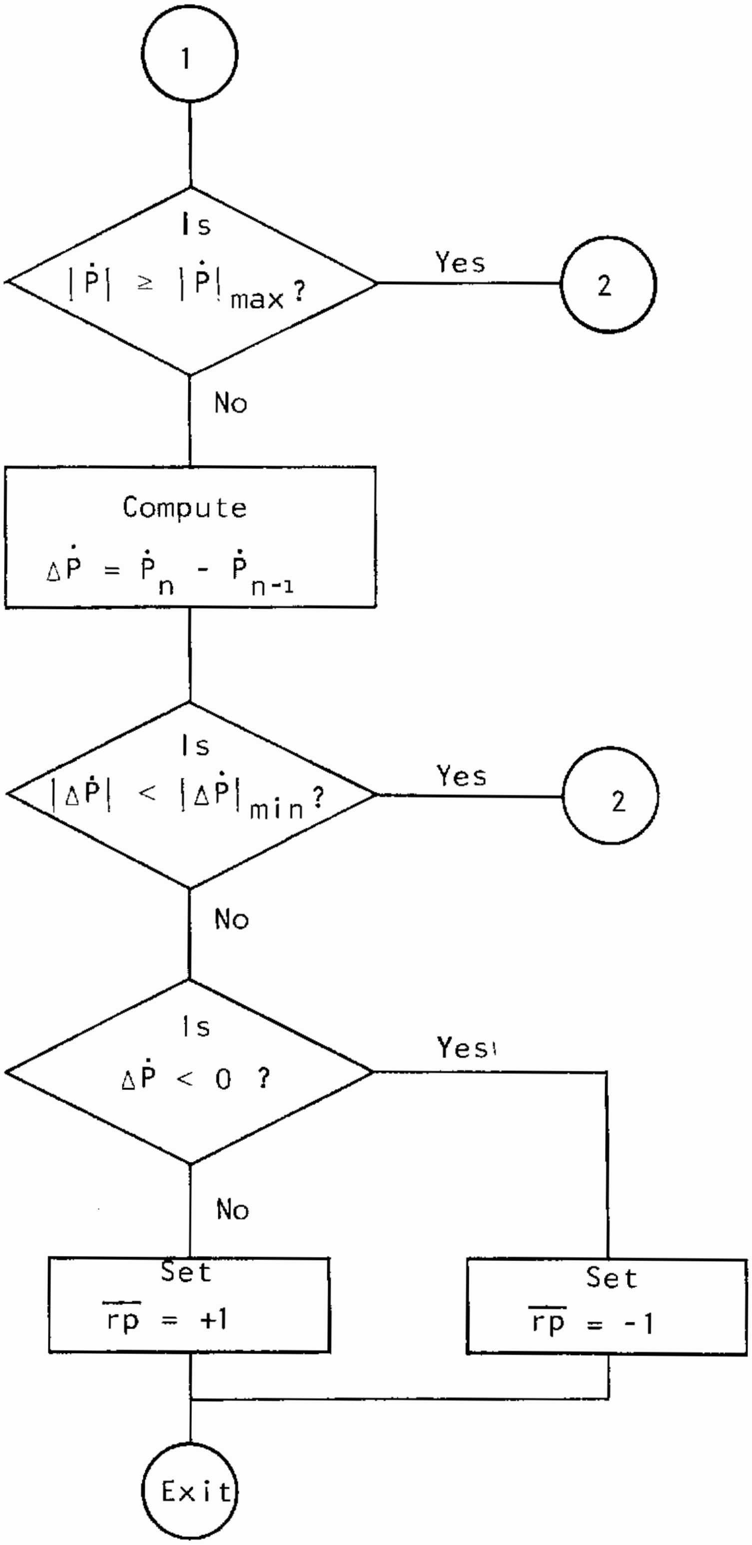


Figure A3: Performance Assessment, Continued

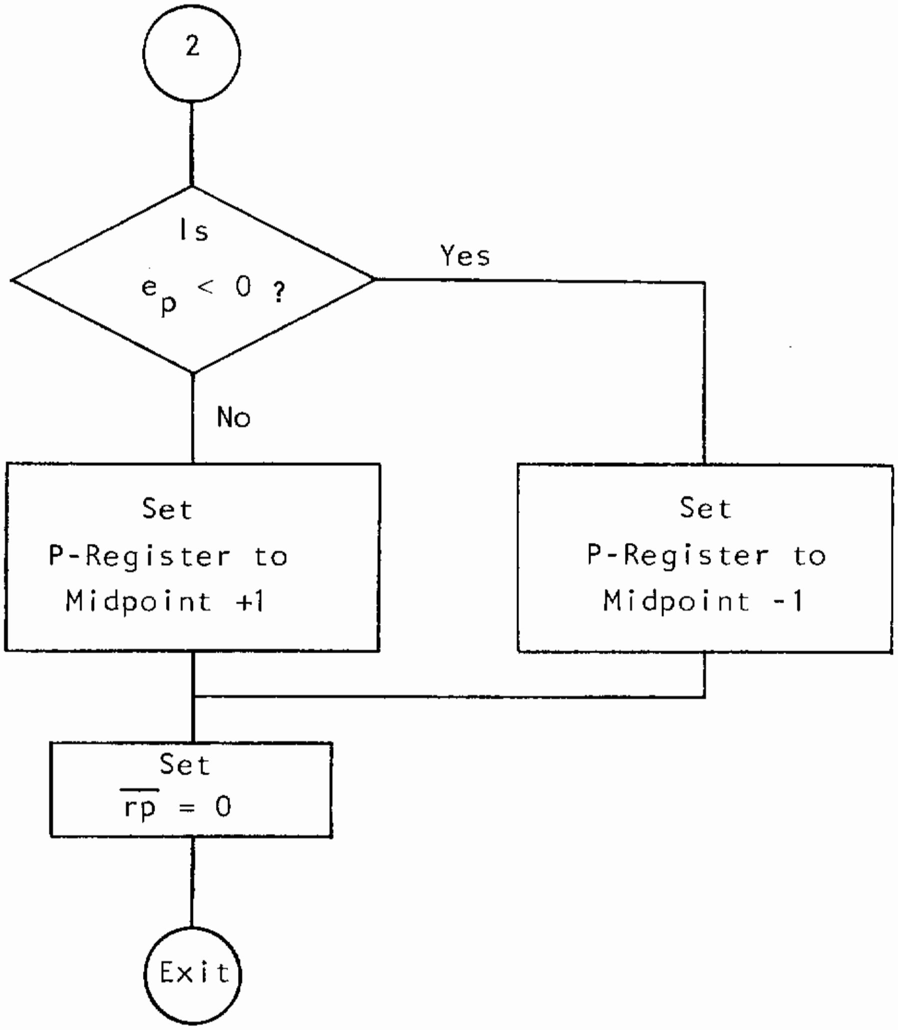


Figure A3: Performance Assessment, Concluded expressed in the more compact form

$$\dot{P} = -(\text{sgn } e_p) \frac{c}{T} \dot{e}_p \quad \ldots\ldots\ldots\ldots \quad A{:}4$$

Further, we note that

$$\ddot{P} = \frac{\Delta \dot{P}}{\Delta t} = \frac{\dot{P}(t) - \dot{P}(t - \Delta t)}{\Delta t} \quad \ldots\ldots\ldots\ldots \quad A{:}5$$

or, substituting Equation A:4

$$\ddot{P} = -(\text{sgn } e_p) \frac{c}{T \Delta t} \left[ \dot{e}_p(t) - \dot{e}_p(t - \Delta t) \right] \quad \ldots\ldots \quad A{:}6$$

Thus

$$\ddot{P} = -(\text{sgn } e_p) \frac{c}{T} \ddot{e}_p \quad \ldots\ldots\ldots\ldots \quad A{:}7$$

and

$$\text{sgn } \ddot{P} = -\text{sgn } e_p \text{ sgn } \ddot{e}_p \quad \ldots\ldots\ldots\ldots \quad A{:}8$$

But, from Equation A:5

$$\text{sgn } \Delta \dot{P} = \text{sgn } \ddot{P} \quad \ldots\ldots\ldots\ldots \quad A{:}9$$

Therefore

$$\text{sgn } \Delta \dot{P} = -\text{sgn } e_p \text{ sgn } \ddot{e}_p \quad \ldots\ldots\ldots\ldots \quad A{:}10$$

and

$$\overline{rp} = \text{sgn } \Delta \dot{P} \quad \ldots\ldots\ldots\ldots \quad A{:}11$$

used in the digital simulation is a proper analog of the function in the hardware Performance Assessment Module.

In the digital computer simulation, each PSV Module is represented by a data block, as shown in Figure A4. Each P register and K register is represented by one word of storage. In the simulation on the G-15D computer, one word was also used for each stage of the Memory register, as seen in Figure A5. In