Second Edition

Digital Control of Dynamic Systems

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CHAPTER 1

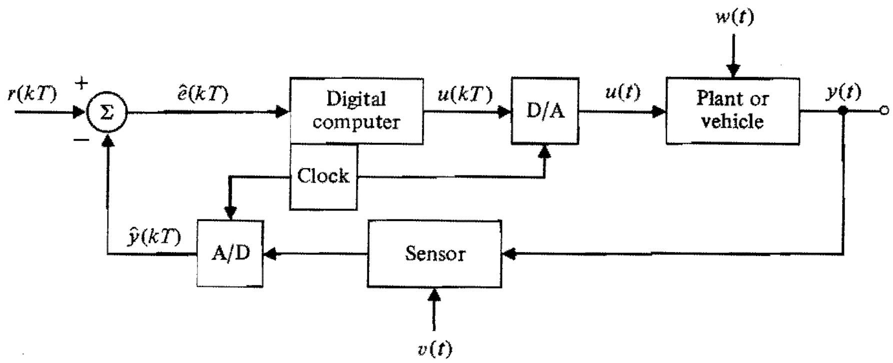
Introduction

1.1 PROBLEM DEFINITION

The control of physical systems with a digital computer is becoming more and more common. Aircraft autopilots, mass-transit vehicles, oil refineries, paper-making machines, and countless electromechanical servomechanisms are among the many existing examples. Furthermore, many new digital control applications are being stimulated by microprocessor technology including control of various aspects of automobiles and household appliances. Among the advantages of digital logic for control are the increased flexibility of the control programs and the decision-making or logic capability of digital systems, which can be combined with the dynamic control function to meet other system requirements.

The digital controls studied in this book are for closed-loop (feedback) systems in which the dynamic response of the process being controlled is a major consideration in the design. A typical topology of the elementary type of system that will occupy most of our attention is sketched schematically in Fig. 1.1. This figure will help to define our basic notation and to introduce several features that distinguish digital controls from those implemented with analog devices. The process to be controlled is called the plant and may be any of the physical processes mentioned above whose satisfactory response requires control action.

By "satisfactory response" we mean that the plant output, $y(t)$, is to be forced to follow or track the reference input, $r(t)$, despite the presence of disturbance inputs to the plant [$w(t)$ in Fig. 1.1] and despite errors in the sensor [represented by $v(t)$ in Fig. 1.1]. It is also essential that the tracking succeed even if the dynamics of the plant should change somewhat during



Notation:

- r = reference or command inputs
- u = control or actuator input signal
- y = controlled or output signal
- $\hat{y}$ = instrument or sensor output, usually an approximation to or estimate of y. (For any variable, say θ, the notation $\hat{\theta}$ is now commonly taken from statistics to mean an estimate of θ.)
- $\hat{e}$ = $r - \hat{y}$ = indicated error
- e = $r - y$ = system error
- w = disturbance input to the plant
- v = disturbance or noise in the sensor
- A/D = analog-to-digital converter
- D/A = digital-to-analog converter

Figure 1.1 Block diagram of a basic control system.

the operation. The process of holding $y(t)$ close to $r(t)$, including the case where $r \equiv 0$, is referred to generally as the process of *regulation*. A system that has good regulation in the presence of disturbance signals is said to have good *disturbance rejection*. A system that has good regulation in the face of changes in the plant parameters is said to have low *sensitivity* to these parameters. A system that has both good disturbance rejection and low sensitivity we call *robust*.

The means by which robust regulation is to be accomplished is through the control inputs to the plant [$u(t)$ in Fig. 1.1]. It was discovered long ago[1] that a scheme of feedback wherein the plant output is measured (or sensed) and compared directly with the reference input has many advantages in the effort to design robust controls over systems that do not use such feedback. Much of our effort in later parts of this book will be devoted to illustrating this discovery and demonstrating how to exploit the advantages of feedback. However, the problem of control as discussed thus far is in no way restricted

[1]See especially the book by Bode (1945).

to digital control. For that we must consider the unique features of Fig. 1.1 introduced by the use of a digital device to generate the control action.

We consider first the action of the analog-to-digital (A/D) converter on a signal. This device acts on a physical variable, most commonly an electrical voltage, and converts it into a stream of numbers. In Fig. 1.1, the A/D converter acts on the sensor output and supplies numbers to the digital computer. It is common for the sensor output, $\hat{y}$, to be sampled and to have the error formed in the computer. We need to know the times at which these numbers arrive if we are to analyze the dynamics of this system.

In this book we will make the assumption that all the numbers arrive with the same fixed period T, called the *sampling period*. In practice, digital control systems sometimes have varying sample periods and/or different periods in different feedback paths. Usually there is a clock as part of the computer logic which supplies a pulse or *interrupt* every T seconds, and the A/D converter sends a number to the computer each time the interrupt arrives. An alternative implementation is simply to access the A/D upon completion of each cycle of the code execution, a scheme often referred to as *free running*. In the first case the sample period is precisely fixed; in the latter case the sample period is essentially fixed by the length of the code, providing no logic branches are present that could vary the amount of code executed. Thus in Fig. 1.1 we identify the sequence of numbers into the computer as $\hat{e}(kT)$. We conclude from the periodic sampling action of the A/D converter that some of the signals in the digital control system, like $\hat{e}(kT)$, are variable only at discrete times. We call these variables *discrete signals* to distinguish them from variables like w and y, which change continuously in time. A system having both discrete and continuous signals is called a *sampled-data* system.

In addition to generating a discrete signal, however, the A/D converter also provides a *quantized* signal. By this we mean that the output of the A/D converter must be stored in digital logic composed of a finite number of digits. Most commonly, of course, the logic is based on binary digits (i.e., bits) composed of 0's and 1's, but the essential feature is that the representation has a finite number of digits. A common situation is that the conversion of y to $\hat{y}$ is done so that $\hat{y}$ can be thought of as a number with a fixed number of places of accuracy. If we plot the values of y versus the resulting values of $\hat{y}$ we can obtain a plot like that shown in Fig. 1.2. We would say that $\hat{y}$ has been truncated to one decimal place, or that $\hat{y}$ is *quantized* with a q of 0.1, since $\hat{y}$ changes only in fixed quanta of, in this case, 0.1 units. (We will use q for quantum size, in general.) Note that quantization is a nonlinear function. A signal that is both discrete and quantized is called

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