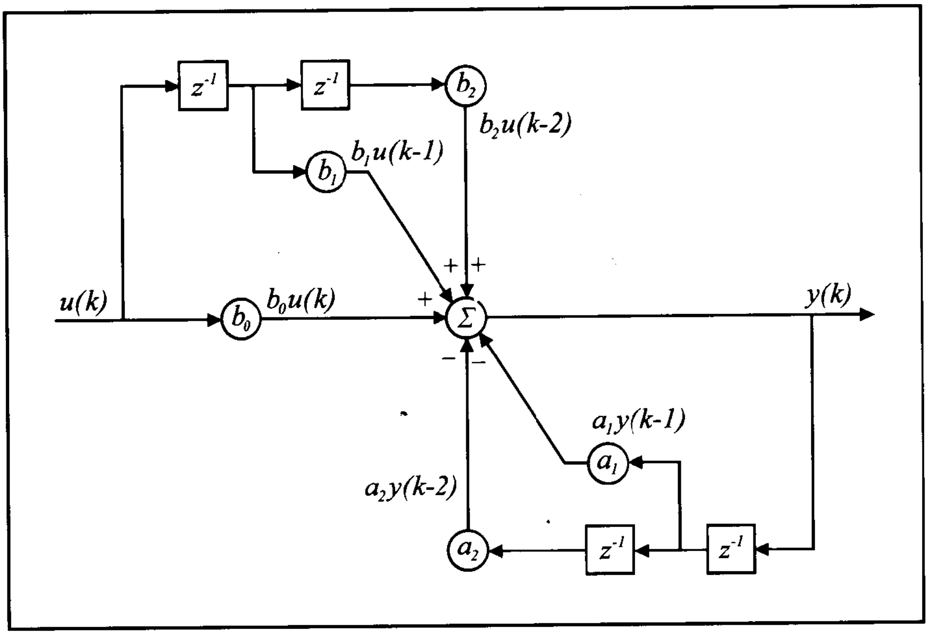
Control Engineering Series

MODERN CONTROL ENGINEERING



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MODERN CONTROL ENGINEERING

CONTROL ENGINEERING

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To my wife, Mary, and our son, Nikos

Series Introduction

Many textbooks have been written on control engineering, describing new techniques for controlling systems, or new and better ways of mathematically formulating existing methods to solve the ever-increasing complex problems faced by practicing engineers. However, few of these books fully address the applications aspects of control engineering. It is the intention of this new series to redress this situation.

The series will stress applications issues, and not just the mathematics of control engineering. It will provide texts that present not only both new and well-established techniques, but also detailed examples of the application of these methods to the solution of real-world problems. The authors will be drawn from both the academic world and the relevant applications sectors.

There are already many exciting examples of the application of control techniques in the established fields of electrical, mechanical (including aerospace), and chemical engineering. We have only to look around in today's highly automated society to see the use of advanced robotics techniques in the manufacturing industries; the use of automated control and navigation systems in air and surface transport systems; the increasing use of intelligent control systems in the many artifacts available to the domestic consumer market; and the reliable supply of water, gas, and electrical power to the domestic consumer and to industry. However, there are currently many challenging problems that could benefit from wider exposure to the applicability of control methodologies, and the systematic systems-oriented basis inherent in the application of control techniques.

This series presents books that draw on expertise from both the academic world and the applications domains, and will be useful not only as academically recommended course texts but also as handbooks for practitioners in many applications domains. *Modern Control Engineering* is another outstanding entry to Dekker's Control Engineering series.

Neil Munro

Preface

Automatic control is one of today's most significant areas of science and technology. This can be attributed to the fact that automation is linked to the development of almost every form of technology. By its very nature, automatic control is a multidisciplinary subject; it constitutes a core course in many engineering departments, such as electrical, electronic, mechanical, chemical, and aeronautical. Automatic control requires both a rather strong mathematical foundation, and implementation skills to work with controllers in practice.

The goal of this book is to present control engineering methods using only the essential mathematical tools and to stress the application procedures and skills by giving insight into physical system behavior and characteristics. Overall, the approach used herein is to help the student understand and assimilate the basic concepts in control system modeling, analysis, and design.