addition to the PSV Data Block, a table of probability values and a table of K values are required. The statistical source noise generator is represented by a random number generator, which may use the power residue method to produce a series of pseudo-random numbers having uniform distribution.

The flow chart for the PSV Module conditioning algorithm is depicted in Figure A6. This routine was coded in machine language, and all operations were performed in the binary number system. A table look-up procedure was used to map the P register contents into a probability value and the binary K register into a floating point decimal output.

Since Figure A6 represents the simulation as programmed on the G-15D and thus is not generalized to the same extent as the other portions of the program, more detailed discussion of this routine is desirable. The programming is nearly optimal for the G-15D but may not be so for computers with different characteristics.

Refer now to Figure A6. Step 1 is the action to determine whether to increment or decrement the P register by the $\overline{rp}$ signal. Recall that the $\overline{rp}$ signal is ternary, i.e., -1, 0, or +1 for simulation purposes. The $G_i$ are the K register outputs in binary for the time period these outputs are held in memory, the $G_i$ being spaced at $\Delta t$ intervals. A comparison of $G_{n-i}$ to $G_{n-1-i}$ reflects the direction of change in the K register. If no change took place, the output of the K register was one of its limiting values. The test $G_{n-i}$:0 establishes which limiting value, since $G_{n-i} = 0$ implies the lower limit of K-register travel.

