COMPUTER-CONTROLLED SYSTEMS

THEORY AND DESIGN

SECOND EDITION

Prentice-Hall International Editions

KARL J. ÅSTRÖM
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PREFACE

In the Sixties a control engineer had to master analog computing technology because of its use in analog computers in the simulation of control systems and as the major tool for computations. Analog technology in mechanics, pneumatics, and electronics was also used in control systems.

The scene is now rapidly changing due to the dramatic developments in digital computers and microelectronics. Digital computers were originally used as components in complicated process-control systems. However, because of their small size and low price, digital computers are now also being used in regulators for individual control loops. In several areas digital computers are now outperforming their analog counterparts and are cheaper as well.

Digital computers are also being used increasingly as tools for analysis and design of control systems. The control engineer thus has much more powerful tools available now than in the past. Digital computers are still in a state of rapid development because of the progress in Very Large-Scale Integration (VLSI) technology. Thus substantial technological improvements can be expected in the future.

Because of these developments, the approach to analysis, design, and implementation of control systems is changing drastically. Originally it was only a matter of "translating" the earlier analog designs into the new technology. However, it has been realized that there is much to be gained by exploiting the full potential of the new technology. Fortunately, control theory has also developed substantially over the past 35 years. For a while it was quite unrealistic to implement the type of regulators that the new theory produced except in a few exotic mostly in aerospace or advanced process control. However, due to the revolutionary development of microelectronics, advanced regulators can be implemented even for basic applications. It is also possible to do analysis and design at a reasonable cost with the interactive design tools that are becoming increasingly available.

The purpose of this book is to present control theory that is relevant to the analysis and design of computer-controlled systems, with an emphasis on basic concepts and ideas. It is assumed that a digital computer with a reasonable software is available for computations and simulations so that many tedious details can be left to the computer. The control-system design is also carried out up to the stage of implementation in the form of computer programs in a high-level language.

The book is organized as follows: An overview of the development of computer control is given in Chapter 1. A survey of the development of the theory is also given in order to provide some perspective. (Those who do not know history are bound to repeat it.)

Sampling, which is a fundamental property of computer-controlled systems, is discussed in Chapter 2. The basic mathematical models needed are given in Chapters 3, 4, and 6. Chapter 3 gives the models as seen from the computer, while Chapter 4 treats the models as seen from the process. Without disturbances there are no control problems; it is therefore important to find suitable ways to characterize disturbances, which is done in Chapter 6.

In Chapter 5 the major tools for analysis and simulation are given. Simulation plays an important role because there are many detailed questions that are very hard to answer through analysis alone. Simnon, an interactive simulation language that is used throughout the book, is presented in an appendix. It is not very difficult to translate the programs into other simulation languages. The fact that a powerful simulation tool is available makes a drastic change in attitudes and techniques. It is very important that the simulations be accompanied by analysis that can give order-of-magnitude estimates to ensure that the simulation results are reasonable. At the same time it is not necessary to provide tools for very accurate calculations because these can easily be done by the computer. Chapters 7 through 12 are devoted to the design problem. An overview is given in Chapter 7. Translation of analog design methods is discussed in Chapter 8. State-space design techniques for deterministic systems based on pole assignment are discussed in Chapter 9. The same problem is discussed in Chapter 10 using input-output models. Optimal design methods based on Kalman filters, linear quadratic, and linear quadratic Gaussian control are treated in Chapter 11 based on state-space models and in Chapter 12 using input-output models.

A characteristic feature of many of the new design methods is that a model of the process and its disturbances is needed. Chapter 13 discusses how such models can be obtained. A brief treatment of parameter-adaptive control systems is given in Chapter 14. This may be viewed as a combination of the design methods in Chapters 9 to 12 with the recursive identification methods in Chapter 13. Chapter 15 discusses different aspects of implementation of computer-control algorithms.

The theory is organized in such a way that all models and specifications are given in continuous time. This makes applications easier because of the close connections with physics. Multivariable systems are covered whenever state-space techniques are used; however, the treatment of input-output models using the polynomial approach is limited to the single-input–single-output case. Both deterministic and stochastic aspects of the analysis and the design problem are given.

