Sixth Edition

Modern Control Systems

Richard C. Dorf

SIXTH EDITION

Modern Control Systems

Richard C. Dorf

University of California, Davis

ADDISON-WESLEY PUBLISHING COMPANY

Reading, Massachusetts • Menlo Park, California • New York
Don Mills, Ontario • Wokingham, England • Amsterdam • Bonn
Sydney • Singapore • Tokyo • Madrid • San Juan • Milan • Paris

This book is in the Addison-Wesley Series in Electrical and Computer Engineering: Control Engineering
Consulting Editor: Karl J. Åström

Adaptive Control, 09720
Karl J. Åström and Björn Wittenmark

Introduction to Robotics, Second Edition, 09528
John J. Craig

Modern Control Systems, Sixth Edition, 51713
Richard C. Dorf

Digital Control of Dynamic Systems, Second Edition, 11938
Gene F. Franklin, J. David Powell, and Michael L. Workman

Computer Control of Machines and Processes, 10645
John G. Bollinger and Neil A. Duffie

Feedback Control of Dynamic Systems, Second Edition, 50862
Gene F. Franklin, J. David Powell, and Abbas Emami-Naeini

Adaptive Control of Mechanical Manipulators, 10490
John J. Craig

Library of Congress Cataloging-in-Publication Data

Dorf, Richard C.
Modern control systems / Richard C. Dorf. — 6th ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-201-51713-2
1. Feedback control systems. I. Title.
TJ216.D67 1992
629.8'3—dc20 91-2731
CIP

Reprinted with corrections May, 1992

2 3 4 5 6 7 8 9 10-HA-95949392

PREFACE

The National Academy of Engineering identified in 1990 the ten outstanding engineering achievements of the preceding twenty-five years. These feats included five accomplishments made possible by utilizing modern control engineering: the Apollo lunar landing, satellites, computer-aided manufacturing, computerized axial tomography, and the jumbo jet.

Automation and robotics are critical ingredients in the world's efforts toward an improved standard of living for all. Automation, the automatic operation of processes, and robotics, which includes the manipulator, controller, and associated devices, are all critical to effective operation of our plants, factories, and institutions. The most important and productive approach to learning is for each of us to rediscover and recreate anew the answers and methods of the past. Thus the ideal is to present the student with a series of problems and questions and point to some of the answers that have been obtained over the past decades. The traditional method—to confront the student not with the problem but with the finished solution—is to deprive the student of all excitement, to shut off the creative impulse, to reduce the adventure of humankind to a dusty heap of theorems. The issue, then, is to present some of the unanswered and important problems which we continue to confront. For it may be asserted that what we have truly learned and understood we discovered ourselves.

The purpose of this book is to present the structure of feedback control theory and to provide a sequence of exciting discoveries as we proceed through the text and problems. If this book is able to assist the student in discovering feedback control system theory and practice, it will have succeeded.

The book is organized around the concepts of control system theory as they have been developed in the frequency- and time-domain. A real attempt has been made to make the selection of topics, as well as the systems discussed in the examples and problems, modern in the best sense. Therefore this book includes a discussion of sensitivity, performance indices, state variables, robotics, and computer control systems, to name a few. However, a valiant attempt has been made to retain the classical topics of control theory that have proved to be so very useful in practice.

Written in an integrated form, the text should be read from the first to the last chapter. However, it is not necessary to include all the sections of a given chapter in any given course, and there appears to be quite a large number of combinations of sequences of the sections for study. The book is designed for an introductory undergraduate course in control systems for engineering students. There is very little demarcation between electrical, mechanical, chemical, and industrial engineering in control system practice; therefore this text is written without any conscious bias toward one discipline. Thus it is hoped that this book will be equally useful for all engineering disciplines and, perhaps, will assist in illustrating the unity of control engineering. The problems and examples are chosen from all fields, and the examples of the sociological, biological, ecological, and economic control systems are intended to provide the reader with an awareness of the general applicability of control theory to many facets of life.

The book is primarily concerned with linear, constant parameter control systems. This is a deliberate limitation because I believe that for an introduction to control systems, it is wisest initially to consider linear systems. Nevertheless, several nonlinear systems are introduced and discussed where appropriate.