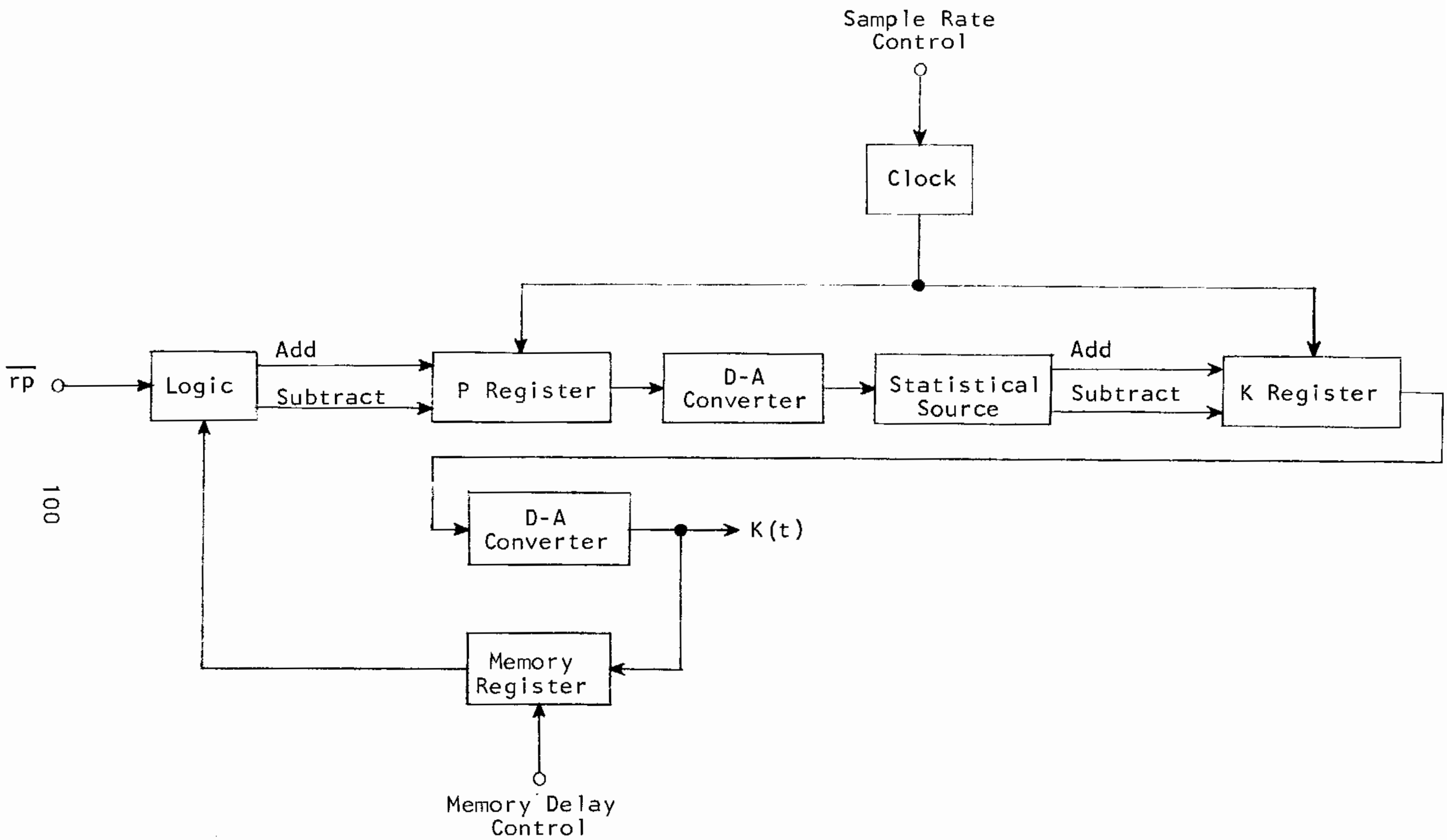


Figure A4: Probability State Variable (PSV) Conditioning Logic Module

| Word | Contents | Flow Chart Symbol | Number System |
|---|---|---|---|
| 1 | P Register | $\gamma$ | Binary |
| 2 | K Register | K | Decimal |
| 3 | Memory Register | $G_n$ | Binary |
| 4 | | $G_{n-1}$ | Binary |
| 5 | | $G_{n-2}$ | Binary |
| 6 | | $G_{n-3}$ | Binary |
| 7 | | $G_{n-4}$ | Binary |
| 8 | | $G_{n-5}$ | Binary |

