International Journal of Automatic Control System
Vol. 1: Issue 1
www.journalspub.com

Review of Analyzing and Designing an Automatic Control System

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Abstract

Automatically controlling systems are technologies made to perform some aggregates of operations aimed at sustaining or improving the functioning of controlled objects without any direct human or manual intervention and with a controlled objective which is applied by regulating the energy feed. Automatic control is the work done in control theory for the regulation of continuous processes and are the simplest type of automatic loops, with a measured value of a process with a desired set value, which keeps on processing the resulting error signals for changing inputs in such a way that the process stays at its set point without any alteration or disturbances. Designing any such useful system with enabled automatic control requires feeding of electrical energy in order to enhance the dynamic features of the otherwise systems.

Keywords: *Control system, auxiliary operations, transient behavior, control loop*

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INTRODUCTION

Automatic controlling techniques are employed in many technological as well as biological techniques for performing most unfeasible operations humanly due to processing of huge amounts of data in a limited period of time. It is also used for increasing the labor productivities along with accuracy and qualities of regulation. This also removes hassles of working in hazardous health conditions. The objective of control in one form or another has to do with the temporal variation of the regulated (controlled) quantity, the output variable of the controlled object. In order to accomplish the control objective while taking into account the peculiarities of controlled objects that have various characteristics and the specific features of individual classes of systems, one organizes an action (the control action) on the object's control units. This action is also designed to compensate for the effects of external disturbances that tend to interfere with the required behavior of the controlled quantity. The control effect is produced by a control device (CD). The totality of interactions between the control device and the controlled object constitutes an automatic control system [1–6].

AUTOMATIC CONTROL SYSTEMS

An automatic control system (ACS) sustains or improves the functioning of a controlled object. In a number of cases, the auxiliary operations for the ACS, starting, stopping, monitoring, adjusting, and so on, can also be automated. An ACS functions mainly as a member of a production or some other complex.

The history of technology contains many early examples of designs that have all the distinguishing features of an ACS, for example, a "shaker" to regulate the flow of grain in a mill, and the means of regulating the water level in the steam boiler of a Polzunov machine (1765). The first closed ACS, which has been widely used in technology, was the automatic regulation system with a centrifugal governor for a steam engine, developed by Watt in 1784. As steam engines, turbines, and internal combustion engines were improved, various mechanical regulating systems, which had developed considerably by the turn of the 20th century, were employed more and more extensively.

This new stage in automatic control was characterized by the introduction of electronic elements and devices for automation and remote control. Electronic advances were responsible for the appearance of highly accurate tracking and guidance systems, remote control and telemetering, and automatic monitoring and correcting systems. The 1950s were notable for the appearance of complex control systems for production processes and industrial complexes based on electronic control computers.

ACS's are classified mainly according to the control objectives, the type of control circuit, and the method of transmitting the signals. Initially, the problem that faced ACS's was the maintenance of specified relationships for time-related changes in the controlled quantities. In this class of systems we distinguish automatic regulation systems (ARS), whose task is to keep a controlled quantity constant; program control systems, where the controlled quantity is varied in accordance with a specified program; and servomechanisms, for which the control program is not known beforehand. Subsequently the objective of the control became associated directly with particular complex indexes of quality that characterized a system according to its productivity, the accuracy of reproduction, and so on; requirements can be placed on the quality index to attain maximum or minimum limits, and for this purpose adaptive, or self-adapting, systems were developed [4–10].

In these, the method of control varies: in self-adjusting systems the parameters of the control device are varied until optimal or nearly optimal values of the controlled quantity are attained; in self-adjusting systems it is possible to change the structure for the same purpose. Broader in principle are the possibilities of self-teaching systems, which improve the functional algorithm on the basis of an analysis of the control experience. Optimizing the mode in adaptive ACS's can be accomplished both by means of an automatic scan and by a non-scanning method.