Automatic control has developed rapidly over the last 60 years. An impressive boost to this development was provided by the technologies that grew out of space exploration and World War II. In the last 20 years, automatic control has undergone a significant and rapid development due mainly to digital computers. Indeed, recent developments in digital computers—especially their increasingly low cost—facilitate their use in controlling complex systems and processes.

Automatic control is a vast technological area whose central aim is to develop control strategies that improve performance when they are applied to a system or a process. The results reported thus far on control design techniques are significant from both a theoretical and a practical perspective. From the theoretical perspective, these results are presented in great depth, covering a wide variety of modern control problems, such as optimal and stochastic control, adaptive and robust control, Kalman filtering, and system identification. From the practical point of view, these results have been successfully implemented in numerous practical systems and processes—for example, in controlling temperature, pressure, and fluid level; in electrical energy plants; in industrial plants producing paper, cement, steel, sugar, plastics, clothes, and food; in nuclear and chemical reactors; in ground, sea, and air transportation systems; and in robotics, space applications, farming, biotechnology, and medicine.

I should note that *classical* control techniques—especially those using proportional-integral-derivative (PID) controllers, which have existed since 1942—predominate in the overall practice of control engineering today. Despite the impressive progress since the 1940s, practical applications of *modern* control techniques are limited. This is indeed a serious gap between theory and practice. To reduce this gap, techniques of modern control engineering should be designed with an eye toward applicability, so as to facilitate their use in practice. To this end, modern control techniques must be presented in a simple and user-friendly fashion to engineering students in introductory control courses, so that these techniques may find immediate and widespread application. In turn, control engineering could serve human needs better and provide the same breadth of technological application found in other, related areas, such as communications and computer science. This book has been written in this spirit.

Modern Control Engineering is based on the introductory course on control systems that I teach to junior undergraduate students in the Department of Electrical and Computer Engineering at the National Technical University of Athens. It begins with a description and analysis of linear time-invariant systems. Next, classical (Bode and Nyquist diagrams, the root locus, compensating networks, and PID controllers) and modern (pole placement, state observers, and optimal control) controller design techniques are presented. Subsequent chapters cover more advanced techniques of modern control: digital control, system identification, adaptive control, robust control, and fuzzy control. This text is thus appropriate for undergraduate and first-year graduate courses in modern control engineering, and it should also prove useful for practicing engineers. The book has 16 chapters, which may be grouped into two parts: Classical Control (Chapters 1 through 9) and Modern Control (Chapters 10 through 16). (Please note that, throughout the book, bold lowercase letters indicate vectors and bold capital letters indicate matrices.)

CLASSICAL CONTROL

Chapter 1 is an introduction to automatic control systems. Chapter 2 presents the Laplace transform and matrix theory, which is a necessary mathematical background for studying continuous-time systems. Chapter 3 describes and analyzes linear time-invariant systems by using the following mathematical models: differential equations, transfer functions, impulse response, and state-space equations; the topics of block diagrams and signal-flow graphs are also covered.

Chapter 4 describes classical time-domain analysis, covering topics such as time response, model simplification, comparison of open- and closed-loop systems, model reduction, sensitivity analysis, steady-state errors, and disturbance rejection. Chapter 5 describes state-space analysis of linear systems and discusses the important concepts of controllability and observability, along with their relation to the transfer function. Chapter 6 discusses the important problem of stability. It covers the algebraic criteria of Ruth, Hurwitz, and continuous fraction, and provides an introduction to the stability of nonlinear and linear systems using the Lyapunov methods.

Chapter 7 covers the popular root locus method. Chapter 8 describes the frequency response of lincar time-invariant systems, introducing the three well-known frequency domain methods: those of Nyquist, Bode, and Nichols. Chapter 9 is devoted to the classical design techniques, emphasizing controller design methods using controllers of the following types: PID, phase-lead, phase-lag, and phase lead-lag. The chapter also presents an introduction to classical optimal control.

MODERN CONTROL

Chapters 10 and 11 focus on modern controller design techniques carried out in state-space. Chapter 10 covers the design problems of pole assignment, input-output decoupling, model matching, and state observers. Closed-loop system design using state observers is also explained. Chapter 11 elucidates the problem of optimal control, as illustrated in the optimal regulator and servomechanism problems.

