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ADAPTIVE CONTROL SYSTEMS
A GENERAL CLASSIFICATION SCHEME

by

N. K. Sinha

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THE UNIVERSITY OF TENNESSEE
ELECTRICAL ENGINEERING DEPARTMENT
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ADAPTIVE CONTROL SYSTEMS

A GENERAL CLASSIFICATION SCHEME

N. K. Sinha
The University of Tennessee

SUMMARY

A scheme of classification of adaptive control systems is proposed. It is shown that a large variety of so-called "adaptive", "self-optimizing", "learning" and other systems can be fitted into this scheme. The scheme divides all adaptive systems into three classes, namely, basic adaptive systems, static adaptive systems, and dynamic adaptive systems. Examples are given to illustrate the classification.

INTRODUCTION

With the progress being made in space, nuclear, and other industrial technologies, there is a growing need for automatic control systems which are capable of changing their own parameters in order to remain efficient in spite of large changes in their environments. This has led to a good deal of work during the past few years on "adaptive" control systems.

In the literature on adaptive control systems one finds that different research groups have used their own terms and definitions like passive adaptive systems, active adaptive systems, computing type adaptive systems, self-organizing systems, self-optimizing systems, learning systems, pretaught systems, etc. Many of these terms overlap each other and sometimes the same term has been used by various groups for systems which belong to different categories.

It is felt, therefore, that there is a great need for a precise and clear-cut scheme of classifications of different types of systems which can be used for standard definitions. This general classification should include all the possible types. Such a scheme of classifications has been proposed in this report.

ADAPTIVE SYSTEMS

Control systems can be divided into two main classes: adaptive and non-adaptive. Adaptive control systems may be defined as those which are capable of modifying their own parameters with changes in environments in such a

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manner that their performance is optimized on the basis of a prescribed criterion. Non-adaptive systems do not have this facility.

The changes in the environments of a control system can be either variations in the statistical properties of the input or in the plant dynamics, or both. Whenever such changes take place they must be identified and the optimum control strategy for a given environmental situation may be determined by any of the following three methods, or any combination of these:

(1) direct computation
(2) optimum-seeking methods like the hill-climbing method, the relaxation method, Newton's method, etc.
(3) having a complete record of environmental situations and the corresponding optimum control strategies stored in a memory.

Notwithstanding the actual method used, all adaptive systems perform some of the following operations:

(i) Measurement: Some or all of the following measurements must be made, continuously or at regular intervals,
- (a) the input or inputs to the system,
- (b) the input and output of the plant, or alternatively, the response of the plant to a given perturbation signal,
- (c) the error of the system, defined as the difference between the desired output and the acutal output or some function of the error, and
- (d) disturbing or noise signals.

(ii) Identification: Identification involves the use of the measured data for the determination of certain unknown parameters. In particular systems, the following may be identified:
- (a) the statistical properties of the input,
- (b) the plant dynamics
- (c) the statistical properties of the noise,
- (d) the index of performance.

The choice of the index of performance may normally be decided after the identification of the input properties. For example, for deterministic inputs one may use the integral square criterion, and for a Gaussian random input one may use the mean square error.

(iii) Pattern Recognition: Pattern recognition involves the comparison of the present environmental situation with the past records of different sets of such situations, and recognizing it as belonging to a particular set. Evidently, pattern recognition implies the availability of the records of patterns, and the corresponding optimum strategies in the memory of the control system.

(iv) Determination of the Optimum Strategy: This may be done by any of the three methods discussed earlier. Direct computation involves the use of digital and/or analog computers for solving set of equations for the calenlation of optimum controller parameters. The various methods of "trial-and-error" can also be used for a systematic search for the optimum, and these may all be called "optimum-seeking" methods.

(v) Modification: The next operation is the adjustment of the parameters of the controller. In the cases where the optimum strategy is determined by computation, modification follows computation, and is carried out in one step. On the other hand, for "optimum-seeking" systems, modification is carried out in a number of steps as the optimum is reached.

CLASSIFICATION OF ADAPTIVE SYSTEMS

I. The Basic Adaptive System

The simplest type of adaptive control systems, which may be called the "Basic Adaptive System" does not have any record of patterns, and is based on the following four operations:

1. Measurements
2. Identification
3. Exploration of the optimum strategy
4. Modification of the controller

A number of control systems belonging to this class have been discussed in the literature, and these may further be subdivided into two types depending upon the method used for the exploration of the optimum strategy, namely,

(i) Computing-type
(ii) Optimum-seeking type

The operation of a primitive adaptive system is shown in Fig. 1.

II. The Static Adaptive System

The static adaptive system has a filled memory with a record of all the expected environmental patterns, and the corresponding control strategies. This type is based on the following operations:

1. Measurements
2. Identification
3. Pattern Recognition
4. Modification

Fig. 2 gives the operation diagram of a static adaptive system. It will be seen that the first two operations are the same in both the basic adaptive system and the static adaptive system. In the case of the latter, however, there is no time lost in the determination of the optimum parameters of the controller. The operation of pattern recognition determines these parameters immediately, provided the present environments correspond to one set in the records. Thus, in most predictable situations, the static adaptive system will be more efficient than the primitive adaptive system.

This system can be compared to the technician who has memorized the solutions to the problems he is most likely to encounter, but is not prepared to learn anything new nor has he the capability of solving a new problem. He can, therefore, handle only these problems very efficiently, but will be completely at a loss when suddenly faced with a new or unexpected problem.

Evidently, the static adaptive system has a limited value. Gibson's pre-taught system[4], with a filled memory, could be said to belong to this class.

III. The Dynamic Adaptive System

The dynamic adaptive system stands at the top of the hiearchy of adaptive control systems. The various functions can be best explained by the operation diagram shown in Fig. 3.

It will be seen that this system is a combination of both the basic and the static adaptive systems, with a provision for updating the memory. It may, therefore, be considered as a 'learning' system. Before any records are stored in the memory, the system would work like the basic adaptive system. With the progress of time, as the memory gets partly filled up, it would 'learn' a number of strategies. Hence, in most cases, it would work like the static adaptive system. But when a new or unexpected situation arises, the pattern for which does not match with any of the stored patterns, the system would temporarily adjust to the pattern closest to the actual pattern, while exploration for the optimum strategy is being made. Once the optimum strategy is determined, the results, and the pattern, are stored in the memory to make the records more complete.

