DIGITAL TECHNIQUES

for computation and control

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FOREWORD

This monumental work presents, for the first time in the technical literature, a comprehensive survey of the basic techniques used for digital computation and control—including code arithmetic, logical networks, multiplexing, conversion, data reduction, digital process control, two-terminal relay circuits, counting techniques, digital computers of all types, computer programming, digital differential analyzers, and combined analog-digital equipments. Basic principles, basic circuits, components and available commercial equipments have been included to make this book powerful both in principle and practice.

Two other factors combine to make this work of high importance. The subject matter itself—digital techniques—lends itself to a host of computation and control activities that are basic to modern research and production; and this volume is the first to present all basic digital techniques within the covers of one text.

Much of the material herein appeared first as a series of articles in the trade publication *Instruments and Automation*, under the title, "Digital Automation." The response to this series was overwhelming; even before the conclusion of the series of articles the work was translated into German and Japanese. This book may become one of the powerful original works of our time.

Milton H. Aronson
Editor, *Instruments and Automation*

PREFACE

This book is designed to be a simple, practical, working design manual on the subject of Digital Techniques for Computation and Control. Although intended primarily for the instrument and electronics engineer, it is written at a level understandable to anyone engaged in the engineering and physical sciences. It is hoped that those on whom responsibility ultimately rests—management groups—find it of sufficient clarity to be read because only basic knowledge of electricity, electron tube circuits, and elementary mathematics through the calculus is required.

This material was developed largely in connection with a data-reduction program undertaken by the Instrument Laboratory of the North American Aviation, Inc., Propulsion Field Laboratory, Chatsworth, Calif. On completing this data-reduction system, it became evident that many of the techniques could be applied to servo systems and process-control systems.

The material was compiled also for a course entitled "Digital Automation" given at Pierce Junior College, Canoga Park, Calif., for practicing professional engineers and technicians. Although the course was nominally designed for electronics engineers, it was attended by engineers of all professions, personnel managers, and other management groups (to the surprise of the authors).

As this is the first exhaustive treatment of the subject, much of the material has never appeared in print. Several approaches are unique and original. Only time and widespread interest will determine if the approach taken is the optimum for the field.

It is customary to acknowledge the help given by many people in making a work such as this possible. In this instance the help was considerably more than cursory, and specific mention is in order. Considerable technical assistance was given by Mr. Richard Rush, who developed several of the analog-digital conversion circuits. Mr. Alan Goudey suffered the immensely difficult task of wiring the innumerable logical circuits, incredibly enough without error.

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Chapter 1 (00001)

Introduction To Digital Techniques

Basic Definitions

This book presents the basic notions, methods, and systems used in Digital Automation. One is immediately confronted with the problem of defining the term "Digital Automation."

During the past few years, the word automation has been adopted to encompass any process where any degree of automaticity has been introduced. It is used in some industries in the broad sense of meaning any minute improvement in automatic technique (such as the substitution of printed circuitry for conventional point-to-point circuitry in the electronics industry). In the oil industry, where automatic control is common, it refers to automatic indication and control of, say, a refining operation.

A specific definition of automation, proposed by M. H. Aronson* in 1954, is "the use of devices—mechanical, pneumatic, hydraulic, electrical and electronic—for performing automatic decisions and/or efforts." In line with this definition, digital automation may be defined as the use of digital techniques in using automation devices for producing controlled decisions and/or efforts automatically.

The word "digital" is used in a restricted sense. It implies discreteness or discontinuity. Just as in the number system 0, 1, 2, etc., each digit is a mark for a discrete quantity of things, thus "digital automation" implies the

*Editor, *Instruments and Automation*.

control of processes using techniques in which the process is either (1) a series of discrete operations or (2) a continuous process controlled by the techniques of discrete quantities.

Conventional feedback control, which is a continuous monitoring of the output and comparison of the output with the input (Fig. 1-1), has become known as *servomechanism control*; most self-controllers are of this type. Digital techniques are perfectly applicable to all cases of continuous control, but the converse is not true.

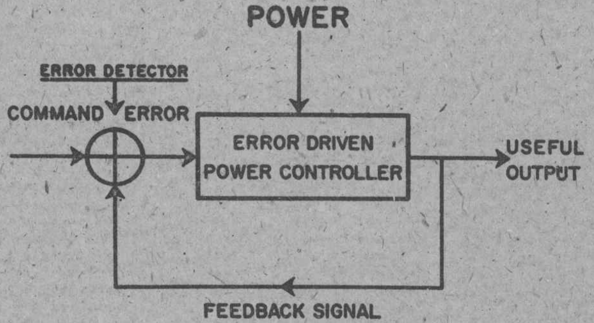

Fig. 1-1 Elements of a closed-loop feedback control system.