Chapter 1 provides an introduction to and basic history of control theory. Chapter 2 is concerned with developing mathematical models of these systems. With the models available, the text describes the characteristics of feedback control systems in Chapter 3 and illustrates why feedback is introduced in a control system. Chapter 4 examines the performance of control systems, and Chapter 5 investigates the stability of feedback systems. Chapter 6 is concerned with the *s*-plane representation of the characteristic equation of a system and the root locus. Chapters 7 and 8 treat the frequency response of a system and the investigation of stability using the Nyquist criterion. Chapter 9 develops the time-domain concepts in terms of the state variables of a system. Chapter 10 describes and develops several approaches to designing and compensating a control system. Chapter 11 discusses computer control systems, robust systems, and robotics. Finally, Chapter 12 introduces and illustrates the all-important topic of engineering design.

This book is suitable for an introductory course in control systems. In its first five editions, the text has been used in senior-level courses for engineering students at more than 400 colleges and universities. Also, it has been used in courses for engineering graduate students with no previous background in control system theory.

The text presumes a reasonable familiarity with the Laplace transformation and transfer functions as developed in a first course in linear system analysis or network analysis. These concepts are discussed in Chapter 2 and are used to develop mathematical models for control system components. Answers to selected exercises are provided along with the exercises. Answers to selected problems are provided at the end of the book.

The sixth edition has incorporated several important developments in the field of control systems, with particular reference to robots and robust systems. In addition, a valuable feature is the exercises immediately preceding the problems. The purpose of these exercises is to permit students to utilize readily the concepts and methods introduced in each chapter in the solution of relatively straightforward exercises before attempting the more complex problems. The sixth edition expands the emphasis on design and incorporates a design example and several design problems in each chapter.

The sixth edition uses the computer program the Control System Design Program (CSDP) to assist in the solution of selected examples throughout the book. The student should first understand and use the tools and concepts before proceeding to utilize computer solutions. Nevertheless, the computer-aided analysis of the CSDP can be an invaluable aid in solving complex problems.

This edition also provides a preview as well as a summary of the terms and concepts for each chapter. There is an expanded Chapter 11, which discusses the useful proportional-integral-derivative (PID) controller and robust control systems. An enhanced Chapter 12 encompassing the all-important topic of design of real-world, complex control systems completes this edition.

This material has been developed with the assistance of many individuals to whom I wish to express my sincere appreciation. Finally, I can only partially acknowledge the encouragement and patience of my wife, Joy, who helped to make this book possible.

Davis, California R.C.D.

CONTENTS

1 Introduction to Control Systems 1

2 Mathematical Models of Systems 35

3 Feedback Control System Characteristics 115

4 The Performance of Feedback Control Systems 157

5 The Stability of Linear Feedback Systems 207

6 The Root Locus Method 235

7 Frequency Response Methods 301

5 20/1/05

8 Stability in the Frequency Domain 353

9 Time-Domain Analysis of Control Systems 429

10 The Design and Compensation of Feedback Control Systems 487

11 Robust Control Systems 573

CHAPTER 1

Introduction to Control Systems

Preview

A system, consisting of interconnected components, is built to achieve a desired purpose. The performance of this system can be examined, and methods for controlling its performance can be proposed. It is the purpose of this chapter to describe the general approach to designing and building a control system.

In order to understand the purpose of a control system, it is useful to examine some examples of control systems through the course of history. Even these early systems incorporated the idea of feedback, which we will discuss throughout this book.

Modern control engineering practice includes the use of control strategies for aircraft, rapid transit, the artificial heart, and steel making, among others. We will examine these very interesting applications of control engineering.

1.1 Introduction

Engineering is concerned with understanding and controlling the materials and forces of nature for the benefit of humankind. Control system engineers are concerned with understanding and controlling segments of their environment, often called *systems*, in order to provide useful economic products for society. The twin goals of understanding and control are complementary because, in order to be controlled more effectively, the systems under control must be understood and modeled. Furthermore, control engineering must often consider the control of poorly understood systems such as chemical process systems. The present challenge to control engineers is the modeling and control of modern, complex, interrelated systems such as traffic-control systems, chemical processes, and robotic systems. However, simultaneously, the fortunate engineer has the opportunity to control many very useful and interesting industrial automation systems. Perhaps the most characteristic quality of control engineering is the opportunity to control machines, and industrial and economic processes for the benefit of society.