Figure A5: PSV Data Block

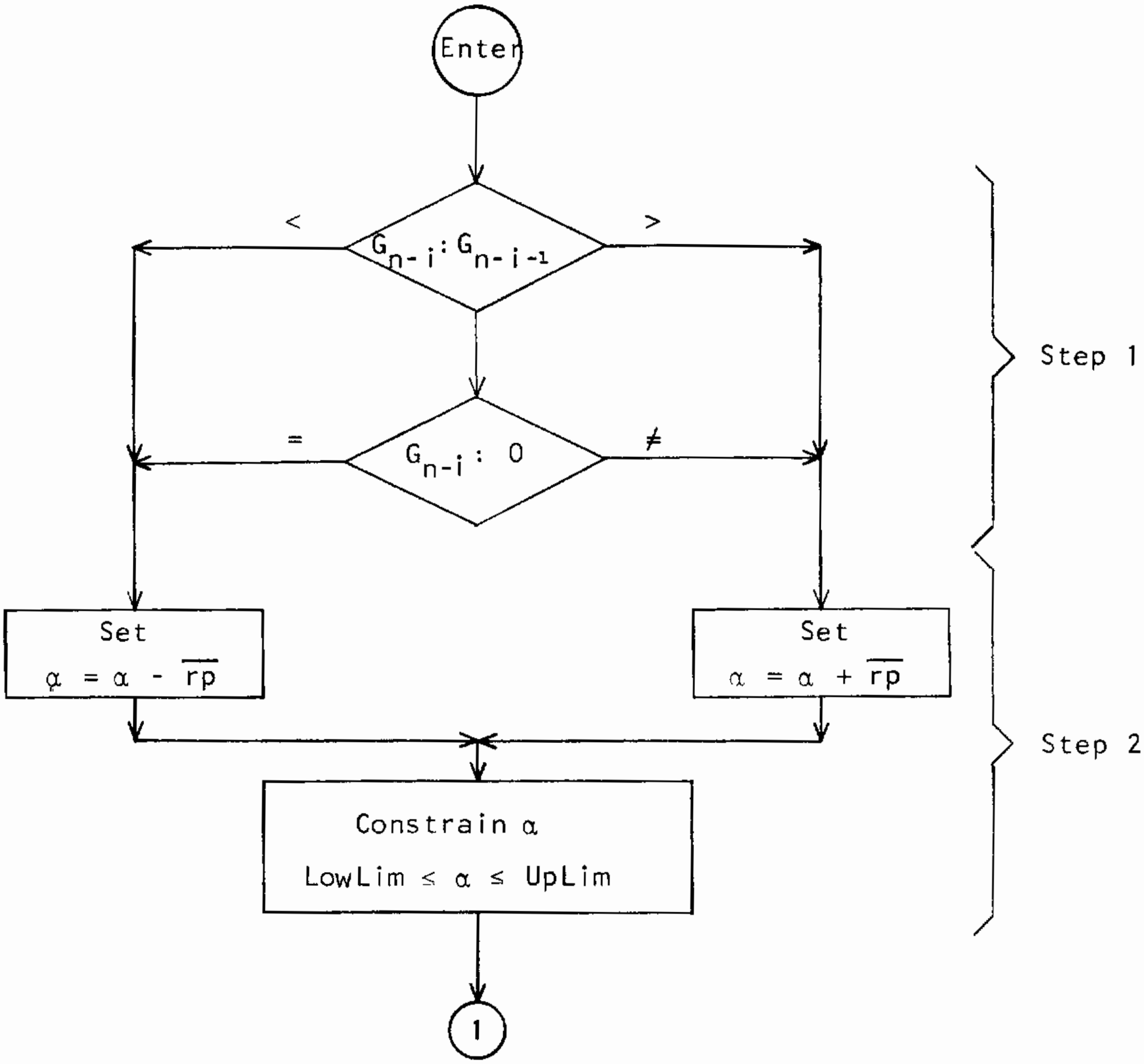


Figure A6: PSV Conditioning Algorithm

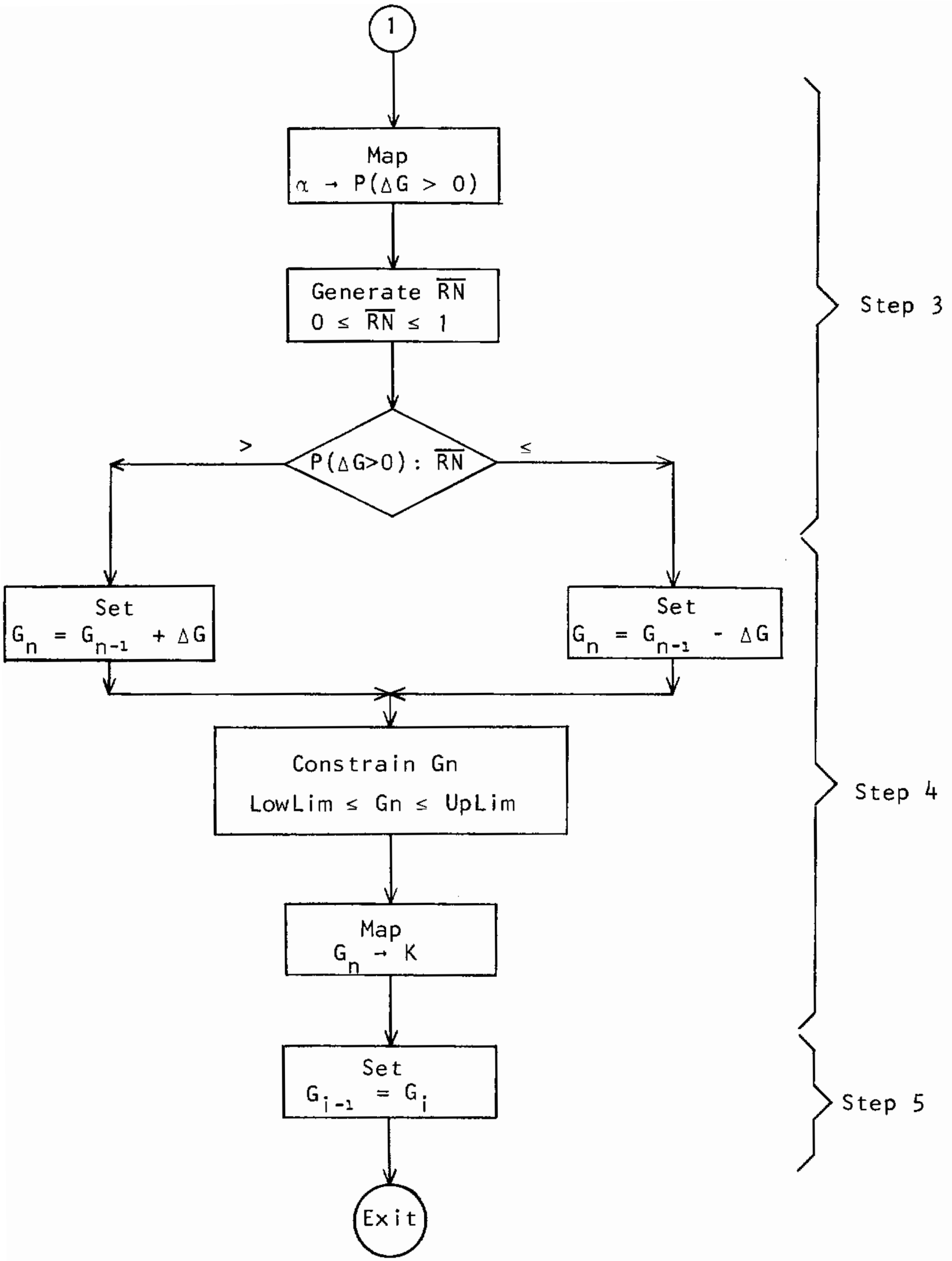


Figure A6: PSV Conditioning Algorithm, Continued

During Step 2, the P register is counted in the indicated direction and is restricted to its bounds. These bounds can be changed to produce a P register of any desired length.

In Step 3, alpha (i.e., the contents of the P register) is mapped into a probability value through a table look-up procedure. The probability of each direction of change of the K register is thus established in accordance with the bias of the P register. This probability value is compared to a random number, which is scaled to the range between zero and unity. The K register is subsequently changed as indicated by the comparison.

In Step 4, the change in the K register takes place. This change was performed in binary arithmetic in the G-15D simulation. $\Delta G$ was one increment. The upper and lower bounds on G can be set to produce a K register of any desired length. The final operation in Step 4 is to map $G_n$ into K, a floating point decimal number. This mapping is also done through a table look-up.

Step 5 shifts the contents of the Memory register and returns program execution to Step 1 one sample period later.