Because of the greater versatility of the dynamic adaptive system, it can be used in all cases where the possible variations in the environments are only partly known.

CLASSIFICATION OF SOME TYPICAL ADAPTIVE CONTROL SYSTEMS

The effectiveness of the proposed scheme of classification will be demonstrated by applying it to a number of schemes for adaptive control which have been proposed in the literature during the last four years.

Example 1. A typical example of the computing-type basic adaptive system is the control system for a nuclear reactor, developed by Corbin[1] and Mishkin, the block diagram for which is shown in Fig. 4.

The neutron level n is varied by changing the reactivity ρ of the control rods; which in turn, depends on the position x of the control rod. The control rod is positioned by the acturator in accordance with the error

$$e = n_d - n$$

where n_d is the desired neutron level. For a typical reactor the transfer functions G_a, G_c and G_R are given by

$$G_a = K_a, \; G_c = K_c \text{ and } G_R = \frac{K_R(s + a)}{s(s + b)} .$$

Both K_c and K_R vary with changes in n and x, and also depend on the past history of the reactor. The resulting changes in the loop gain cause the closed-loop system poles to move from lightly-damped to overdamped positions. The objective of the adaptive control is to maintain the loop gain at a desired value K_D, chosen to give a good dynamic performance.

The analog computer determines the forward path gain K_m, which is then compared with K_D to obtain the error K_E. The error is used to adjust the gain K of the variable gain amplifier in such a manner that the forward path gain becomes equal to K_D.

Since the operation of this system involves only measurement, identification, determination and modification, it is a basic adaptive system.

Example 2. The second example is the system suggested by Staffin[2], the block diagram for which is shown in Fig. 5. This system is based on the cancellation of the lightly-damped poles of the plant by the zeroes of a tandem compensator. As indicated in the block diagram, a set of compensators, $G_{c1}(s)$, $G_{c2}(s)$, ... and $G_{en}(s)$ are available in order to provide cancellation at different locations in the s-plane, depending upon the position of the dominant poles to be cancelled. Evidently, a primary requirement is the determination of the locations of the dominant poles. This may be done by simply determining the natural frequency ω_n, as it is already known that the poles are lightly damped. An analog computer may be used to determine ω_n. The process observer output ω_n is used to operate the zero selector which selects the particular compensating network. The gain adjustor employs the process observer output K to adjust the gain K_c properly.

The optimization of this system consists of measurement, identification, determination, and modification, so it is a basic adaptive system.

Example 3. Osder[13] has proposed an adaptive flight-control system in which a Performance Computer continuously detects stability boundaries and adjusts the system gains to within a desired margin of these boundaries. An impulse perturbation of the closed-loop system allows the determination of the damping ratio of the dominant poles from which the maximum permissible gain is computed. The magnitude of the periodic excitation impulse is kept below the human pilots' detectable threshold.

These techniques have been applied with considerable success in the simulator studies to both supersonic aircraft displaying severe dynamic changes over a wide range of flight conditions and a rocket powered hypersonic vehicle in planetary atmosphere exit and re-entry maneuvers.

The optimization of this system consists of measurement, identification, determination and modification. Hence, it is a basic adaptive system.

Example 4. The block diagram for Shuck's[13] adaptive flight control system is shown in Fig. 7. The system uses a bang-bang-control in which the gain may also be varied. If the system error is larger in magnitude than a pre-selected value B, full output voltage is obtained from the relay to the limiter. For error reduced below B the output of the relay is decreased exponentially with time. This is, therefore, an adaptive system in which the gain is adjusted with variations in the magnitude of the error. Evidently it is one of the simplest types of the basic adaptive class.

Example 5. An example of the optimum-sensing basic adaptive system is the system suggested by McGrath, Rajaraman and Rideout[3], the block diagram for which is shown in Fig. 8. The system error, t, contains a component of frequency ω at which a controllable parameter, a, is being perturbed. The amplitude and phase of this component give the magnitude and sign of a signal which can be recovered by multiplication and integration as shown. This is fed back negatively to reduce the short-time average of $e^2(t)$.

Example 6. Fig. 9 is a system proposed by Clark and Wheeler[5]. The system has a linear plant with two variable parameters inducing a large initial error. The error is reduced by adjustments made in the parameters of the controller. An adaptive computer, the logical design of which is based on a modification of Newton's method of descent, generates the controller-parameter changes from measurements of the integral-of-error squared. No records are kept of the optimum controller parameters for a given set of input and plant parameters.

This system can, obviously, be classified as a basic adaptive system of the optimum-seeking type.

Example 7. The adaptive system proposed by Smith[6] is of the model reference type. The block diagram is shown in Fig. 10. A sine wave test signal is added continuously to the basic loop input and to a model. The phase-shift or the amplitude of the basic loop output is measured by an adaptive computer which adjusts the forward-path gain in an attempt to hold the measured phase-shift or amplitude constant.

This is, therefore, a basic adaptive system of the computing type.

Example 8. Huber[7] has proposed another type of a model reference system. Here the transfer function of the model is the inverse of the desired transfer function of the closed-loop system as far as practically realizable. The system is then adjusted until the poles of the closed-loop system are cancelled by the zeroes of the model. Special filters are designed to aid in the detection of this cancellation.

This is seen to be a basic adaptive system of the optimum-seeking type.

Example 9. The system proposed by Moe and Murphy[8] is interesting. Here the optimum controller parameters are determined by using the moments of the error signals resulting from a unit step input. A feature of this system is that it is not necessary to know the degree of the differential equation describing the plant. This may, again, be classified as a basic adaptive system of the optimum-seeking type.

Example 10. The multiparameter adaptive system proposed by Narendra and McBride[9] depends on the continuous computation of the gradient of a criterian function in a multidimensional parameter space. The parameters are adjusted for minimum mean square error along a path of steepest descent. This is a more general basic adaptive system of the optimum seeking type.