Means for compensating disturbances are related to the kind of control system circuitry. In open ACS's no signals carrying information about the current state of the controlled object reach the CD's, for either the primary disturbances are measured and compensated or the control is effected according to a fixed program with no analysis of any factors during operation. The principal type of ACS is the closed one in which regulation is effected in accordance with the deviation and the signal transmission circuit forms a closed loop that includes the controlled object and the CD's; the deviations of the controlled quantity from the desired values are compensated by the feedback action which is independent of the causes of these deviations. Combining the principles of control; according to the deviation and to the disturbance; results in compound systems. Frequently, besides the basic control circuit, which is a primary closed feedback loop, an ACS has auxiliary circuits (multi-loop systems) to stabilize and correct the dynamic properties as in Figure 1. The simultaneous control of several quantities that affect one another is accomplished in multiple-connected control or regulating systems. Discrete and continuous ACS's have different signal shapes. In discrete ACS's the signals, in at least one point of the circuit, are quantified with respect to time, or to level, or to both level and time [8–12].

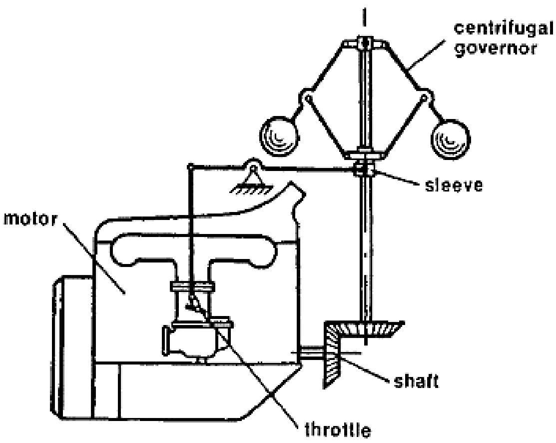

Fig. 1: *Direct Regulation of a Motor's Speed.*

The simplest example of an ACS is a system for the direct regulation of a motor's speed of rotation (Figure 1). The control objective is to maintain a constant speed of rotation of a flywheel; the controlled object is the motor, the control effect is the position of the regulating slide of the throttle, the CD is the centrifugal governor, which has a sleeve that is shifted by the centrifugal forces when the speed of rotation of the shaft, which is rigidly connected to the flywheel, deviates from the specified value. When the sleeve is shifted, the position of the throttle's slide is changed. A block diagram of this example (Figure 2) is representative of many ACS's regardless of their physical characteristics. The system shown is a closed, single-loop continuous system of automatic control for a mechanical action that can be linearized for analysis.

Industry produces universal regulators, among them those operating in response to a derivative or an integral and extremal regulators for controlling various objects. Specialized ACS's are extensively used in a variety of technical fields, for example, a servo control system for a tracer milling machine with a fixed master; an ACS for metal-working lathes with program control from a magnetic tape, a punched tape, or a punched card (the advantages of such a control consists in its relative universality, the ease of rearranging the program, and the high accuracy in machining parts); and a program control system for a reversible rolling mill which includes a control computer in its loop. For the relatively slow technological processes of the chemical and petroleum industries multiple-connected ACS's which regulate a large number of associated quantities are widely used; thus, in petroleum refining the information on temperature, pressure, flow, and composition of the petroleum products obtained from several hundred transducers is utilized to make up the control signals for dozens of different regulators. ACS's play an important role in aviation and space flight; for instance, an automatic pilot is an ACS associated with a regulator and sometimes with a self-adjusting system. Highly accurate servo systems that often include computers—for example, the angle tracking system in radar stations—are used in military technology. The characteristic features of ACS's can be observed in an analysis of the many physiological processes in a living organism such as blood circulation, the body temperature regulation of warm-blooded animals, and motor operations.

The problems of synthesizing an automatic control device and of analyzing the process in the controlled systems are the subject matter of automatic control theory.

Automatic Control Theory According to R. S. Rutman

Automatic control theory (ACT) deals with the design principles of automatic control systems and the rules for the processes taking place in them, which are investigated by means of dynamic simulations of the real systems, taking into account the operating conditions, the specific purpose, and the structural features of the controlled object and the automatic devices, so that efficient and accurate control systems can be designed.

