# Computer-Controlled Systems

## Theory and Design

### THIRD EDITION

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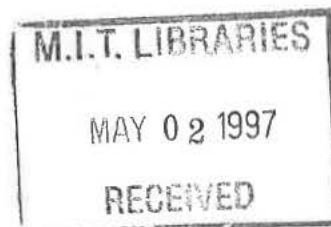
# Computer Control

## 1.1 Introduction

Practically all control systems that are implemented today are based on computer control. It is therefore important to understand computer-controlled systems well. Such systems can be viewed as approximations of analog-control systems, but this is a poor approach because the full potential of computer control is not used. At best the results are only as good as those obtained with analog control. It is much better to master computer-controlled systems, so that the full potential of computer control can be used. There are also phenomena that occur in computer-controlled systems that have no correspondence in analog systems. It is important for an engineer to understand this. The main goal of this book is to provide a solid background for understanding, analyzing, and designing computer-controlled systems.

A computer-controlled system can be described schematically as in Fig. 1.1. The output from the process $y(t)$ is a continuous-time signal. The output is converted into digital form by the analog-to-digital (A-D) converter. The A-D converter can be included in the computer or regarded as a separate unit, according to one's preference. The conversion is done at the sampling times, $t_k$. The computer interprets the converted signal, $\{y(t_k)\}$, as a sequence of numbers, processes the measurements using an algorithm, and gives a new sequence of numbers, $\{u(t_k)\}$. This sequence is converted to an analog signal by a digital-to-analog (D-A) converter. The events are synchronized by the real-time clock in the computer. The digital computer operates sequentially in time and each operation takes some time. The D-A converter must, however, produce a continuous-time signal. This is normally done by keeping the control signal constant between the conversions. In this case the system runs open loop in the time interval between the sampling instants because the control signal is constant irrespective of the value of the output.

The computer-controlled system contains both continuous-time signals and *sampled*, or *discrete-time*, signals. Such systems have traditionally been called
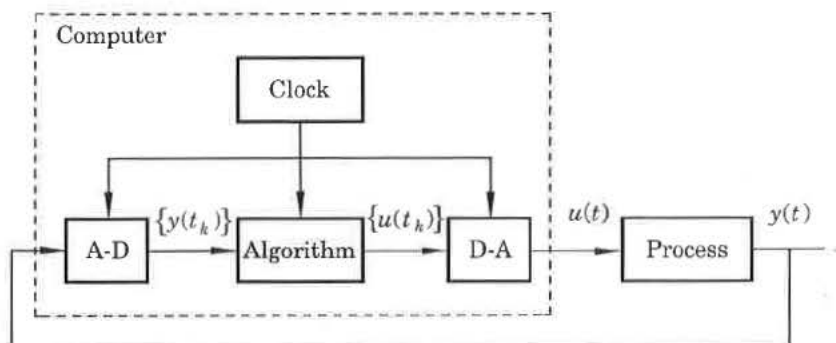
**Figure 1.1**  Schematic diagram of a computer-controlled system.

*sampled-data systems*, and this term will be used here as a synonym for *computer-controlled systems*.

The mixture of different types of signals sometimes causes difficulties. In most cases it is, however, sufficient to describe the behavior of the system at the sampling instants. The signals are then of interest only at discrete times. Such systems will be called *discrete-time systems*. Discrete-time systems deal with sequences of numbers, so a natural way to represent these systems is to use difference equations.

The purpose of the book is to present the control theory that is relevant to the analysis and design of computer-controlled systems. This chapter provides some background. A brief overview of the development of computer-control technology is given in Sec. 1.2. The need for a suitable theory is discussed in Sec. 1.3. Examples are used to demonstrate that computer-controlled systems cannot be fully understood by the theory of linear time-invariant continuous-time systems. An example shows not only that computer-controlled systems can be designed using continuous-time theory and approximations, but also that substantial improvements can be obtained by other techniques that use the full potential of computer control. Section 1.4 gives some examples of inherently sampled systems. The development of the theory of sampled-data systems is outlined in Sec. 1.5.

## 1.2 Computer Technology

The idea of using digital computers as components in control systems emerged around 1950. Applications in missile and aircraft control were investigated first. Studies showed that there was no potential for using the general-purpose digital computers that were available at that time. The computers were too big, they consumed too much power, and they were not sufficiently reliable. For this reason special-purpose computers—digital differential analyzers (DDAs)—were developed for the early aerospace applications.

The idea of using digital computers for process control emerged in the mid-1950s. Serious work started in March 1956 when the aerospace company Thomson Ramo Woodridge (TRW) contacted Texaco to set up a feasibility study. After preliminary discussions it was decided to investigate a polymerization unit at the Port Arthur, Texas, refinery. A group of engineers from TRW and Texaco made a thorough feasibility study, which required about 30 people-years. A computer-controlled system for the polymerization unit was designed based on the RW-300 computer. The control system went on-line March 12, 1959. The system controlled 26 flows, 72 temperatures, 3 pressures, and 3 compositions. The essential functions were to minimize the reactor pressure, to determine an optimal distribution among the feeds of 5 reactors, to control the hot-water inflow based on measurement of catalyst activity, and to determine the optimal recirculation.

The pioneering work done by TRW was noticed by many computer manufacturers, who saw a large potential market for their products. Many different feasibility studies were initiated and vigorous development was started. To discuss the dramatic developments, it is useful to introduce six periods:

Pioneering period ≈ 1955

Direct-digital-control period ≈ 1962

Minicomputer period ≈ 1967

Microcomputer period ≈ 1972

General use of digital control ≈ 1980

Distributed control ≈ 1990

It is difficult to give precise dates, because the development was highly diversified. There was a wide difference between different application areas and different industries; there was also considerable overlap. The dates given refer to the emergence of new approaches.

### Pioneering Period

The work done by TRW and Texaco evoked substantial interest in process industries, among computer manufacturers, and in research organizations. The industries saw a potential tool for increased automation, the computer industries saw new markets, and universities saw a new research field. Many feasibility studies were initiated by the computer manufacturers because they were eager to learn the new technology and were very interested in knowing what a proper process-control computer should look like. Feasibility studies continued throughout the sixties.

The computer systems that were used were slow, expensive, and unreliable. The earlier systems used vacuum tubes. Typical data for a computer around 1958 were an addition time of 1 ms, a multiplication time of 20 ms, and a mean time between failures (MTBF) for a central processing unit of 50–100 h. To make full use of the expensive computers, it was necessary to have them perform many

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