Chapter 12 is an introduction to digital control that provides extensive coverage of basic problems in discrete-time system description, analysis, stability, controllability, observability, and classical control techniques. Chapter 13 explains discrete-time system identification and gives the basic algorithms for off-line and on-line parametric identification.

Chapter 14 covers discrete-time system adaptive control. The following four adaptive schemes are presented: the gradient method (MIT rule), model reference, adaptive control, and self-tuning regulators. Chapter 15 is an introduction to robust control, focusing on topics such as model uncertainty, robust stability, robust performance, and Kharitonov s theorem. Chapter 16 is an introduction to fuzzy control, emphasizing the design of fuzzy controllers.

The book concludes with three appendixes that provide useful background information. Appendix A presents the Laplace transform tables, Appendix B demonstrates the Z-transform technique necessary for analyzing and designing the discrete-time (or digital) control systems presented in Chapter 12, and Appendix C gives the Z-transform tables.

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P. N. Paraskevopoulos

Contents

1

Introduction to Automatic Control Systems

1.1 INTRODUCTION

An automatic control system is a combination of components that act together in such a way that the overall system behaves automatically in a prespecified desired manner.

A close examination of the various machines and apparatus that are manufactured today leads to the conclusion that they are partially or entirely automated, e.g., the refrigerator, the water heater, the clothes washing machine, the elevator, the TV remote control, the worldwide telephone communication systems, and the Internet. Industries are also partially or entirely automated, e.g., the food, paper, cement, and car industries. Examples from other areas of control applications abound: electrical power plants, reactors (nuclear and chemical), transportation systems (cars, airplanes, ships, helicopters, submarines, etc.), robots (for assembly, welding, etc.), weapon systems (fire control systems, missiles, etc.), computers (printers, disk drives, magnetic tapes, etc.), farming (greenhouses, irrigation, etc.), and many others, such as control of position or velocity, temperature, voltage, pressure, fluid level, traffic, and office automation, computer-integrated manufacturing, and energy management for buildings. All these examples lead to the conclusion that automatic control is used in all facets of human technical activities and contributes to the advancement of modern technology.

The distinct characteristic of automatic control is that it reduces, as much as possible, the human participation in all the aforementioned technical activities. This usually results in decreasing labor cost, which in turn allows the production of more goods and the construction of more works. Furthermore, automatic control reduces work hazards, while it contributes in reducing working hours, thus offering to working people a better quality of life (more free time to rest, develop hobbies, have fun, etc.).

Automatic control is a subject which is met not only in technology but also in other areas such as biology, medicine, economics, management, and social sciences. In particular, with regard to biology, one can claim that plants and animals owe their very existence to control. To understand this point, consider for example the human body, where a tremendous number of processes take place automatically: hunger, thirst, digestion, respiration, body temperature, blood circulation, reproduction of cells, healing of wounds, etc. Also, think of the fact that we don't even decide when to drink, when to eat, when to go to sleep, and when to go to the toilet. Clearly, no form of life could exist if it were not for the numerous control systems that govern all processes in every living organism.

It is important to mention that modern technology has, in certain cases, succeeded in replacing body organs or mechanisms, as for example in replacing a human hand, cut off at the wrist, with an artificial hand that can move its fingers automatically, as if it were a natural hand. Although the use of this artificial hand is usually limited to simple tasks, such as opening a door, lifting an object, and eating, all these functions are a great relief to people who were unfortunate enough to lose a hand.

1.2 A BRIEF HISTORICAL REVIEW OF AUTOMATIC CONTROL SYSTEMS

Control systems have been in existence since ancient times. A well-known ancient automatic control system is the regulator of Heron of Alexandria (Figure 1.1). This control system was designed to open the doors of a temple automatically when a fire was lit at the altar located outside the temple and to close the doors when the fire was put out. In particular, the regulator operated in the following way: the fire, acting as the input to the system, heated the air underneath the altar and the warm (expanded)