# APPENDIX B

# ANALOG SIMULATION

# APPENDIX B: ANALOG SIMULATION

This appendix describes the analog simulation circuits and computer diagrams that were used in evaluation of the Mark I and Mark II engineering models of the self-organizing spacecraft attitude controllers.*

Figure B1 shows the simulation circuit incorporated in the Mark I system. Amplifier A1 provides, by permitting variation of $C_1$ and $C_2$, a variable lead-lag filter which is intended for use as a phase compensation network where required. Amplifier A2 is in a first-order lag circuit with selectable time constant for simulation of the motor and inertia-wheel actuator. A3 is in a differentiating circuit which computes $\ddot{\omega}$, the inertia-wheel acceleration. A two-position switch, S1, inserts or removes saturation limits on $\dot{\omega}$. A4 and A5 are in integrating circuits which simulate the rotational dynamics of the vehicle. An input is provided to permit the study of torque disturbance effects. The input to the simulation circuit (Figure B1) is K(t), the PSV logic output signal, and the output is $\theta$(t), which is the vehicle attitude.

Figure B2 shows the basic analog computer network which was implemented on an EAI Model 231R to provide a simulation of a representative space vehicle momentum-wheel control loop (see Ref. 1 and discussion in Section 4). Except for a considerable difference in forward gain, this network is functionally the same as the Mark I simulation. The nominal potentiometer settings for the network are listed below:

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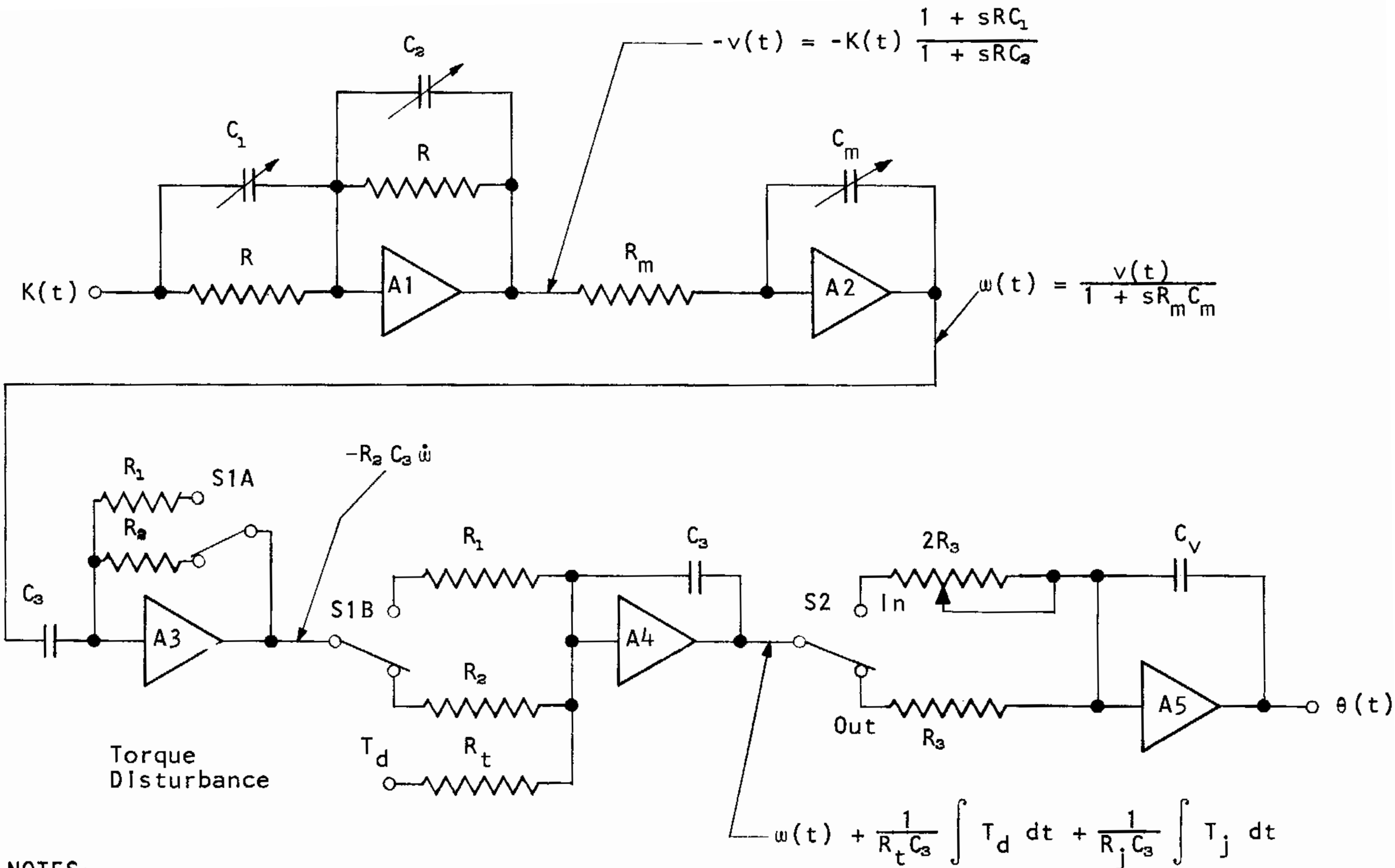
*See footnote, p. 51.