Example 11. The "learning" control system proposed by the Purdue University Group[10], has the structure of the dynamic adaptive system. The optimum parameters of the controller are obtained either from the memory following pattern recognition, or by an optimum-seeking technique.

Example 11. Widrow's[11] scheme for "closed-loop adaptation" involves an optimum-seeking technique together with a record of all previous control situations and the corresponding optimum control strategies. Hence, this may also be considered as a dynamic adaptive system.

CONCLUSION

A scheme of classification of adaptive control systems has been developed, and it has been shown that a large variety of adaptive, "self-optimizing" and "learning" control systems can be fitted into this scheme.

The scheme divides all adaptive systems into three classes, namely, basic adaptive systems, static adaptive systems, and dynamic systems.

It may be pointed out that in the literature on the so-called "learning" systems, there is some controversy on the proper use of the world learning[4, 10, 13] systems belonging to the dynamic adaptive class could be considered as really of the learning type, but probably it is desirable not to use the word "learning" due to the confusion it may create.

Electrical Engineering Department
The University of Tennessee
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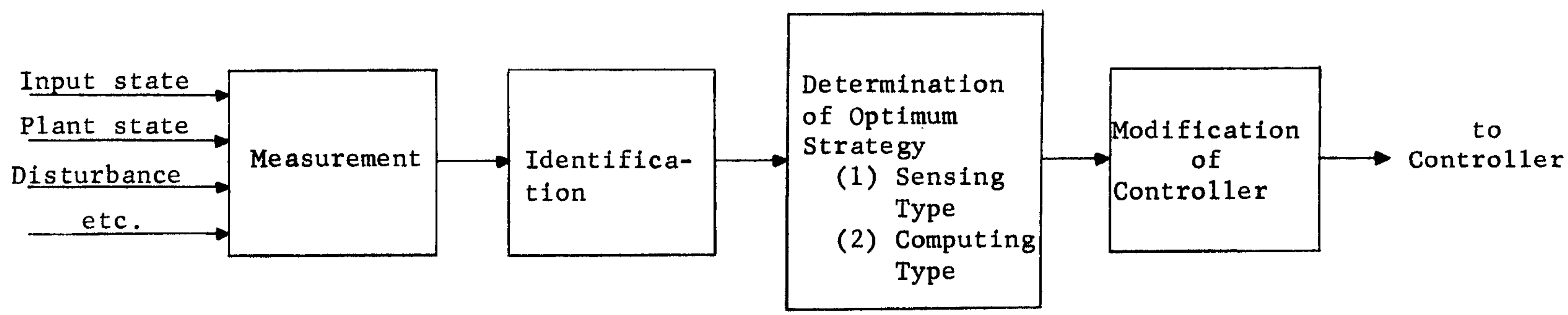


