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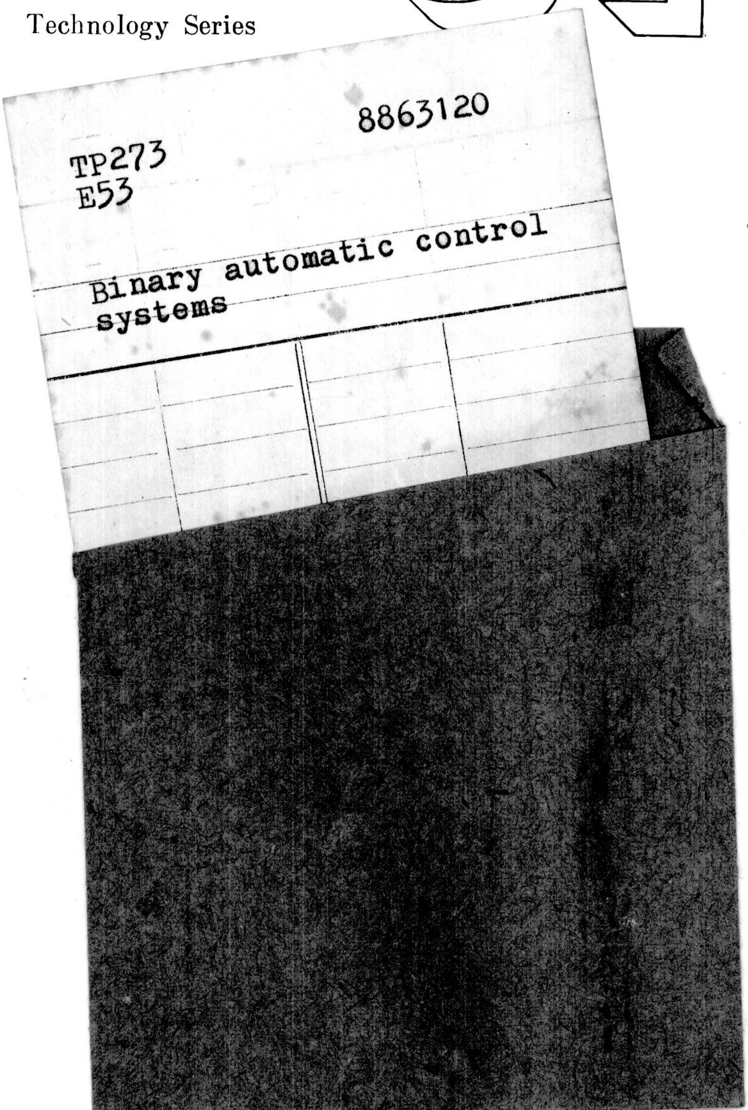

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INTRODUCTION

Modern industrial technology involving sophisticated machinery, flexible automatic production lines, and wide-scale robotization presents system technologists and industrial managers with a number of new problems. They can be solved only on the condition that the functional capabilities of available automatic control systems be further expanded and the systems themselves acquire the quality of rapid adaptation to varying environmental and operational conditions including those brought about by the properties of the plant being controlled. Wide-scale implementation of such control systems would alleviate many labor consuming problems of system design, adjustment, and operation.

At present the development of automatic control systems is a complicated multistage process involving the expert skill of analysts at each stage. As a rule, a development begins with an analysis of the object of automation. A mathematical model of the process is built on the basis of the pertinent laws of natural sciences. This evolves as a manifold of cause-effect relationships. The principal difficulties facing the analyst at this stage consist in deciding on to what degree of detail the model should be elaborated. No ready recipes exist for selection of optimum model size. One may devote much time to problem evaluation and arrive at a very sophisticated model reflecting many subtle features of the plant. Such a model will considerably complicate the subsequent stages of control system development while the contribution of the fine features to the final result may prove insignificant. Conversely, a relatively simple mathematical model may be rapidly built and bring about good results.

Choosing a model, therefore, is a nonformal creative stage, and what comes out of it must be consistent with the overall objective. The model size should take into account the technical means available in the implementation of the control system concerned. In any case, the model mirrors to some approximation the behavior of the physical system. It is generated as a set of equations and relations between the physical variables (or their functions) whose time variations are essential for solving the control problem at hand. Other variables either remain unrepresented in the mathematical description of the controlled system or enter this description as parameters. The latter not only define the nature and ranges of parameter variations with time but also give the degree of uncertainty under which the model will have to be handled as the variation laws for these variables are not known exactly. This implies that the analyst working out control laws has to tackle uncertain (ill-defined) dynamic systems.