Control engineering is based on the foundations of feedback theory and linear system analysis, and it integrates the concepts of network theory and communication theory. Therefore control engineering is not limited to any engineering discipline but is equally applicable for aeronautical, chemical, mechanical, environmental, civil, and electrical engineering. For example, quite often a control system includes electrical, mechanical, and chemical components. Furthermore, as the understanding of the dynamics of business, social, and political systems increases, the ability to control these systems will increase also.

A *control system* is an interconnection of components forming a system configuration that will provide a desired system response. The basis for analysis of a system is the foundation provided by linear system theory, which assumes a cause-effect relationship for the components of a system. Therefore a component or *process* to be controlled can be represented by a block as shown in Fig. 1.1. The input-output relationship represents the cause and effect relationship of the process, which in turn represents a processing of the input signal to provide an output signal variable, often with a power amplification. An *open-loop* control system utilizes a controller or control actuator in order to obtain the desired response, as shown in Fig. 1.2.

In contrast to an open-loop control system, a closed-loop control system utilizes an additional measure of the actual output in order to compare the actual output with the desired output response. The measure of the output is called the *feedback signal.* A simple *closed-loop feedback control system* is shown in Fig. 1.3.

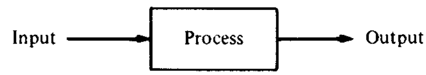

Figure 1.1. Process to be controlled.

Figure 1.2. Open-loop control system.

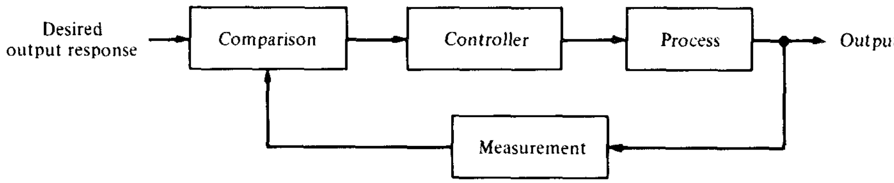

Figure 1.3. Closed-loop feedback control system.

A standard definition of a feedback control system is as follows: A feedback control system is a control system that tends to maintain a prescribed relationship of one system variable to another by comparing functions of these variables and using the difference as a means of control.

A feedback control system often uses a function of a prescribed relationship between the output and reference input to control the process. Often the difference between the output of the process under control and the reference input is amplified and used to control the process so that the difference is continually reduced. The feedback concept has been the foundation for control system analysis and design.

Due to the increasing complexity of the system under control and the interest in achieving optimum performance, the importance of control system engineering has grown in this decade. Furthermore, as the systems become more complex, the interrelationship of many controlled variables must be considered in the control scheme. A block diagram depicting a *multivariable control system* is shown in Fig. 1.4. A humorous example of a closed-loop feedback system is shown in Fig. 1.5.

A common example of an open-loop control system is an electric toaster in the kitchen. An example of a closed-loop control system is a person steering an automobile (assuming his or her eyes are open).

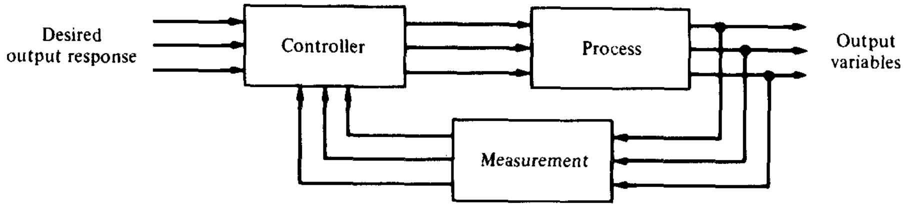

Figure 1.4. Multivariable control system.