When designing a system it is often advantageous to see a problem from several viewpoints. Since the goal of the book is to give a good foundation for design of computer-controlled systems, it is necessary to cover a wide range of topics. A reasonable balance between detail and overview has been achieved; however, Chapters 6, 11, 12, 13, and 14 require complete books to cover each topic fully.

In sampled-data theory it has been the custom to let the same symbol z denote both a complex variable and a forward-shift operator. We have found this practice confusing for students and have therefore introduced the symbol q to denote the forward-shift operator. This is analogous to the use of s as a complex variable and $p = d/dt$ as a differential operator for continuous-time systems. The notation q^{-1} is used to denote the backward-shift operator.

The delta operator is defined as $\delta = (q - 1)/h$ is an alternative to the shift operator. It has the advantage that is an approximation of the differential operator.

From the very beginning of the development of sampled-data theory there has been a discussion of the relative merits of shift and delta operators. This discussion is renewed every now and then. It is our opinion that it is useful to keep the shift operator and the z-transform and to view the delta operators as a useful numerical device. One reason for this is that z-transforms naturally appear in many branches of applied mathematics such as analysis of difference equations and generalized functions in probability theory.

This book can be used in many different ways. Chapters 2, 3, 5, 7, 8, 9, 10, and 15 and Sections 6.1–6.3 are suited for an undergraduate course in sampled-data systems. A detailed treatment of Chapters 4, 6, 7, and 9 through 15 can form the core of a graduate course in design of computer-controlled systems. We have given courses to industrial audiences based on Chapters 3, 4, 5, 8, 9, 10, 13, 14, and 15. In all cases we have found it very advantageous to have access to computer simulation and to supplement lectures and exercises with laboratory experiments. Some suggestions for this are given in the solutions manual.

Many students and colleagues have given very good suggestions for improving the book. We are grateful for this feedback which has resulted in significant changes in this second edition. Some modifications were also motivated by the fact that we have learned more ourselves about computer-controlled systems. The major changes have been made in Chapters 8–12, which deal with control-system design. Large sections have been rewritten, larger design examples are introduced. This reflects our belief that more emphasis should be given to control-system design. To compare different design techniques, they have been applied to the same examples. Many issues of practical relevance have been added. A typical case is antialiasing filters and their effect on control design. Chapter 15 has also been modified significantly by including more material on realization of digital controllers. Numerics and quantization are also treated in more detail. These are more relevant now when digital control systems are implemented using digital signal processors and custom VLSI.

The general availability of tools for Computer-Aided Control Engineering has drastically changed the way we can teach automatic control. For instance, it allows us to solve more realistic examples. Since much of the routine work can be done using the computer, we can devote more time to the fundamentals. It is, however, absolutely essential to instill an attitude of sound criticism in the minds of students so that they can judge the results of the computations. The specific tools needed for computer-controlled systems are software for calculating with matrices and polynomials and a nonlinear simulator for verifying the results. We are currently using Matlab for the calculations and the interactive simulation program Simnon. All the graphs in the book showing time responses were generated using Simnon. The graphs were generated by macros which are available to our students. To recreate the simulation of Figure 10.9, the student simply types fig109. In this way it is possible to have students explore many things that were previously not possible. There are also convenient interfaces between Matlab and Simnon so that a design can be carried out in Matlab and transferred to Simnon.

Simnon is available for MS-DOS computers, Vax, and Sun work-stations. More information about the program can be obtained using the tear-out card at the end of the book or by writing directly to the authors. For instructors, the macros are available for a handling charge.

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CONTENTS

1 COMPUTER CONTROL

GOAL

To Introduce the Subject and to Give Some Historical Background on the Development of Computer-Control Technology and Theory.

1.1 Introduction

Digital computers are increasingly being used to implement control systems. It is therefore important to understand computer-controlled systems well. One can view computer-controlled systems 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. Alternatively, one can learn about computer-controlled systems, so that the full potential of computer control is used. The main goal of this book is to provide the required background.

A computer-controlled system can be schematically described 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. Notice that the system runs open loop in the interval between the A-D and the D-A conversion. The events are synchronized by the real-time clock in the computer. The digital computer operates sequentially in time and each