Initially ACT developed as an automatic regulation theory (ART) and was one of the divisions of theoretical and applied mechanics. At this stage ACT dealt with the control processes of steam boilers and electrical machines but was separately confined to heat engineering and electrical engineering. The rapid development of all branches of technology and industry was accompanied by the perfection of methods and facilities for control technology; the similarity of the control processes in technological apparatus, regardless of their nature and purpose, was discovered.

With the development of control in technology came also the investigation of control problems in organisms and in economic systems. Until the middle of the 20th century there was no connection between the studies of control processes in these dissimilar fields. In technology, the control devices, without regard to the objects, were developed separately and only then linked with the objects to form a single control system. From a study of the interaction of these devices with objects the generality of control processes was revealed. Arid thus ART, conceived in technology, was converted into an independent technological science.

In living organisms and in economics the control units form an integral part of these objects. In this instance it is not necessary to construct separately acting control units, and the study of the whole control mechanism led directly to the corresponding fields of knowledge without participation by control specialists. However, the control processes which have specific characteristics in biology and economics required the cooperative effort of specialists in various fields of science and technology, especially when the modern level of scientific development was reached, when the need for a mutual exchange of knowledge became evident. N. Wiener formed the concepts of the commonality of control processes in technology, living organisms, and economics and of the necessity for cooperation among scientists of different specialties. It was discovered that the technological science of ART could account for the control processes and could affect them, not merely in technology alone: its sphere of application was broadened, but in so doing the purposes and methods of the theory were made more complicated and it received the new name of automatic control theory [6–10].

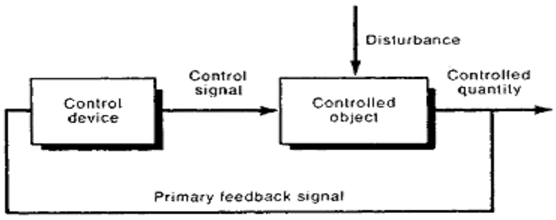

Fig 2: *Typical Control System.*

A typical problem of ART is to stabilize a specified state of an object. In ACT this is a component part in the problem of adjustment, or adaptation, which is peculiar to living organisms and economic organizations. But for technology these problems are very pressing when one takes into account the variability of a controlled object’s parameters, their operation under changing conditions, and also an evaluation of the effectiveness of this operation in purely economic terms such as profitability or reduction of labor and material costs. In this way the problems of synthesizing and analyzing automatic control systems—the fundamental problems of ACT’s—came into being. Their solution required a study of the dynamic properties of ACS’s for which a mathematical description of transient behavior of all system elements was needed.

In general, the processes in objects are described by systems of ordinary or partial differential equations according to whether the objects have lumped or distributed parameters. The elements of automatic devices are also described by systems of differential equations. The subsequent transition from linear equations to transfer functions—operational expressions for differential and difference equations—was unique in ACT. The transfer functions made it easy to represent the mathematical model of a system in the form of a block diagram composed of standard dynamic components. ACT introduced the concept of dynamic responses, that is, transfer functions and frequency and time responses that simplify the formation of mathematical models for a system and the subsequent analysis and synthesis. A dynamic analysis of an ACS ascertains its operational status and accuracy. A necessary condition for an operating condition in an ACS is stability. In order to investigate this, stability criteria have been developed that make it possible to determine the stability conditions and the necessary margins by indirect tests, thus avoiding the very difficult operation of integrating the system's equations of motion.

Stability is obtained by varying the parameters of a system and its structure. In nonlinear ACS's the condition of self-oscillation, which is possible for such systems, is investigated. If these oscillations are unavoidable by virtue of the ACS operating principle itself, for relay systems as an example, then acceptable parameters for the amplitude and frequency of the oscillations are established. The accuracy of an ACS is evaluated by means of indexes that, taken together, are known as quality control. The most important indexes of ACS quality are the static and dynamic errors and the regulation time. These indexes are determined by comparing the actual transient response of the controlled quantities with their specified law of change; they are usually given for one of the standard laws of change of the controlled quantity.