NOTES:
1. S1 Switches Between Linear and Saturating Actuator Mode
2. S2 Switches a Torque Disturbance In or Out

Figure B1: Simulated Environment, Mark I Self-Organizing Controller

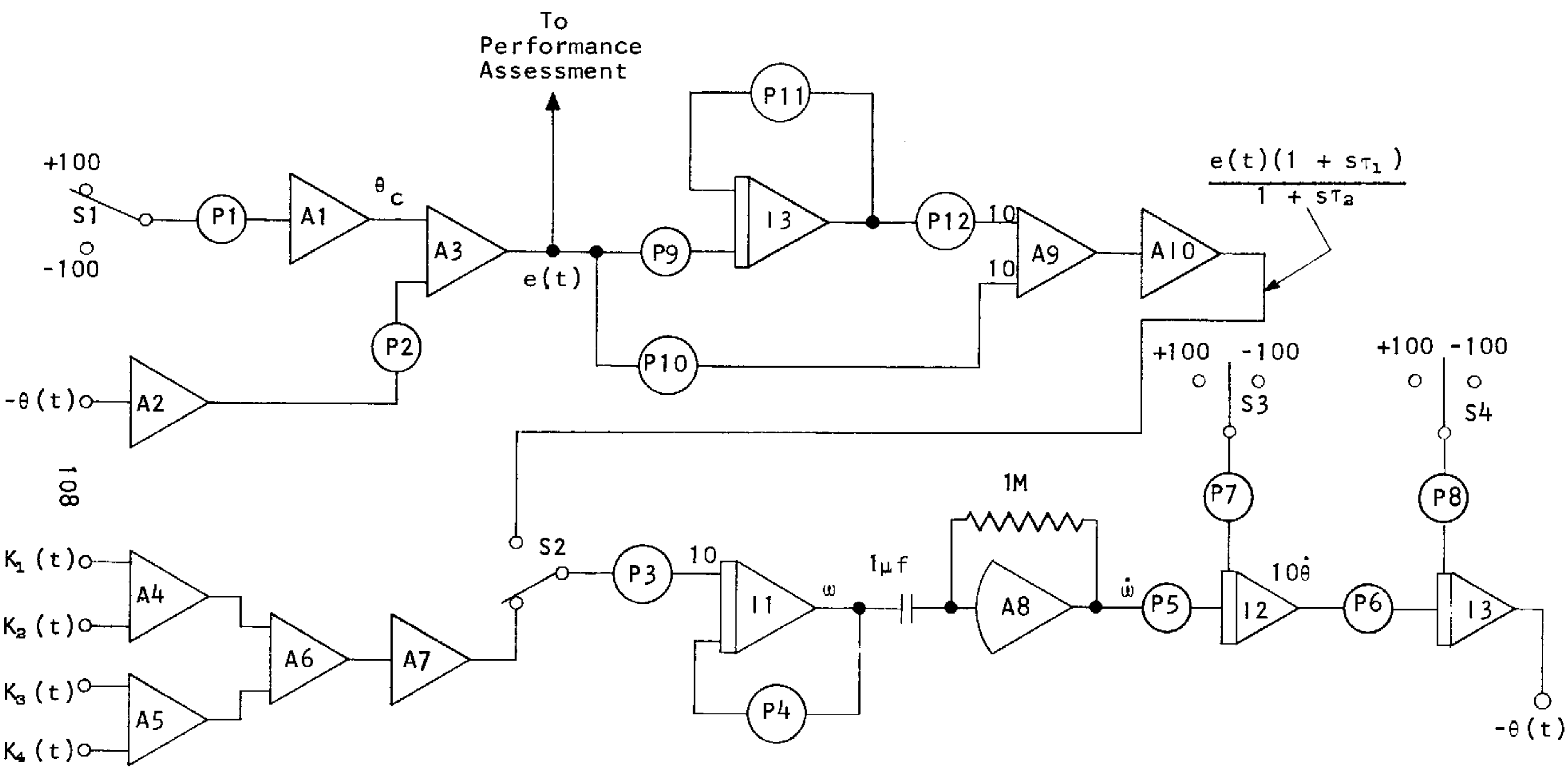



Figure B2: OAO Coarse Momentum-Wheel Simulation

| | | |
|---|---|---|
| P1 | 0.020 | $\theta_c = 2$ Degrees |
| P2 | 1.00 | |
| P3 | 0.150 | $K_a = 30$ |
| P4 | 0.0500 | $\tau_m = 20$ |
| P5 | 0.0274 | } 57.3 $I_w/I_v$ |
| P6 | 0.100 | |
| P7 | 0.025 | $\dot{\theta}(0) = 0.25$ Deg/Sec |
| P8 | 0.010 | $\theta(0) = 1$ Degree |

Amplifier A3, Figure B2, is the control loop error sensor, computing the difference between the reference input, $\theta_c$, and the vehicle attitude, $\theta(t)$. Switch S1 selects a positive, negative, or zero reference input. Integrator I3, and amplifiers A9 and A10 form a lead-lag filter which is used for phase-lead compensation when the loop is operated as a fixed-gain controller. Switch S2 selects either a fixed-gain conventional loop, or the self-organizing control loop. Amplifiers A4 - A7 serve as a summation circuit for the PSV Module outputs. Integrator I1 is the motor momentum-wheel simulation, whose gain and time constant are controlled by P3 and P4. A8 differentiates the wheel rate, $\omega$, to compute $\dot{\omega}$ for possible application of acceleration limits. Integrators I2 and I3 are the simulation of the satellite rotational dynamics, with P5 and P6 giving the correct ratio between wheel and satellite inertias. Initial conditions of rate and position are inserted when required by S3 and S4. Figure B2 shows the self-organizing controller in the control computer configuration. The gain-learning and additive operating configurations described in Section 4 were obtained by appropriate scaling and combination of the outputs of A7 and A10, with the combination applied to P3.

Figure B3 shows the analog computer network which was used to simulate the cold-gas reaction-jet dynamics (see Ref. 1 and Appendix C). A combination of error and rate feedback is used to actuate the jet control valves, which are simulated by Amplifiers A3, A4, A7, and A8. Relay comparators M0 and M1 provide the required hysteresis and switching. Amplifier A10 simulates the delay associated with physical jet actuation. In hybrid system operation, the jet torque output is applied to the vehicle simulation circuits shown in Figure B2.