Fig. 1. Operation Diagram of a Basic Adaptive System

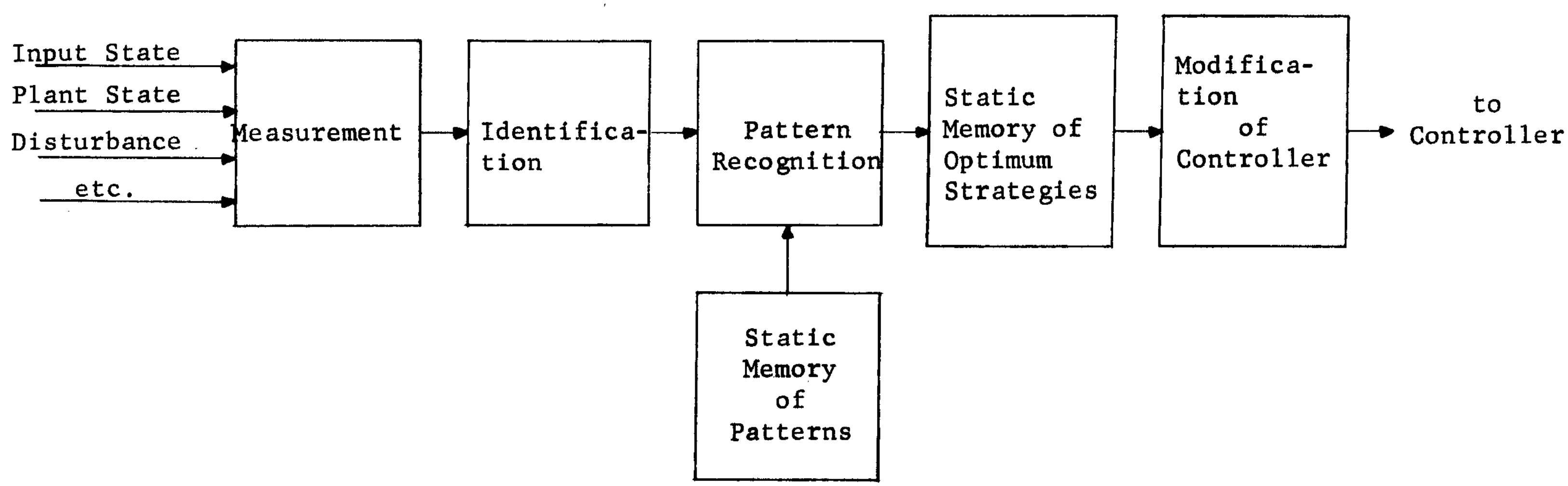


Fig. 2. Operation Diagram of a Static Adaptive System