In ACT, as when analyzing stability, indirect methods that do not require a solution of the original equations are employed to analyze the quality. For this purpose quality criteria are introduced that are indirect estimates of the quality indexes. When random disturbances act on an ACS, the most widely used quality criterion for the dynamic accuracy is the root-mean-square error. This quantity can be correlated fairly easily with the statistical characteristics of the disturbing effects and the parameters of a system's transfer function. An ACS in which an extreme value of some quality index is achieved is called an optimal system. Nonlinear systems have broader possibilities of achieving an optimum for a specified quality index than do linear systems. This motivates the use of nonlinear connections to increase control system quality.

An analysis of a control system establishes the system properties for a given structure. Building up a control algorithm, developing a corresponding system structure which fulfills a specified purpose with the requisite quality control, and determining the parameter values for this system make up the content of the synthesis problem. Before starting to develop a control system it is necessary to have access to some initial data: the properties of the controlled object, the nature of the disturbances acting on it, the objective of the control, and the control accuracy required. A control unit is associated with the object being controlled; the control action is transmitted through the control unit from the control device to the object. The characteristics of the actuating mechanism are determined as soon as the characteristics of the control unit are known. But this disrupts the circuit of the control system's parts whose properties are determined simply by their interaction. In this way the concept of an unalterable part of a control system is introduced; it is unalterable in that its properties are specified prior to constructing a control algorithm and, as a rule, cannot be changed. The specified objective of the control determines the means of control. As a result, a block diagram of the control system is outlined.

Two methods of solving synthesis problems—the analytical method and the method of sequential approximations—are usually used. In the first method either the form of the transfer function of the automatic device or the control algorithm is found, or the values for the parameters of the selected structure of the given device that give the extremum of the quality criterion are established. This method makes it possible to find the optimal solution immediately, but it often leads to complicated and cumbersome calculations. In the second method the transfer function of the automatic device is determined for a specified quality criterion, and then a comparison is made of the specified indexes and the actual values for the resulting system. If the approximation proves acceptable, the design is considered to be finished and the construction of the apparatus can be started. If the approximation is unacceptable, the form of the transfer function is then changed to obtain a variant that meets the specified accuracy requirement.

Another method of designing complicated control systems, in addition to theoretical ones, is simulation by means of analog and digital computers. The computers reproduce the equations describing the entire control system in general. Depending on the results of the calculations, they are terminated when the required quality indexes are achieved, and the structure of the control device is determined. This method of synthesis is similar in concept to the method of successive approximations. Simulation permits the evaluation of such factors as nonlinearity of constraints on the coordinates and variability of the parameters that pose nearly insuperable obstacles for an analytical study. Computers obviate computational difficulties. They are also employed as part of ACS's for executing complicated control algorithms that are particularly representative of adaptive and optimal systems and of systems that predict the final result of the control [9–12].

Theories of Optimal Control, Statistical Dynamics, and Control System Sensitivity

The solution of ACS synthesis problems promoted the emergence of new, effective control principles and the development of important independent trends in ACT: optimal control, statistical dynamics, and control system sensitivity. The theory of optimal control has made it possible to ascertain the structures of control systems that have the highest attainable quality indexes with due regard for the actual restraints imposed on the variables. The indexes of optimality may be quite varied. Their selection depends on the specific formulation of the task. Such indexes serve as indicators of the dynamic properties of all systems in general, as criteria of the efficiency of the controlled object's conditions, and so on. Systems that are optimized for speed of response and that transfer the object from one state to another in a minimum time interval are in wide use.