Sequence Control

A significant application of digital systems lies in the field of sequence control. For example, let it be required that three different events take place in the sequence *b*, then *a*, then *c*. In a chemical plant the events could be (1) start burner to heat mixture, (2) when a certain temperature is reached, open valve to allow a chemical to enter, and (3) when a certain amount of chemical has entered the mixture, close valve and ring bell to show the sequence has been completed. It might be required that if the sequence of events does not take place as planned, the entire process be stopped and an alarm given. As an alternate, a second plan of action might be desired in the event the first failed. All of these situations are control of a *sequence of events.*

This type of problem suits itself simply to automatic control by digital techniques. The control of complex sequences and alternatives is simple by digital techniques; operations which could not be retained by the human mind because of their complexity are accomplished with a rapidity several hundred thousand times that capable by a human. Examples of important sequences are to be found in aircraft or missile control, operation of a turret lathe, or any process where the events to take place can be placed in a fixed sequence—with possible alternate sequences to account for things going wrong. Digital automation lends itself readily to this type of control.

Simple Servo Control

Another application of digital techniques is found in simple servo control. In a servo system, a command is given to a remotely actuated device. If for any reason the device does not arrive at the position required, or does not perform as commanded, a correction is made automatically. Remote antenna positioners or motor speed controllers are examples of simple servo systems in which the remotely actuated device continues in a self-correcting state until the error between the command given and the result of the command is minimized. This is the purpose of a servo system—to permit a system to correct its own errors in following remotely given commands. The value of the system depends upon the speed and precision with which the system can take up its own errors and follow the commands given.

It has been conventional to develop servo systems on the basis of an analog or continuous-recording technique. However, digital techniques are being recognized as useful in accomplishing the same type of control—with several distinct advantages which will be discussed.

Data Reduction Systems

In the control of complex processes, data may be accumulated from hundreds of points. Usually these are recorded continuously, using a galvanometer or oscillographic or potentiometer techniques involving moving recording paper, inked pens, etc. Reducing this data for use becomes a tedious problem; wind tunnels are constantly confronted with the problem of reducing data from many points to numerical form for subsequent computation. The true automation system will not only control the process, but will also produce data in a form useful for automatic computation. This is within the realm of digital automation.

Data recorded in digital form can be processed directly by "programming." The result will be a printed number which is the answer required. Inventory, cost records, and production scheduling are within this realm of digital automation via data reduction. Business machinery in use for over twenty-five years operate exclusively in digital techniques; similar techniques can be applied to engineering data obtained in digital form. Business accounting is merely a special program for data handling; we shall borrow a number of well-developed techniques from this first and well-worked-out aspect of automation.

Feedback Control

All the foregoing aspects of automation are related; the common factor in all useful control systems is *feedback.* Feedback is accomplished by sensing in some manner what is happening to a system after a command is given. This measure of what is actually happening is compared with the command given the system. If these two quantities, command and output, do not agree, the system had made *an error* in following the command. This error is then used to allow the system to rectify its own error. This is controlled by feedback (Fig. 1-1). Note that it is not the command that actuates the system, but the *error* between the command and the result of the command. The ideal system is one which will instantly cause the system to move into the situation required by the command; this ideal can never be realized because the error must be finite.

Consider a human operator of a refinery process or a milling machine. If things progress properly he merely watches and does nothing. If something goes wrong, he recognizes the error, measures the degree of the error, and takes corrective action. From the automation point of view, this is complete inefficiency. When things are going right, you are paying the operator to do nothing; when something goes wrong you are relying on human judgment to measure the error and correct it.

Note also that a human operator is a feedback controller. First, he gives the commands as to what shall be done; secondly, he determines when the process is in error by referring to his gages and comparing the information with his command, mentally; thirdly, he takes the necessary corrective action by adjusting valves, motors, etc. to minimize the error. The operator is actually a feedback control system, but one whose limitations in speed, response, calculating, etc., are entirely human.

Elements for Automatic Control

The basic operations performed by the human operator are:

1. Command a device to perform a task.
2. Sense errors in the process.
3. Feed back this information and compare it with the command given.
4. Take corrective action to minimize this error.
5. Record data on the progress of the operations.

Each of these tasks can be done more rapidly and efficiently by mechanical, pneumatic, electrical, or electronic devices; design of an automation system depends on the application of such equipments to perform these basic actions.

Let us examine briefly the nature of the equipment to accomplish this. *Sensing* is accomplished with a transducer; there are innumerable commercial devices available. As electrical signals are most easily applicable to digital automation systems, we will concern ourselves with devices which produce an electrical signal. Pressure, temperature, displacement, velocity, acceleration, flow rate, force, angularity, and other variables can be measured in electrical form by suitable transducers.

This information in electrical form, is fed back and *comparison* is made with command given, which is also in electrical form. This comparison can be accomplished in several ways, such as by unbalancing a bridge or moving the shaft of a potentiometer to produce the electrical error signal.

This electrical error signal is used in suitable amplifiers, computers and other circuitry to *actuate* the devices (valves, motors, shafts) that make the corrective action minimizing the error. The same sensing element, (the transducer) can be used to *record* data on the progress of the process or operation. This is the automation system by feedback control.

It is possible to "control" a process without feedback—

that is, to arrange things to occur in certain order without sensing what is actually happening; things might occur properly. This is known as *open-loop control*, and is actually no control at all; it is hardly worth considering as an automation technique. Thus, each of the five elements listed are essential in the true control system.