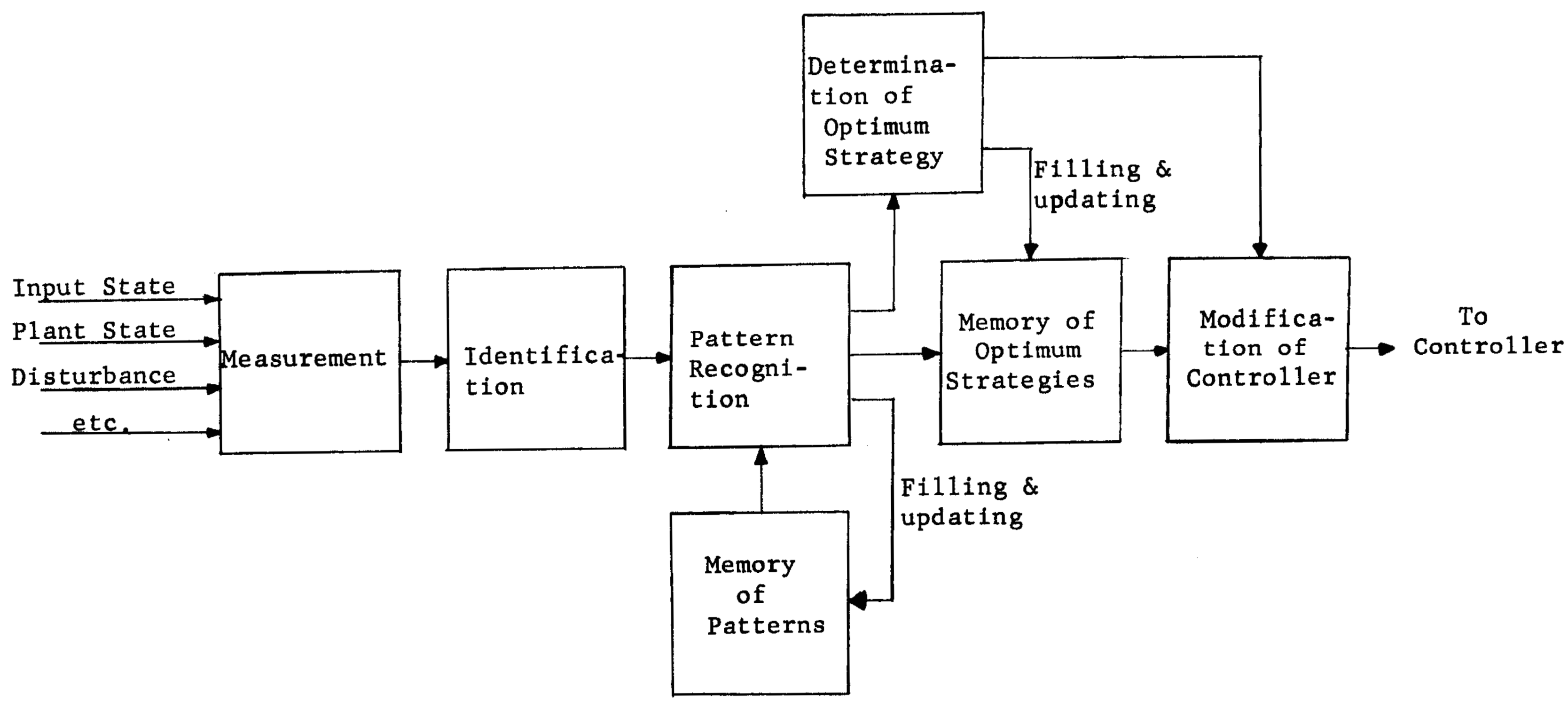


Fig. 3. Operation Diagram of a Dynamic Adaptive System

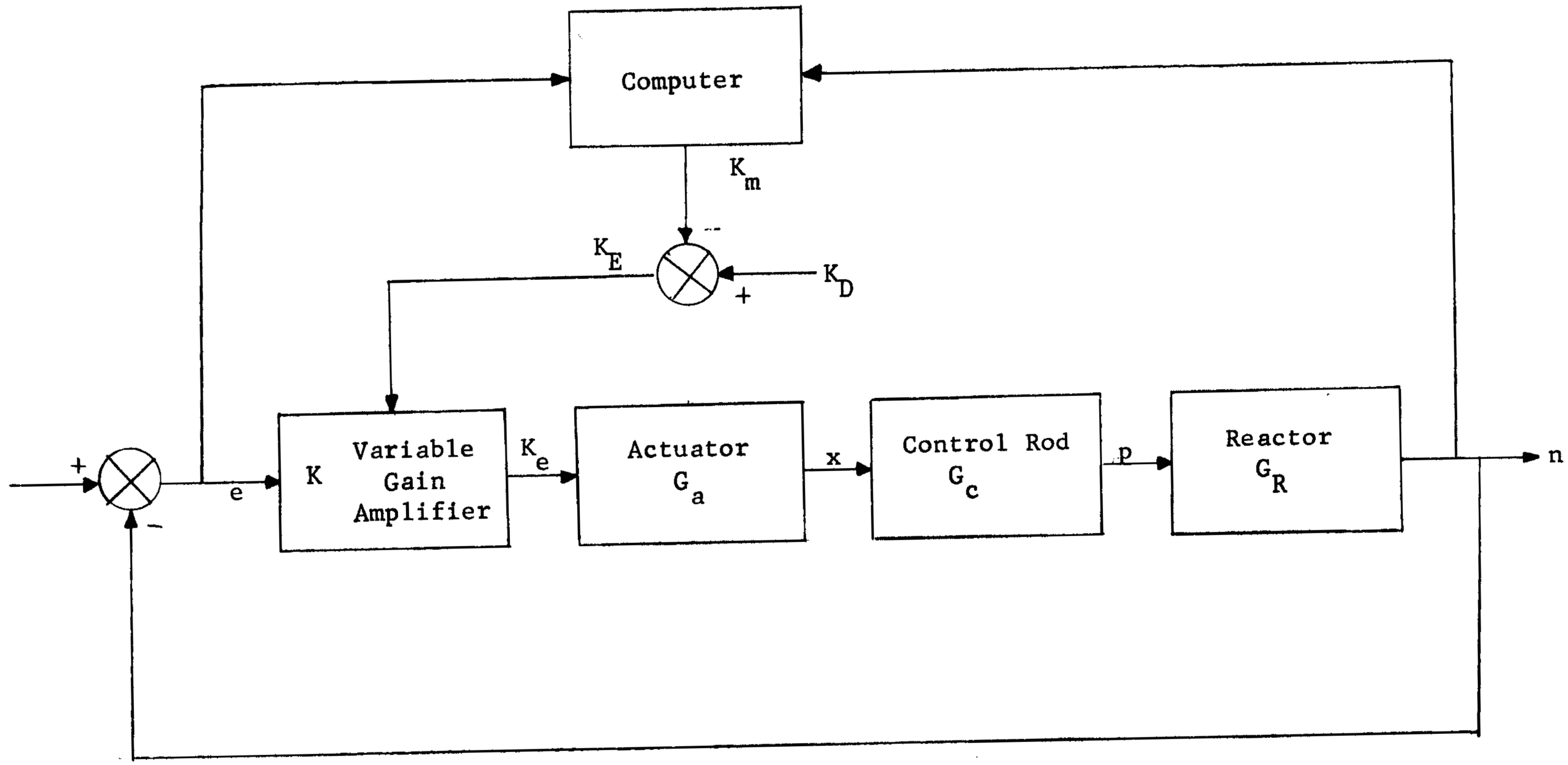


Fig. 4. Corbin and Mishkin's Adaptive Reactor Control System