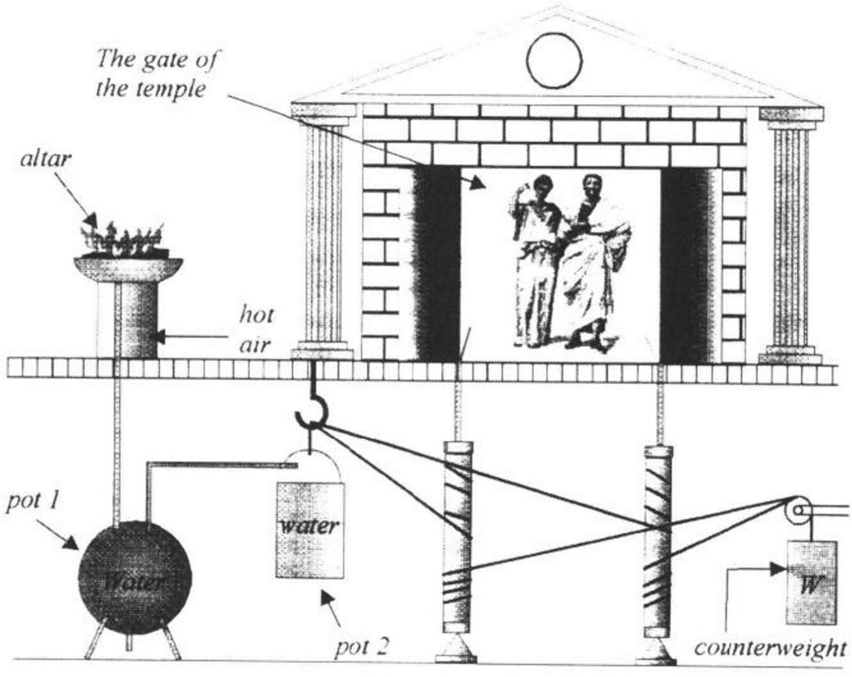

Figure 1.1 The regulator of Heron of Alexandria.

air pushed the water from the water container (pot 1) to the bucket (pot 2). The position of the water container was fixed, while the bucket was hanging from ropes wrapped around a mechanism (the door spindles) with a counterweight W. When pot 2 was empty, this mechanism, under the pull of the counterweight W, held the doors closed. When pot 2 was filled with adequate amount of water from pot 1, it moved downwards, while the counterweight W moved upwards. As a result of the downward motion of pot 2, the door spindles turned and the doors opened. When the fire was put out, water from pot 2 returned to pot 1, and the counterweight W moved downwards forcing the gates to close. Apparently, this control system was used to impress believers, since it was not visible or known to the masses (it was hidden underground).

Until about the middle of the 18th century, automatic control has no particular progress to show. The use of control started to advance in the second half of the 18th century, due to James Watt, who, in 1769, invented the first centrifugal speed regulator (Figure 1.2) which subsequently has been widely used in practice, most often for the control of locomotives. In particular, this regulator was used to control the speed of the steam engine. This is accomplished as follows: as the angular velocity of the steam engine increases, the centrifugal force pushes the masses m upwards and the steam valve closes. As the steam valve closes, the steam entering the engine from the boiler is reduced and the steam engine's angular velocity decreases, and vice versa: as the angular velocity of the steam engine decreases, the masses m go down, the steam valve opens, the amount of steam entering the engine increases, resulting in an increase of the angular velocity. This way, one can regulate the speed of the engine.

The period until about the middle of the 19th century is characterized by developments based on intuition, i.e., there was no mathematical background for control design. Maxwell in 1868 [82, 83] and Vyshnegradskii in 1877 [52] set the first