The statistical dynamics of control systems deal with the effect of random disturbances on these systems. The methods of this theory make it possible to synthesize control systems that ensure the minimum dynamic error, that solve the problems of designing smoothing and predictive servo systems, and that determine the dynamic characteristics of the controlled objects from the data of the experience during normal functioning without the application of test disturbances. Statistical methods of investigation are prevalent for studying various types of control systems. These methods are very valuable for adaptive systems. The theory of control system sensitivity deals with the dependence of the dynamic properties of these systems on their varying parameters and characteristics. The sensitivity index is a measure of the dependence of these properties on the parameter variations. Sensitivity theory in many cases makes it possible to indicate the way to achieve non-scanning, self-adjusting systems.

The last question is closely associated with one trend in ACT which has been intensively developed in recent years—a general theory of adaptation developed on the basis of statistical methods and linear programming methods in mathematics. A distinctive feature of ACT is a close and intensifying interaction not only with mathematics but also with physics and the technical sciences that deal with the properties of objects; it is becoming possible to create detailed dynamic models of the objects needed to solve the complicated problems of automatic control.

PROGRAM CONTROL

The holding constant (stabilization) of a controlled variable that characterizes a technical process or the altering of the variable in accordance with a given law (program control) or with a measured external process (feedback control); the change in the value of the controlled variable is effected by applying a control action to the control element of the controlled system. In automatic control, the control action *u(t)* is usually a function of the dynamic error, that is, of the deviation *ε(t)* of the controlled variable *x(t)* from its desired value, called the set point, *x0(t): ε(t) =x0(t)–x(t)*. Control in this case is based on the feedback principle (eq. 1), which is often associated with the names of Polzunov and Watt. Also sometimes classed with automatic control is control where *u(t)* is generated by a compensating unit as a function of the disturbing action *f* (load) on the controlled system. In this case we speak of disturbance-stimulated control (eq. 2), a principle sometimes associated with the name of Poncelet. Finally, a combination of deviation- and disturbance-stimulated control is also made use of (eq. 3).

In order to realize automatic control, the set of devices that make up the controller is connected to the controlled system. The controlled system and the controller form an automatic control system. If the automatic control system is based on feedback, it is a closed-loop system; if it is based on disturbance-stimulation, it is an open-loop system. The mathematical expression of the functional dependence of the desired or required control action *u0(t)* on the quantities measured by the controller is called the law or algorithm of control. The most frequently used laws of automatic control are the following:

Proportional (static),

U0=kε

Integral (floating),

$$u_0 = \frac{1}{T_i} \int \epsilon \, dt \qquad (1)$$

Proportional plus integral (isodromic), and

$$u_0 = k\left(\epsilon + \frac{1}{T_i} \int \epsilon \, dt\right) \qquad (2)$$

Proportional plus integral plus derivative.

$$u_0 = k\left(\epsilon + \frac{1}{T_i}\int \epsilon\, dt + T_d \frac{d\epsilon}{dt}\right) \quad (3)$$

Here, *k* is the gain of the controller, and *Ti* and *Td* are the integral action time and the derivative action time, respectively. The actual action *u(t)* differs from *u0(t)* owing to the time lag of the controller. An automatic control system is a dynamic system, in which processes are described by, for example, differential and difference-differential equations. An automatic control system may be in a state of equilibrium: there may occur in it steady-state and transient processes, whose quantitative characteristics are studied by the theory of automatic control. In static systems, the steady-state error *εst* for a constant load on the controlled system depends on the magnitude of the load. To increase the static precision, the gain *k* of the controller is increased. However, when k reaches a certain critical value *kcr*, the system usually loses its stability. By introducing integral elements into the controller, a floating control system can be obtained in which there is no static error for any constant load. The theory of automatic control studies the conditions of stability; the quality indexes of the control process, including dynamic and static precision, control time, oscillation of the system, degree of stability, and stability margins; and methods of synthesizing the automatic control system, that is, methods of determining the structure and parameters of correcting devices introduced into the controller to increase stability and provide the required quality indexes for automatic control.