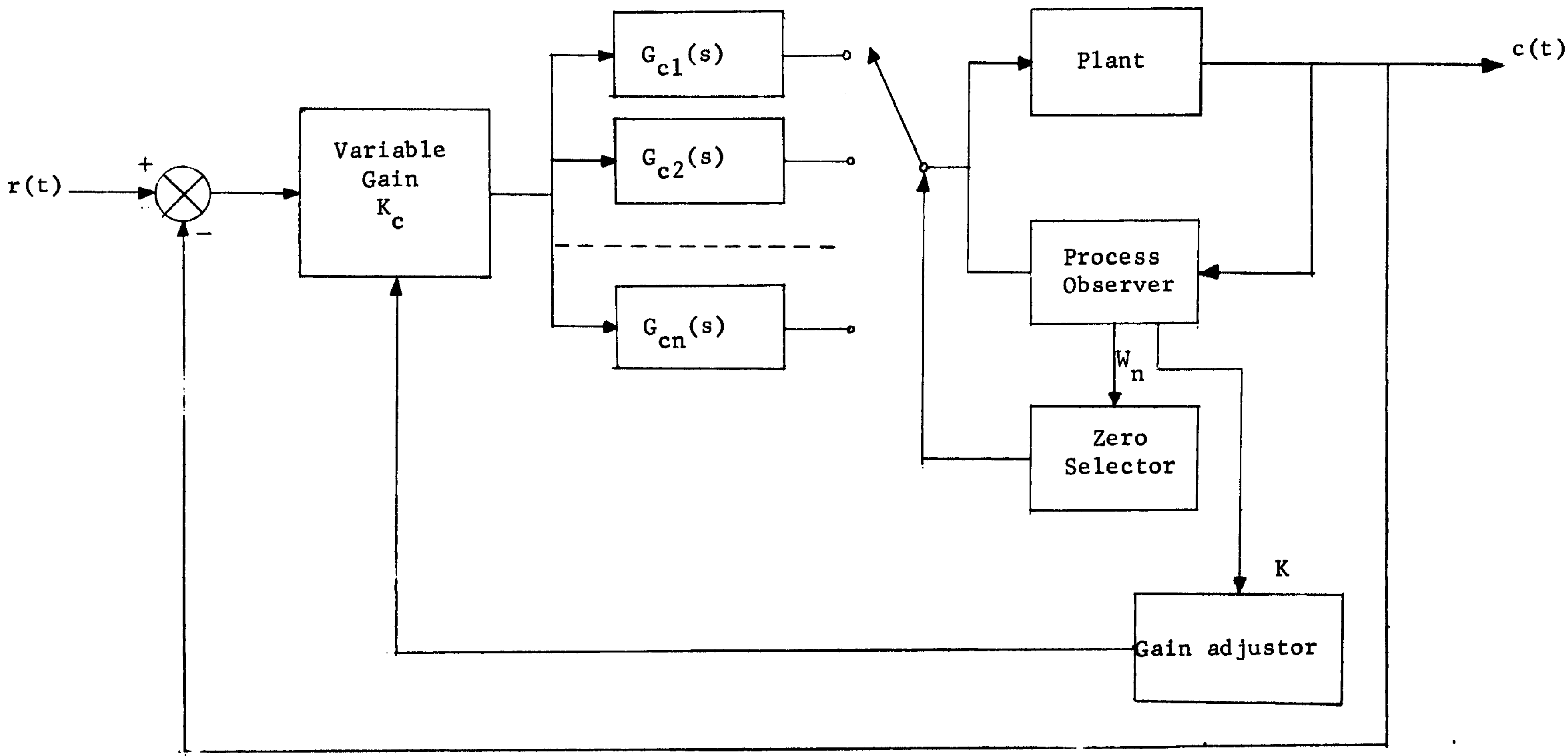


Fig. 5. Staffin's Adaptive System

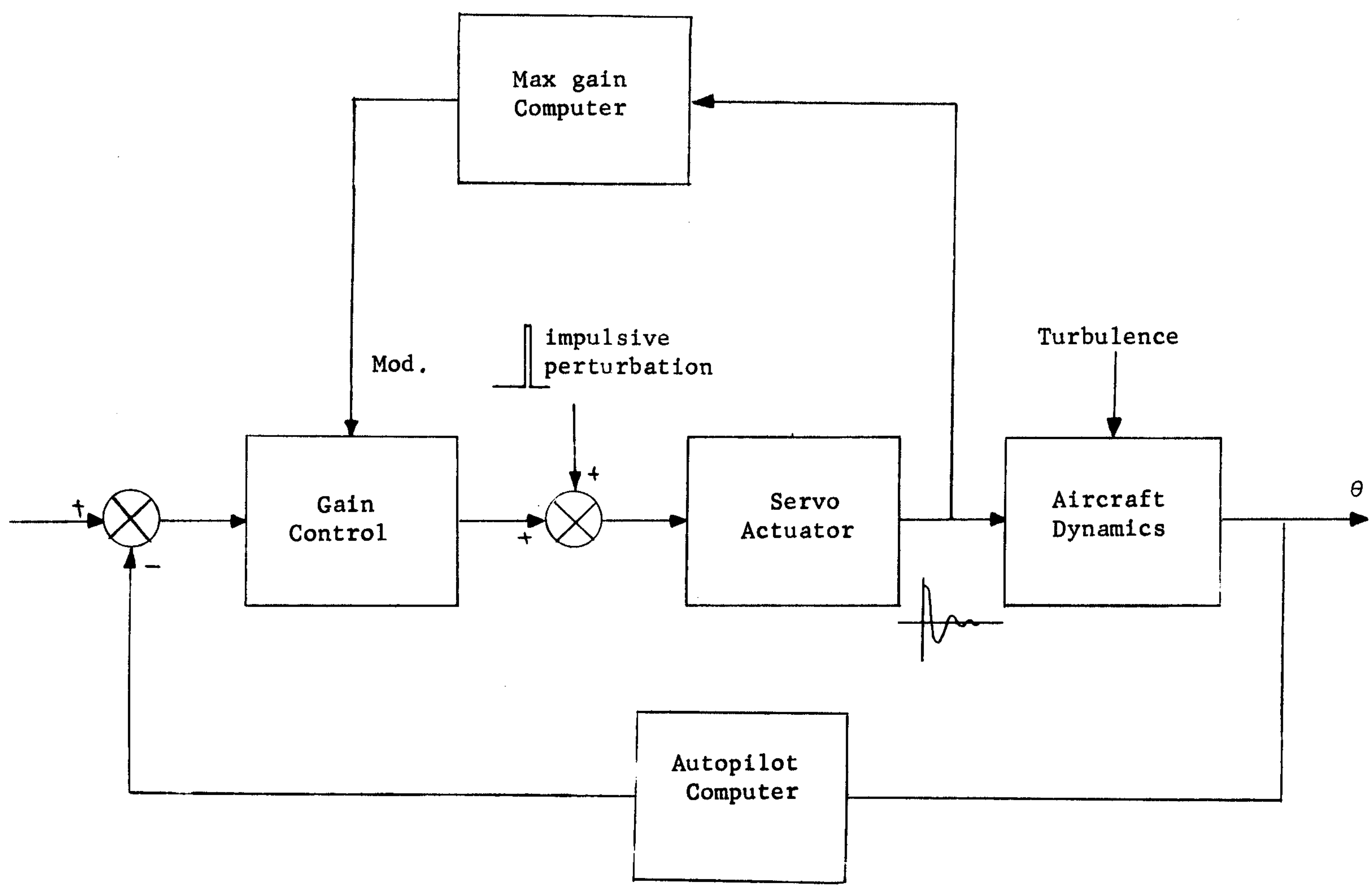
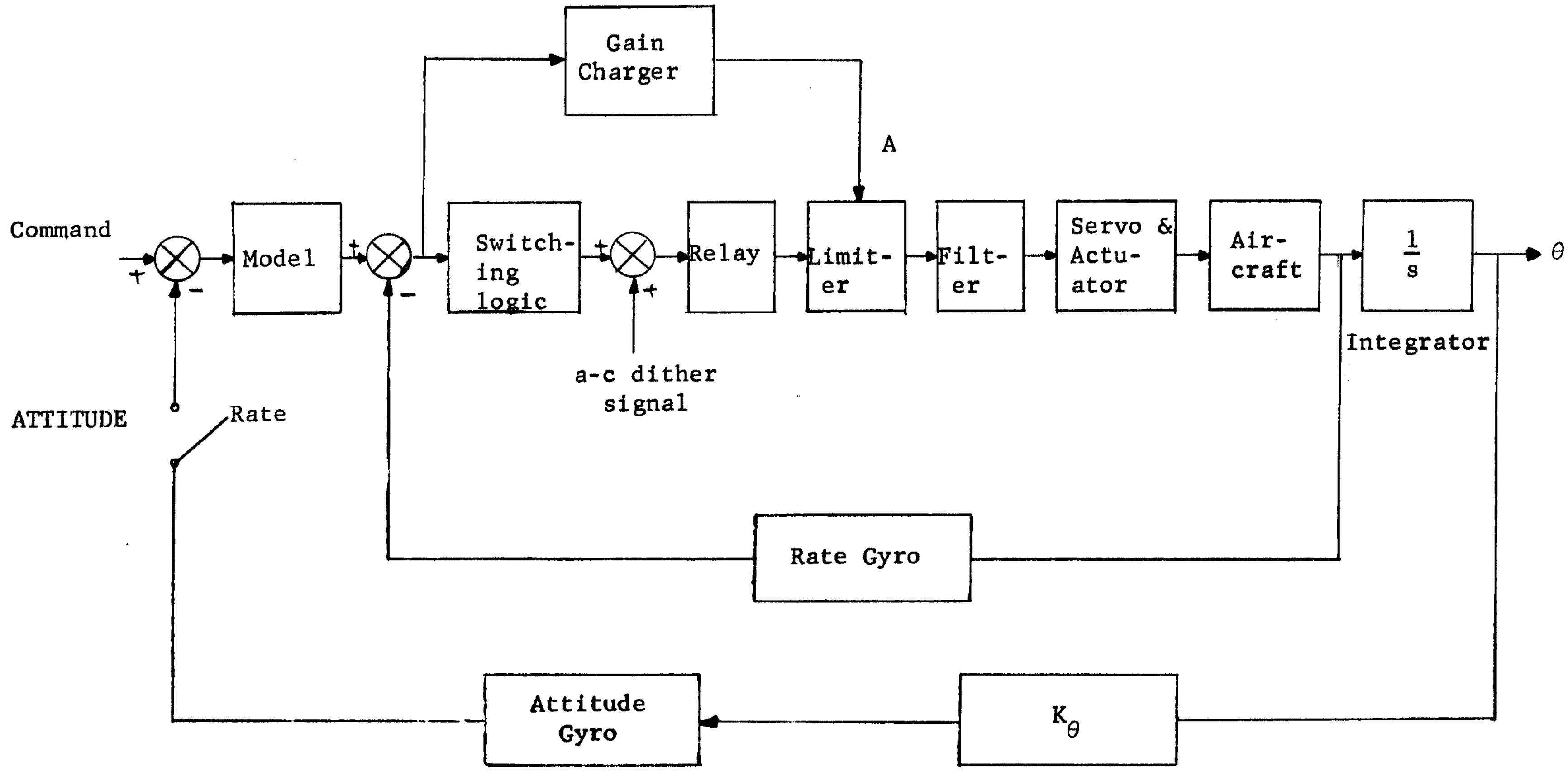