The second stage of development of such a control system is therefore concerned with the elimination of this uncertainty. Here the designer strives to identify the model parameters, establish their time variation laws or if impossible estimate the variation ranges for these parameters. For many important applications the identification problem has to be solved not only at the design phase but in system operation as well, either intermittently or consistently (on line). The identification problem is critical and complicated. Its solution is pivotal for system performance as a whole.

The next stage of system development concerns itself with the choice of a feedback law. First, the general form of control law is determined from the mathematical model and the objectives of control, then the solutions to the identification problem are incorporated to compute the parameters of the chosen law. In some applications, now rather rare, the solution of problems occurring at this stage may turn out relatively simple. Other situations necessitate solving auxiliary problems involving large amount of computational work, and even additional investigations. The procedure can be improved to a certain degree by invoking computer aided design (CAD) systems. It is quite obvious that a nonstationary plant requires that the control law parameters be corrected consistently, and this correction be set on line by skilled personnel.

Once the problems of the previous stage have been solved, the general structure of automatic control system becomes clear enough to be realized by technical means. The latter naturally can perform the necessary functions to some accuracy, thus introducing additional constraints and interferences into system performance. Allowance for these constraints is not always possible at the preceding stages hence a simulation experiment is needed. This experiment is carried out with all, or a considerable part, of equipment being the same as that expected to be in the actual system, while the plant and some measuring and actuating devices are represented by simulation models. The objective of this experiment is to test the designed system for compliance with the performance specifications and, if necessary, to introduce corrections into the settings of controller's parameters.

The final stage of development is devoted to performance tests of the control system. Some final adjustments are introduced into the control system on site as needed occasionally by actual operation and effected by the maintenance personnel.

The list of problems as given above is typical of control system development. The solution to these problems requires the efforts of many skilled designers. Under the conditions of large-scale automation the need for such experts increases sharply and may be a stumbling block on the way to extensive automation in the industrial and social milieus.

A possible solution to this problem may be the creation of a control theory which would be capable of handling ill-defined plants, accounting for actual constraints on the variables, parameters, and controls intrinsic to the plant and technical means, excluding the need for exact identification of model parameters and ensuring efficient plant operation at arbitrary variation of circuit parameters over wide ranges. The respective control algorithms, of course, may become rather sophisticated and require considerable computer capacities for their implementation. However the progress in computing achieved in the last decades has provided a strong foundation for practical implementation of the new approach to automation. The reliable, cheap, and efficient microprocessor hardware has changed drastically the idea of the technical means of automation and has eliminated many traditional limitations associated with the hardships of implementation and the reliability of controllers.

All the aforementioned ideas and facts indicate that control system designers are faced with new problems and at a new level of possibilities in the implementation of control algorithms. New methods, principles and procedures of control system development are therefore highly desirable. A new theory of automatic control outlined in this volume is an answer to this appeal. It is devised to tackle the problems of automation outlined in the preceding paragraphs. More specifically it develops new methods of analysis and synthesis for essentially nonlinear systems. The theory is advantageous in that it reduces the amount of necessary prior data and is content with variation ranges instead of the exact characteristics of the plant.

The theory yields a final set of control algorithms each of which is efficient in the control of a wide class of plants. A simple recursive rule of control system buildup is another feature of the theory which in fact is a natural extension of classical control theory. Experience with simulation and application of control systems developed in this way has verified that they can be implemented easily and most efficiently on the basis of computer logic, specifically microprocessor technology.

I Binary Systems of Automatic Control: Motivation, Definitions and Conceptualization

This part outlines the basic principles and definitions of binary dynamic systems. It describes how the error-closure control principle and binary system concepts are used in the development of automatic control systems for ill-defined dynamic processes or plants operated under uncertainty. The principal properties and features of binary control systems are emphasized and compared with traditional control systems devised to solve the same control problem.

1 Basic Principles and Definitions

1.1 Functional Diagrams of Control Systems in Classical Control Theory Setting

Functional block diagrams are widely used in different disciplines to convey the principal features of processes and phenomena under study. Block diagrams are convenient means of graphica representation indicating in a straightforward manner the presence and character of interactions between different processes in complicated systems. They are appealing to the analyst's intuition and facilitate the system reappraisal and alteration to change its behavior in the desired direction. The block-diagram representation has proved efficient in solving many a problem including those of automatic control for systems with lumped [1, 2, 4-6] and distributed [1, 7-10] parameters.