The theory of automatic control of linear systems has been developed most fully; it makes use of analytic and frequency methods of investigation. Small deviations from equilibrium states in continuous nonlinear automatic control systems are studied by means of linearization of the initial equations. Phase-space methods are used to study processes with large deviations and the specific characteristics of nonlinear automatic control systems, such as limit cycles, hunting, locking-in, and non-localized modes. Approximate methods, for example, the small-parameter and harmonic balance methods, are also used to study periodic systems. Stability with large deviations is investigated by Liapunov's second (direct) method and the absolute stability method developed by V. M. Popov of Rumania. A special branch of the theory of automatic control is devoted to automatic control with random disturbances.

The 1950s saw the development of the theory of invariant automatic control systems, which provide the independence of *x(t)* from disturbances, and the theory of multiple-loop automatic control systems, in which many are interconnected through the controlled system. Additional connections between the controllers are often introduced into such automatic control systems to obtain certain properties, in particular self-regulation, that is, independence of the processes of control of separate variables. In the 1960s, the theory of variable structure systems was developed, and found application. Such systems are especially effective where large changes occur in the parameters of the system and the environment, since transient processes in the systems are determined by the properties of the control device and depend little on the parameters of the controlled system and the environment.

Discrete-data automatic control systems, in which signal quantization occurs, occupy a special place in the theory of automatic control. The best studied such systems are pulse systems (with time quantization), relay systems (with level quantization), and digital systems (with time and level quantization). A special form of relay system is the two-position, or on-off, controller, in which the control element can occupy only one of two extreme positions.

FROM THE HISTORY

The dates of the invention of the first control devices are unknown, as are the names of the inventors. For example, the use of a float control to regulate the water level in water clocks was known to the Arabs as long ago as the beginning of the Common Era; control in this case was based on the feedback principle. In the middle Ages, flour mills used centrifugal pendulums to regulate the speed of rotation of the millstone. The first controllers to find broad practical application in industry were Polzunov's charge regulator for the boiler of his steam engine (1765) and Watt's centrifugal governor, which controlled the speed of his steam engine (1784).

The first controllers were of the self-operated type, where the measuring elements act directly on the control element. Such automatic control was possible only in low-power machines, where no great power was required to move the control elements, which were levers or wheels. In 1873 the French engineer J. Farcot became the first to achieve indirect automatic control when he introduced an amplifier—a hydraulic servomotor with rigid feedback—into the control loop. This made it possible not only to increase the power of the controller action but also to obtain more flexible automatic-control algorithms. In 1884 there appeared an indirect controller with a supplementary relay feedback that operated when the deviation was nonzero. The relay connection was subsequently replaced by a continuous differential connection, which came to be called Isodromic.

In the second half of the 19th century, automatic control was used in a great variety of devices, such as steam boilers, compressors, and electric machines. The development of the science of automatic control began in this same period. J. C. Maxwell, in his paper "On Governors" (1868), was the first to consider the mathematical problem of the stability of a linear automatic control system. I. A. Vyshnegradskii's work on direct-action regulators (1877) laid the foundation for the theory of automatic control as a new scientific and technical discipline. The theory was further developed and systematically expounded by A. Stodola, Ia. I. Grdina, and N. E. Zhukovskii [5–12].

CONCLUSION

A new stage in the development of automatic control will come with the use of electronic elements, particularly computing devices, in controllers. This advance greatly increased the possibility of improving control algorithms by introducing actions based on higher derivatives, integrals, and more complex functions. The advantages of electronic controllers were seen especially clearly in adaptive systems, the first of which were optimizing controllers. Landmarks here were the development of a control system for the furnace of a steam boiler in 1926, of an electrical efficiency controller in 1940, and of aviation control systems in 1944. Such controllers, however, are used only in the simple cases, for example, to maintain the extremum of a function of one variable.

In more complex automatic control systems, it is advisable to divide the control system into two parts:

(1) A computing device determining the optimal setting of the controller and
(2) The controller proper

In complex control systems, automatic control is used only at the lowest level of the control hierarchy; the controllers act directly on the controlled system as the performers of the instructions of computers or operators located at higher levels of control.

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