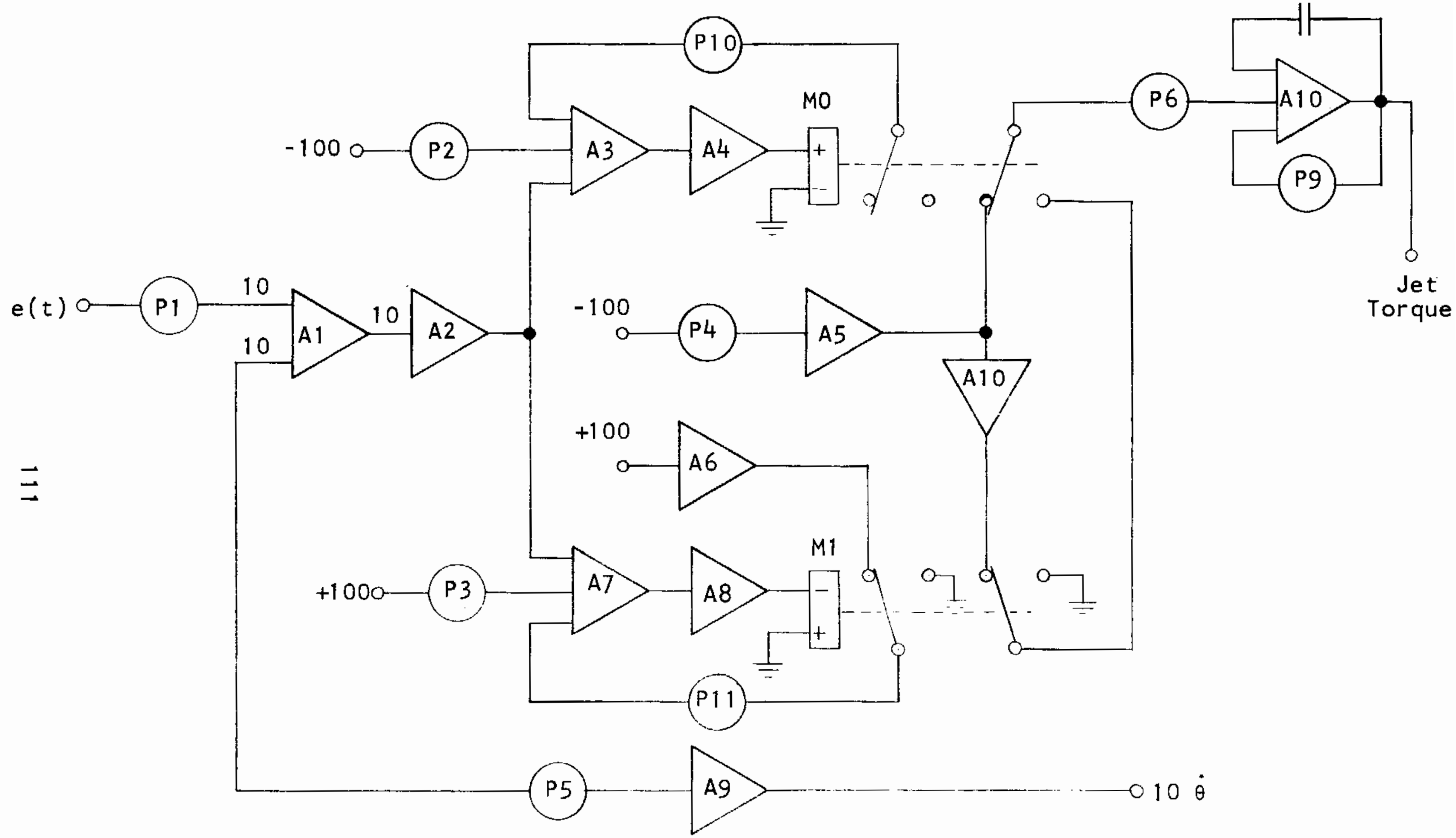



Figure B3: Reaction-Jet Actuator Simulation

# APPENDIX C: APPROACHES TO SELF-ORGANIZATION IN ON-OFF CONTROL LOOPS

This appendix treats the application of self-organizing control techniques to on-off type control loops. The performance assessment requirements in SOC design for on-off control devices are different from the requirements discussed in the body of this report for two major reasons:

(1) The large discontinuities in actuator output prevent use of prediction for performance assessments.

(2) The need for conservation of stored propellants can introduce an additional goal requirement.

It is emphasized that, as indicated in the body of this report, jet actuations which take place in loops external to a momentum-wheel loop do not raise difficulties insofar as stabilization and control via the momentum-wheel loop are concerned.

The formulation of performance assessment criteria will now be re-examined briefly to facilitate discussion of alternate approaches for on-off loops.

For successful employment of predictive performance assessments, continuous or at least quasi-continuous plant operation is usually necessary. To help clarify this statement, let us again consider self-organizing techniques which make successive performance assessments at discrete times, $t_j$, j = 0, 1, ..., N. Suppose the following performance index form is used

$$I = \sum_{j=0}^{j=N} \int_{t_j}^{t_j + \Delta t} |f(t)|\,dt \qquad \text{C:1}$$

where $\Delta t$ is the interval between two successive assessments. The summation operator is required in the performance index because over-all response is the aggregate of a sequence of system responses to successive actions by the controller. At each point, $t_j$, the best that the controller can do (unless it is an optimum two-point boundary-value controller) is minimize the quantity

$$I_j = \int_{t_j}^{t_j + \Delta t} |f(t)| dt \quad \text{.......................... C:2}$$

Provided the plant operation is continuous, one may approximate Equation C:2 as follows

$$I_j = \left(|f(t)|\right)_{t=t_j} \Delta t + \left(\frac{d}{dt}|f(t)|\right)_{t=t_j} \frac{\Delta t}{2} +$$

$$\text{higher-order terms} \quad \text{....... C:3}$$

Ignoring the higher-order terms, on the basis of very small sample interval, $\Delta t$, the first derivative of $I_j$ becomes

$$\left(\frac{d}{dt} I_j\right)_{t=t_j} = \left(\frac{d}{dt}|f(t)|\right)_{t=t_j} \Delta t +$$

$$\left(\frac{d^2}{dt^2}|f(t)|\right)_{t=t_j} \frac{\Delta t}{2} \quad \text{........ C:4}$$