In classical control theory, functional block diagrams a variable, or coordinate, is represented by an arrow (Fig. 1.1*a*), while a dynamic element, or operator, which defines a transformation of the input into output variables, is represented by a block as in Fig. 1.1*b*. Each block diagram picturing a control system contains a certain number of operators and connecting coordinate paths between them.

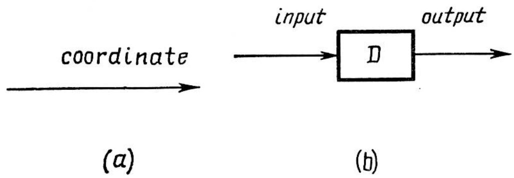

Figure 1.1

A particular type of block diagram depends upon many circumstances, specifically upon the concept of operator being employed—whether the operator represents an individual component or some subsystem constituted by elementary components. Examples of the latter types are the generalized block diagrams given in Fig. 1.2. These block diagrams have received numerous detailed treatments in texts on classical control theory [1-7] and reflect the three basic principles of control, viz. compensation (*a*), feedback (*b*), and combined control (*c*).

In the block diagrams of Fig. 1.2, $y^r(t)$ is the reference input (or setpoint) which is to be reproduced by the controlled variable $y(t)$, with $x(t)$ being the error signal, and $f(t)$ an exterior disturbance acting on the system. The black sector in the summing point shows that the incoming signal arrives with an inverted phase, i.e. has a minus sign.

In classical control theory, the major problem is to appropriately choose operator D_2 representing the controller, time invariant

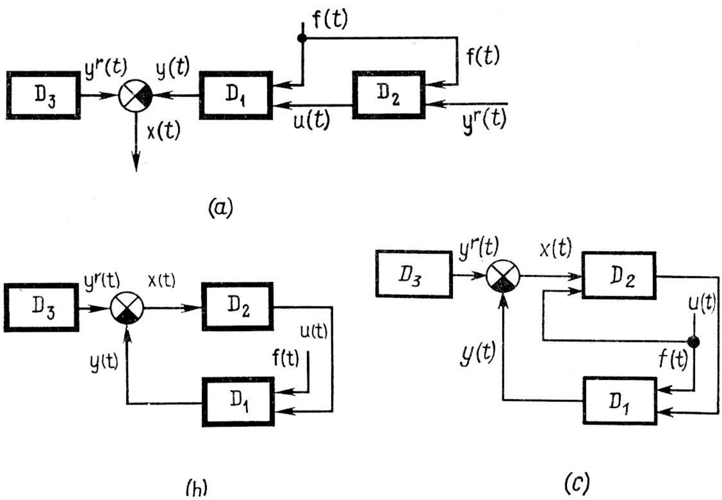

Figure 1.2

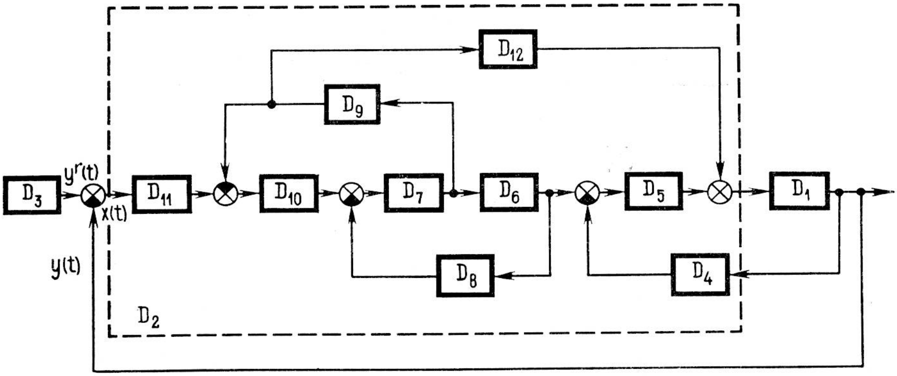

Figure 1.3

as a rule. There is a variety of techniques enabling this choice, dissimilar in many aspects and depending on many factors, specifically on the information that can be employed in the controller to form the control, or manipulated, variable for the controlled plant. Normally, operator D_2 is constituted by elementary components (operators), representing different correcting elements, filters, etc. linked in some arrangement. This arrangement is reflected by the block diagram schematizing the network of operators and different (feedforward, feedback, positive, negative) coordinate paths. An example of such a block diagram, borrowed from Ref. 11, is given in Fig. 1.3.

Classical control theory may be said to deal with systems which can be represented by block diagrams constructed essentially with the use of two basic elements, or concepts, namely, the operator and the variable, or coordinate.