Continuous vs. Digital Control

There are two possible ways to make use of the electrical information. Fig. 1-2 shows a continuous record of electrical information from, say, a pressure transducer. This continuous curve is a type of information widely used in conventional servo systems and simple control systems.

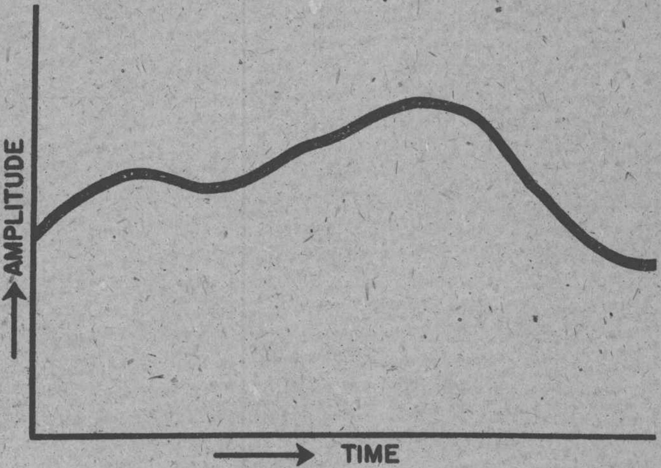

Fig. 1.-2. Continuous curve is analog representation of a variable.

Fig. 1-3 shows the same record in discrete, or digital, form. In this record we have looked at the continuous record at fixed intervals. Each sample is taken to represent the continuous record until the next sample is obtained. We have effectively changed the continuous record into a finite number of fixed readings. This is equivalent to having someone read a graph at fixed intervals and record the numerical value at these fixed intervals, and thus *digitize* or *quantize* the continuous record.

At first sight it would seem that control is best offered by continuously recording what is happening and thereby knowing at every instant exactly what is occurring. However, in using a continuous record, one limits himself

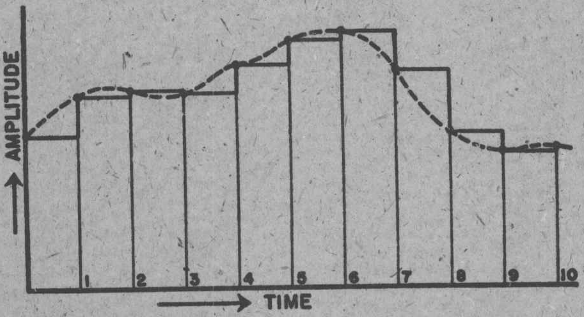

Fig. 1-3. Curve obtained by sampling at fixed intervals.

seriously insofar as automatic control techniques because the analog record precludes digital technique. Note that if samples are taken sufficiently often the continuous record can be more closely approximated (Fig. 1-4). In effect, the discrete readings can be made to be equivalent in accuracy to the continuous record—and the advantage in using the digital form of record is that digital numbers can be manipulated electronically much more simply than the analog record. The advantages of such digital techniques will be explored.

Digital techniques of control are just emerging; automatic digital data reduction has only been commercially available for a limited time. Therefore, we will, in essence, develop a considerable number of methods for the first time.

The most common system used in computer circuitry is the binary coding system, which we will investigate.

This subject should be of interest to almost everyone, and is largely ignored. As the circuitry of digital information is unique, the performance of the basic circuits will be discussed in detail. What is surprising is that the *number* of different circuits used is small; only ten or twelve basic circuits are used over and over. This is a great help.

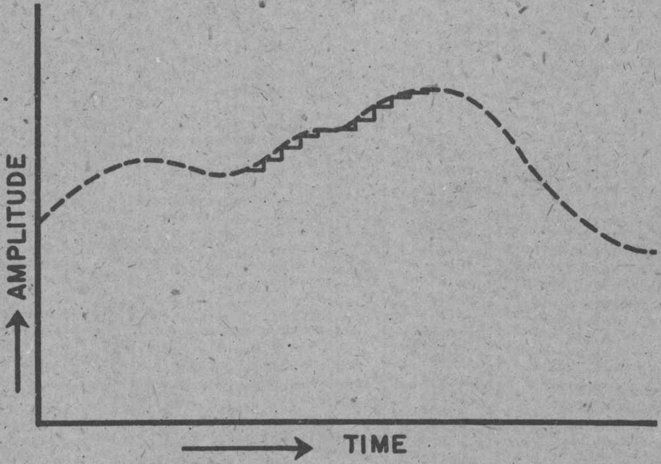

Fig. 1-4. Increasing number of readings causes digital record to approach the analog record.

Automation is essentially a process of logic, and *logical networks* form a large part of the operation of a digital control system, as in computers. An understanding of the methods for designing these circuits is necessary and will be included.

It was mentioned that the digital samples approach the continuous record more and more closely as the sampling rate increases. It is necessary to know what error, if any, is introduced in using digital quantities instead of continuous records. This falls under the heading of *information theory*. In the chapter concerned with sampling rates, a fairly simple and straight-forward explanation is offered and quantitative examples are included for guidance. We will be concerned also with the interference of random and spurious noise on the information to be used for the control, and the advantages of using what is known as *pulse code modulation* for relaying information from one point to another.