If the controller is to minimize $I_j$ (see above), it is apparent that the derivative of $I_j$ must be as strongly negative as possible. This condition leads to a requirement on SOC operation, namely that the SOC maintain (on a better-than-average basis)

$$\left(\frac{d^2}{dt^2}|f(t)|\right)_{t=t_j} < 0 \quad \text{.......................... C:5}$$

A requirement has here been imposed on the second derivative term only, because the first derivative is usually a function solely of plant state variables (and therefore is not subject to alteration at a point in time).

Expression C:5 is, of course, equivalent to the requirement established in Section 3.1, where we wrote

$$V = |f(t)| = |e_p| \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad C:6$$

whence

$$\overline{rp} = -\ddot{V} = -\text{sgn } e_p \text{ sgn } \ddot{e}_p \quad \ldots\ldots\ldots\ldots \quad C:7$$

The above reformulation of the Type 1 performance assessment relationship serves to underscore the importance of continuity of plant operation, for without continuity, the basic assumptions used to develop this relationship are evidently violated.

The Mark II self-organizing controller was tested in a reaction-jet control loop (see discussion of simulation aspects in Appendix B). The SOC was used to vary gain, first in the forward part of the loop and then in the feedback (rate gyro) path, using a Type 0307 PSV Module for both purposes. The Type 1 Performance Assessment Module, as well as a performance assessment unit using

$$\overline{rp}_J = -\dot{V} = -\text{sgn } e_p \text{ sgn } \dot{e}_p \quad \ldots\ldots\ldots\ldots \quad C:8$$

were evaluated in this application. Sample intervals in the range 0.05 - 1.00 sec. were tested. (It was found that longer intervals might be desirable in some cases, but such intervals were not readily available in the existing equipment.)

Transient response performance was not improved in the jet loop using either Equation C:7 or Equation C:8 as the basis for performance assessments. The controller was not able to reach a significant correlation between trials in its gain state and resultant predicted responses, apparently due to the abrupt discontinuities in jet operation. These discontinuities were not always an immediate consequence of gain changes (and therefore could not register on the pertinent predictions). It was also observed that the circuit for computing $\ddot{e}_p$ frequently overloaded because of the large accelerations produced by jet thrusting. However, had the input to this circuit been rescaled to prevent saturation, nominal $\ddot{e}_p$ levels would have then been very much less than the noise level existing at the differentiator output.

The problems which attend use of either C:7 or C:8 in transient operation of an on-off control loop are, of course, forecast by the theory (see above), and the results of tests performed with the Mark II SOC appear to verify that forecast. However, a very interesting phenomenon was observed during steady-state operation: the existence of a random walk in the forward-loop gain state served to damp and, ultimately, remove the limit cycle otherwise present.

The system repeatedly brought itself to rest during the steady-state in this manner, using the jet loop alone, there being no means for momentum storage simulated in this particular aspect of the work. Because of the important implications for spacecraft design, further work is recommended to develop mathematical models and applications criteria for systematic exploitation of this limit-cycle damping phenomenon.

To achieve satisfactory self-organization during transient response phases, it is recommended that <u>historical information</u> performance assessments be employed. These assessments can be based on the difference

$$\Delta I_{j-2,\ j-1} = I_{j-1} - I_{j-2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad C{:}9$$

The SOC should seek to make this difference as strongly negative as possible. The quantities $I_{j-2}$ and $I_{j-1}$ may be computed by analog integration.

The historical information performance assessment requires a tailored system configuration that exhibits acceptable transient response characteristics despite the use of constant parameters throughout the duration of most transients. The gain multiplication mode combined with suitable lead-lag shaping of the error signal would probably meet this requirement, which arises because of the relatively long time periods which must elapse between successive performance assessments. These longer $\Delta t$ intervals result in much slower SOC convergence to optimum parameter levels than is experienced with momentum-wheel SOC loops.

An approach to multiple goals for on-off loop self-organization could proceed from the use of performance indices of the form

$$I_j = \int_{t_j}^{t_j + \Delta t} |f(t)|\,dt + \sum_i k_i \int_{t_j}^{t_j + \Delta t} |g_i(t)|\,dt \quad \ldots . \quad C{:}10$$

where the $g_i(t)$ embody restraint conditions, e.g., fuel-flow rate, etc., and the $k_i$ are positive trade-off factors. $\Delta I_{j-2,\ j-1}$ would be calculated as before. It is recommended that indices of the type in Equation C:10 be investigated in the course of future theoretical work and application studies.

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**13. ABSTRACT**

Results are presented from an investigation of self-organizing attitude control and stabilization for spacecraft. Self-organizing (SOC) control is achieved through high-speed assessments of performance values of successive random experiments with respect to a generalized control criterion, followed by a "reward-punishment" reinforcement process to obtain on-line synthesis of plant actuation signals. The logic is of the Probability State Variable (PSV) type, i.e., reinforcement signals are used to bias the probabilities associated with the SOC experiments. Convergence of SOC output signals to appropriate, time-varying levels generally occurs within several milliseconds, resulting in rapid, well damped, stable control over a very wide range of controller, plant, and disturbance characteristics (including induced artificial failures). A laboratory experimental self-organizing controller has been fabricated. Evaluations of this SOC have been conducted using single-axis analog computer simulations of a representative orbital vehicle. Compared to a conventional controller for this vehicle, the SOC produced superior transient and comparable steady-state performance. The SOC adapted to a range of plant characteristics over which the conventional controller did not provide uniformly satisfactory performance.

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