1.2 Block Diagrams of Adaptive Control Systems

The theory of adaptive control has expanded the possibilities of automatic systems. Methodologically this expansion has been due to the acquisition of a new basic element—the variable-parameter operator; its conventional graphical symbol is depicted in Fig. 1.4. The incoming signal $\varepsilon(t)$ represents a function governing the variation of parameters of operator D [11-14].

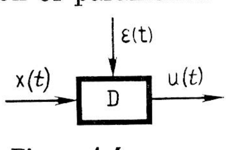

Figure 1.4

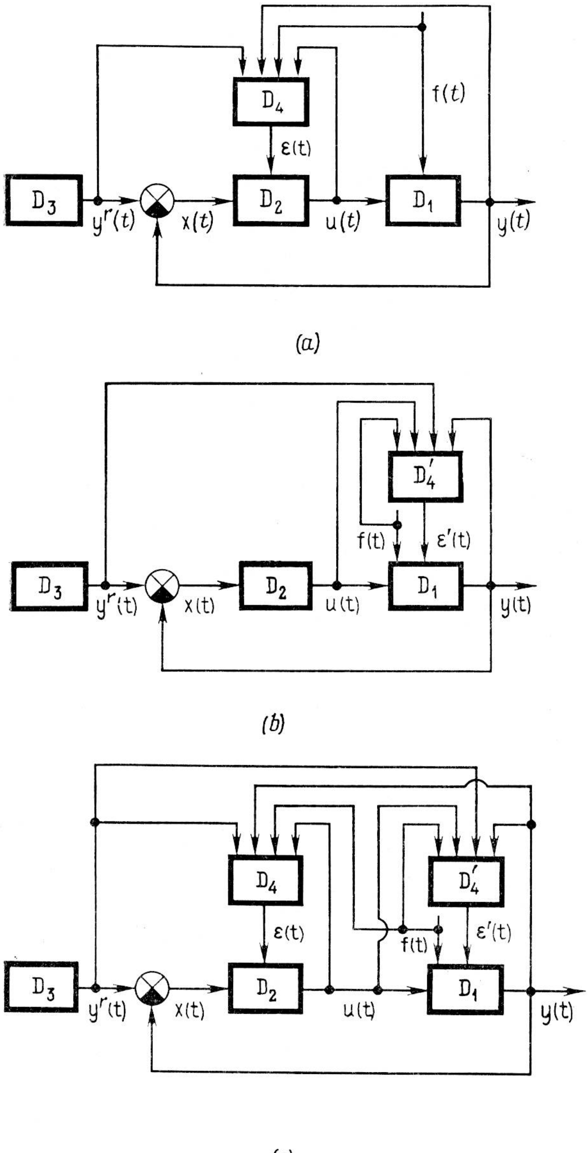

Figure 1.5

Numerous reports on the subject have demonstrated that the incorporation of such an element widens the class of feasible controllers and enables the designer to develop systems capable of efficient control over an entire class of plants.

By way of example, we take up three generalized block diagrams of adaptive control systems which have been studied in sufficient depth. The networks are dissimilar in the way they use the element presented in Fig. 1.4. In the block diagram of Fig. 1.5*a* this element (D_2) represents an algorithm of coordinate control [11, 12]. In the diagram at (*b*) this element (D_1) is used to change some parameters of the plant [13, 15-18]. Finally, the adaptive control network shown at (*c*) realizes both these possibilities [13].

The problem of adaptive control synthesis reduces, therefore, to the choice of a coordinate-control operator D_2 and an operator D_4 (D'_4) which defines the adaptation algorithm. A popular approach given the circumstances is as follows. The analyst selects at first an invariable operator D_2 ensuring the desired quality of control at some fixed parameters of the plant corresponding to its most typical operating mode, and then synthesizes an operator D_4 which will correct the parameters of D_2 to bring the actual closed-loop system characteristics in correspondence with the specified values.

To sum up, the adaptive control systems may be said to correspond to block diagrams constructed with the three basic elements, namely, operators, variable parameter operators, and coordinate paths between them [13, 19-23].

1.3 The Concept of Operator-Variable and the Binary Principle

In what follows we develop a new methodological basis for constructing block diagrams with the aim to widen the capabilities of automatic control systems handling dynamic plants under uncertainty. This methodology relies on the concept of operator-variable, or operator-signal. In block diagrams, this variable will be represented by a double-shafted arrow (Fig. 1.6).