Fig. 6. Osder's Controlling Damping Ratio of Critical Roots



Gain charger operation.

$$A = \begin{cases} A_1 & \text{if} \\ A_2 + (A_1 - A_2)^{-\frac{B_t}{2}} & \text{if} \quad B \end{cases}$$

Fig. 7. Shuck's Adaptive Flight Control Systems

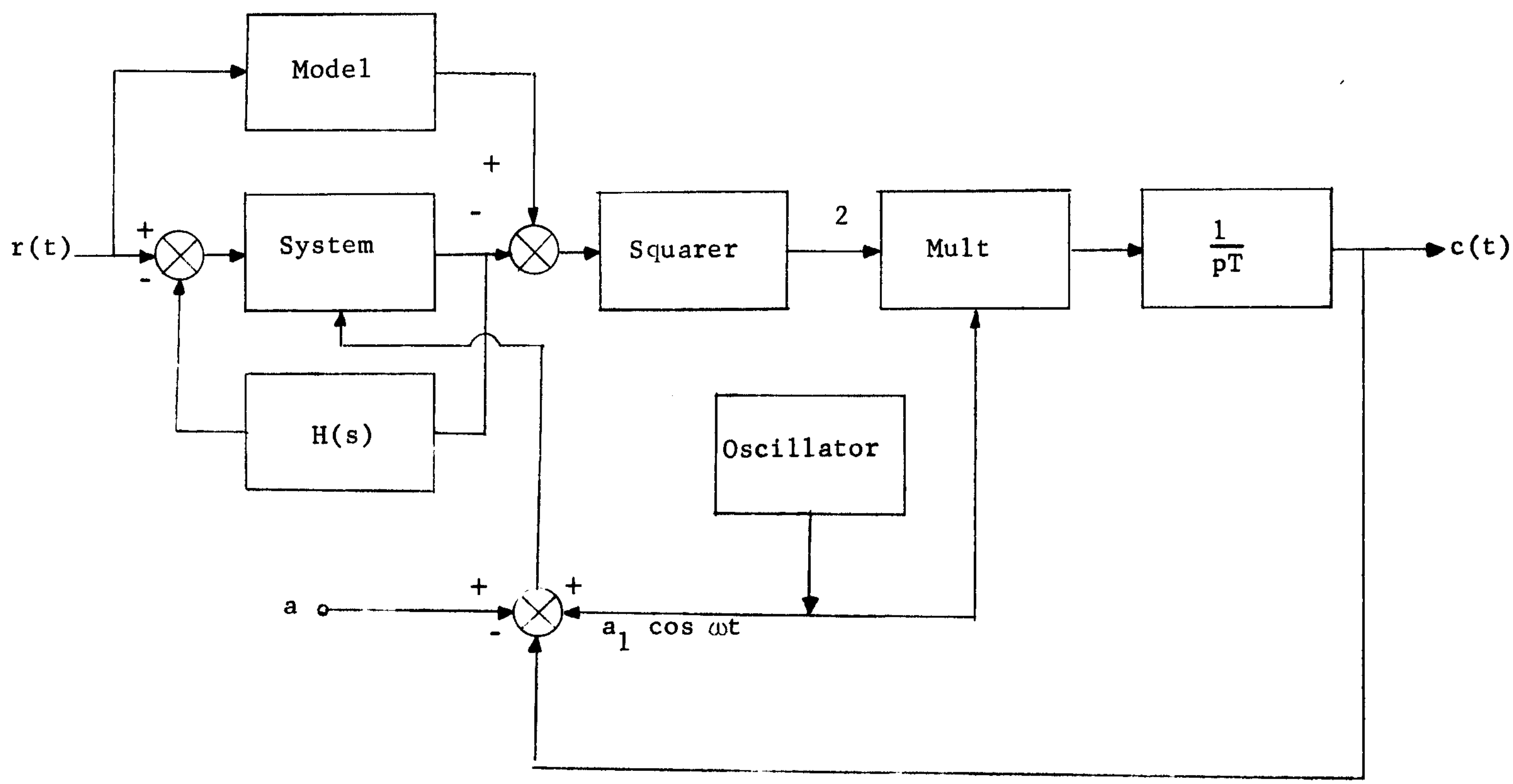


Fig. 8. System Proposed by McGrath, Rajaraman and Rideout

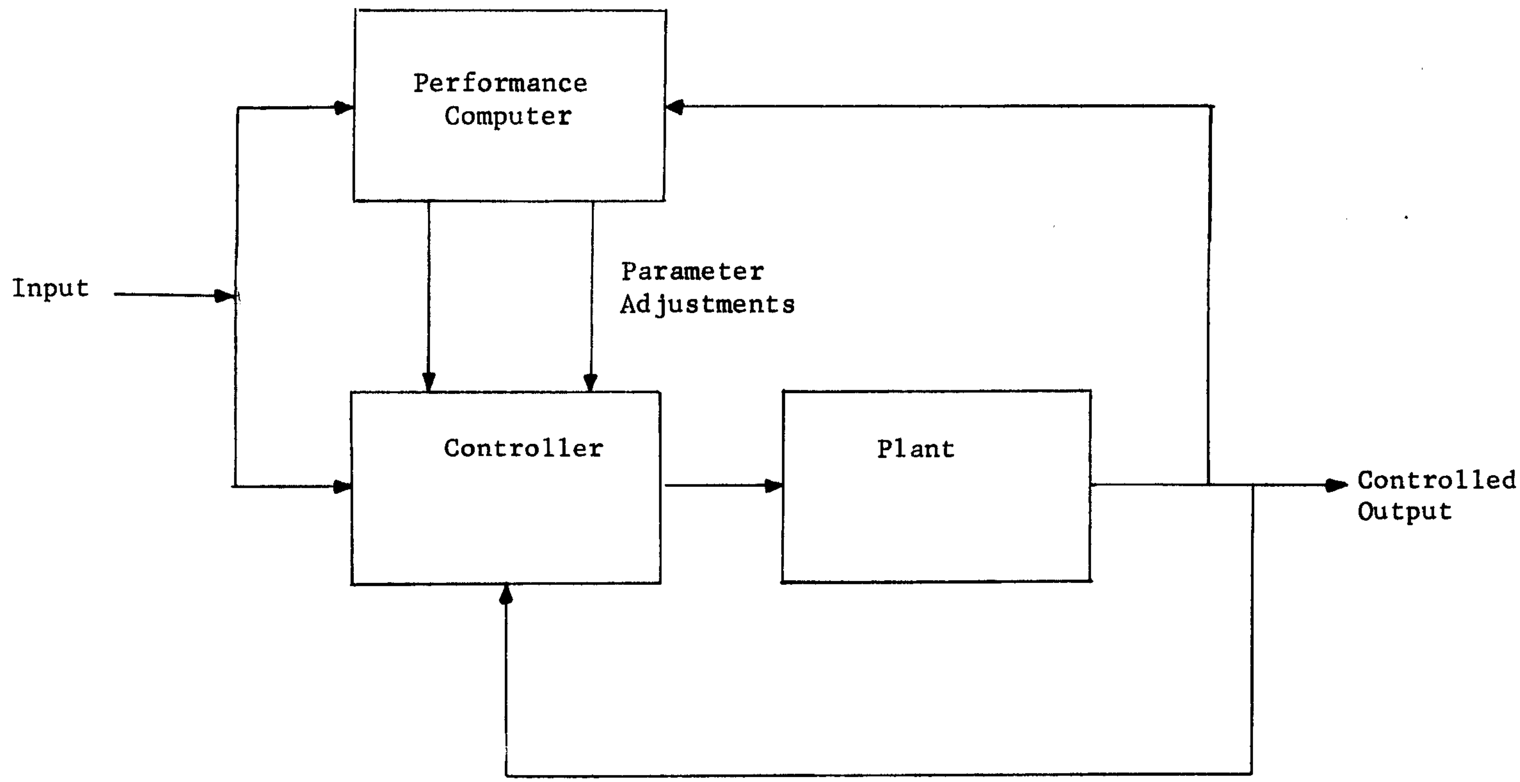


Figure 9. System of Clark and Wheeler

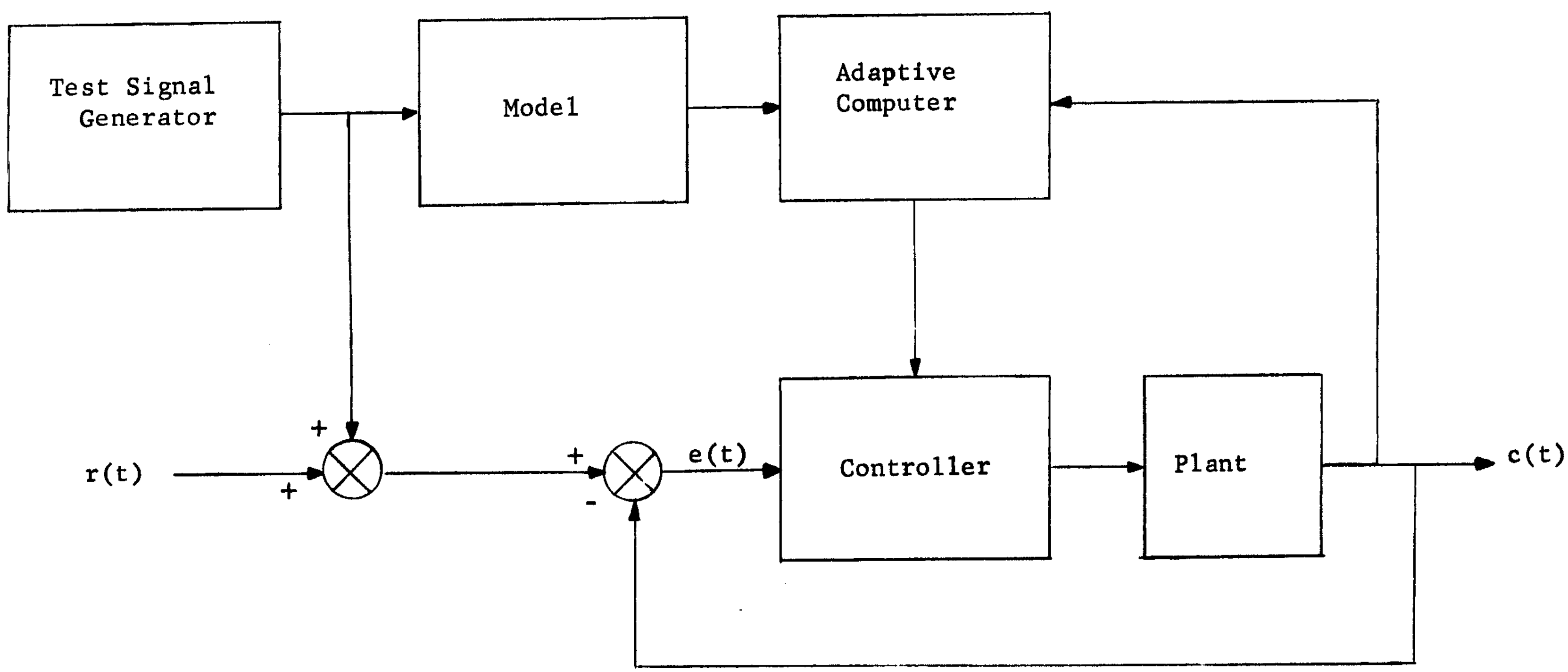


Fig. 10. Smith's System