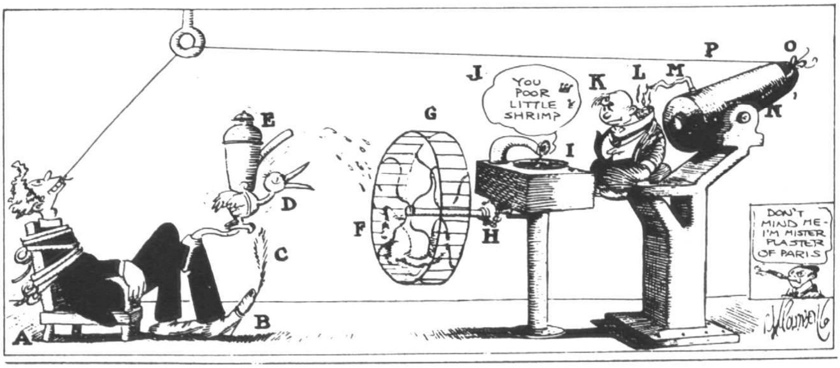

Figure 1.5. Rube Goldberg's elaborate creations were almost all closed-loop feedback systems. Goldberg called this simply, "Be Your Own Dentist." (© Rube Goldberg, permission granted by King Features Syndicate, Inc., 1979.)

1.2 History of Automatic Control

The use of feedback in order to control a system has had a fascinating history. The first applications of feedback control rest in the development of float regulator mechanisms in Greece in the period 300 to 1 B.C. [1, 2]. The water clock of Ktesibios used a float regulator (refer to Problem 1.11). An oil lamp devised by Philon in approximately 250 B.C. used a float regulator in an oil lamp for maintaining a constant level of fuel oil. Heron of Alexandria, who lived in the first century A.D., published a book entitled *Pneumatica,* which outlined several forms of water-level mechanisms using float regulators [1].

The first feedback system to be invented in modern Europe was the temperature regulator of Cornelis Drebbel (1572–1633) of Holland [1]. Dennis Papin [1647–1712] invented the first pressure regulator for steam boilers in 1681. Papin's pressure regulator was a form of safety regulator similar to a pressure-cooker valve.

The first automatic feedback controller used in an industrial process is generally agreed to be James Watt's *flyball governor* developed in 1769 for controlling the speed of a steam engine [1, 2]. The all-mechanical device, shown in Fig. 1.6, measured the speed of the output shaft and utilized the movement of the flyball with speed to control the valve and therefore the amount of steam entering the engine. As the speed increases, the ball weights rise and move away from the shaft axis thus closing the valve. The flyweights require power from the engine in order to turn and therefore make the speed measurement less accurate.

The first historical feedback system claimed by the Soviet Union is the water-level float regulator said to have been invented by I. Polzunov in 1765 [4]. The level regulator system is shown in Fig. 1.7. The float detects the water level and controls the valve that covers the water inlet in the boiler.

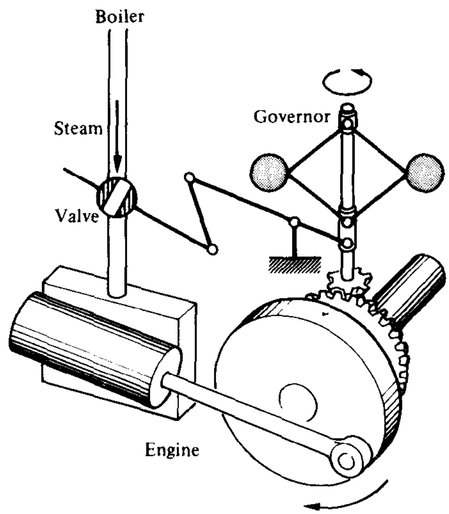

Figure 1.6. Watt flyball governor.

The period preceding 1868 was characterized by the development of automatic control systems by intuitive invention. Efforts to increase the accuracy of the control system led to slower attenuation of the transient oscillations and even to unstable systems. It then became imperative to develop a theory of automatic control. J. C. Maxwell formulated a mathematical theory related to control theory using a differential equation model of a governor [5]. Maxwell's study was concerned with the effect various system parameters had on the system performance. During the same period, I. A. Vyshnegradskii formulated a mathematical theory of regulators [6].

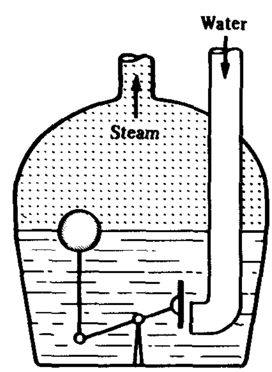

Figure 1.7. Water-level float regulator.