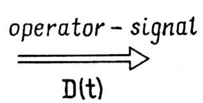

Figure 1.6

The *operator-variable*, or *operator-signal*, formally represents a transformation applied to variables (coordinates). The concept of operator-signal enables us to introduce a new, for control theory, element depicted in Fig. 1.7. This element graphically represents the fact that the transformation of coordinate $x(t)$ into $y(t)$ is governed by an external operator-signal $D(t)$.

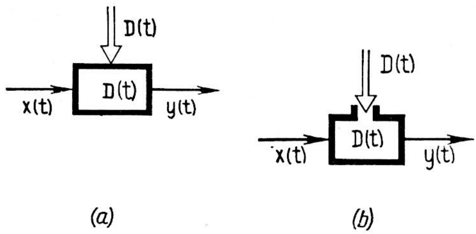

Figure 1.7

It would be proper to note here that $D(t)$ may be an ordinary signal which undergoes various transformations, that is, performs as a *coordinate*. This implies, specifically, that such a variable may be included in the set of system variables where each generic element of the set can be either a coordinate or an operator. The particular label is decided by the role the element assumes in a specific transformation.

The need for the new element has arisen from the fact that many problems involve on-line alterations of data processing algorithms. Physically, such an element can be implemented in many ways. For example, the type of transformation may be changed parametrically; the element concerned is then identical with the one employed in adaptive networks (see Fig. 1.4). Another way consists in using a multiplication of signals. The element then assumes the form represented graphically in Fig. 1.8*a*. The operator-signal may also assume a logic form. Figure 1.8*b* illustrates, for example, how the choice of certain $D_1, D_2, \ldots, D_N$ is governed by the operator-signal $D(t)$. It will be noted that the logic method of varying the transformation operators is widely used in control systems with variable structure [24, 25].

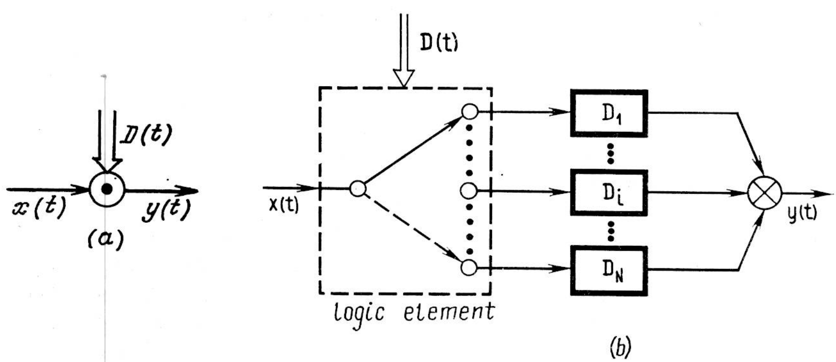

Figure 1.8

In practice, certain signals are responsible for changing the type of transformation, therefore, it would be natural to introduce for them a distinct nomenclature. They will be referred to as *operator-variables*, or *variant-operators*, and denoted by Greek letters shown next to double-shafted arrows (Fig. 1.9). The distinction between

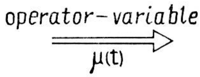

Figure 1.9

variables referred to as *coordinates* and *operator-variables* is merely conditional. For a casual reader unaware of the aforementioned distinction of variables, these are essentially the same—the variables of the nonlinear dynamic system under consideration. The interpretation of these variables is a methodological means whose efficiency in system synthesis and analysis is yet to be demonstrated. In view of the importance of the concepts being introduced for our further consideration, we would like to emphasize once again that there is no formal difference between coordinates and operator-variables. The difference is conditional and associated with the way in which the variable participates in specific local transformations.

We shall call a variable the *coordinate* if it is subjected to some transformation. The same variable will be called the *operator* when it determines the type of transformation performed over a coordinate. This interpretation of state variables of a nonlinear dynamic system will be referred to as the *binary principle*. Dynamic systems built on this principle will, accordingly, be called *binary dynamic systems*.

1.4 Generalized Elements of Binary Dynamic Systems

Here we are content to define the conceptual framework that will be necessary in constructing a theory of binary control systems. Like any variable, the operator-variable may be subjected to a transformation and if the output of such a transformation performs itself as an operator, then this mapping will be referred to as the operator transformation. It is represented in block diagrams as shown in Fig. 1.10*a*. If, on the other hand, the output is to be subjected to another transformation on its downstream way, then the former mapping will be referred to as an *operator-coordinate* transformation and will be schematized as indicated at (*b*). Similar definitions hold for the *coordinate-operator* type (*c*) and *coordinate* type (*d*) transformations. The last one is an ordinary transformation, it coincides