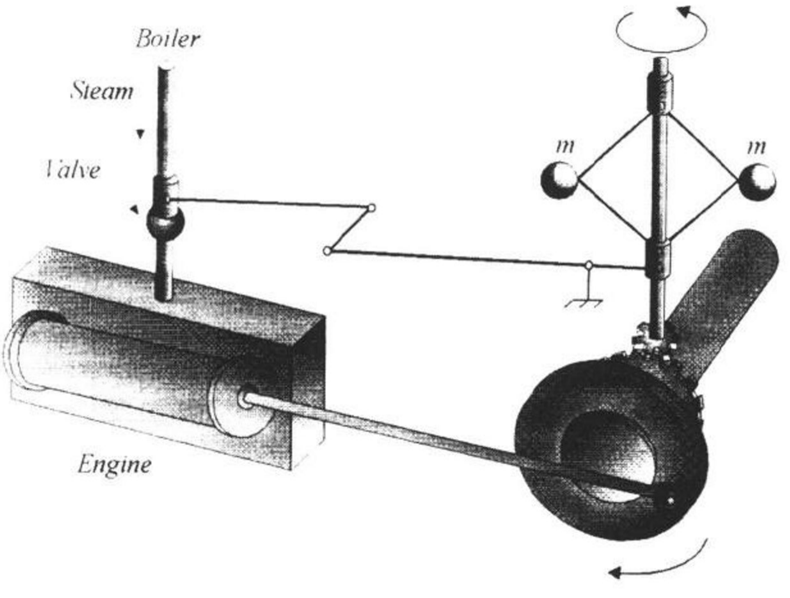

Figure 1.2 Watt's centrifugal speed regulator.

mathematical background for control design for applying their theoretical (mathematical) results on Watt's centrifugal regulator. Routh's mathematical results on stability presented in 1877 [47] were also quite important.

Automatic control theory and its applications have developed rapidly in the last 60 years or so. The period 1930–1940 was important in the history of control, since remarkable theoretical and practical results, such as those of Nyquist [84, 85] and Black [60, 61], were reported.

During the following years and until about 1960, further significant research and development was reported, due mainly to Ziegler and Nichols [92], Bode [11], Wiener [53] and Evans [18, 64]. All the results of the last century, and up to about 1960, constitute what has been termed *classical control*. Progress from 1960 to date has been especially impressive, from both the theoretical and the practical point of view. This last period has been characterized as that of *modern control*, the most significant results of which have been due to Astrom [3–5], Athans [6, 57–59], Bellman [7, 8], Brockett [12, 62], Doyle [63, 66], Francis [63, 66], Jury [24, 25], Kailath [26, 67], Kalman [27, 28, 68–79], Luenberger [33, 80, 81], MacFarlane [34], Rosenbrock [45, 46], Saridis [48], Wonham [54, 89, 90], Wolovich [55], Zames [91], and many others. For more on the historical development of control the reader can refer to [35] and [41].

A significant boost to the development of classical control methods was given by the Second World War, whereas for modern control techniques the launch of Sputnik in 1957 by the former Soviet Union and the American Apollo project, which put men on the moon in 1969, were prime movers. In recent years, an impressive development in control systems has taken place with the ready availability of digital computers. Their power and flexibility have made it possible to control complex systems efficiently, using techniques which were hitherto unknown.

The main differences between the classical and the modern control approaches are the following: classical control refers mainly to single input–single output systems. The design methods are usually graphical (e.g., root locus, Bode and Nyquist diagrams, etc.) and hence they do not require advanced mathematics. Modern control refers to complex multi-input multi-output systems. The design methods are usually analytical and require advanced mathematics. In today's technological control applications, both classical and modern design methods are used. Since classical control is relatively easier to apply than modern control, a control engineer may adopt the following general approach: simple cases, where the design specifications are not very demanding, he uses classical control techniques, while in cases where the design specifications are very demanding, he uses modern control techniques.

Today, automatic control systems is a very important area of scientific research and technological development. Worldwide, a large number of researchers aim to develop new control techniques and apply them to as many fields of human activity as possible. In Sec. 1.4, as in other parts of this book, we present many practical control examples that reflect the development of modern control engineering.

1.3 THE BASIC STRUCTURE OF A CONTROL SYSTEM

A system is a combination of components (appropriately connected to each other) that act together in order to perform a certain task. For a system to perform a certain task, it must be excited by a proper input signal. Figure 1.3 gives a simple

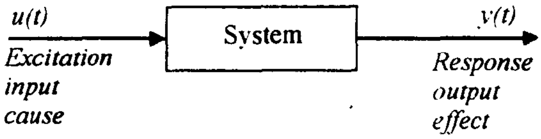

Figure 1.3 Schematic diagram of a system with its input and output.

view of this concept, along with the scientific terms and symbols. Note that the response $y(t)$ is also called system's behavior or performance.

Symbolically, the output $y(t)$ is related to the input u(t) by the following equation

$$y(t) = Tu(t) \tag{1.3-1}$$

where T is an operator. There are three elements involved in Eq. (1.3-1): the input $u(t)$, the system T, and the output $y(t)$. In most engineering problems, we usually know (i.e., we are given) two of these three elements and we are asked to find the third one. As a result, the following three basic engineering problems arise:

1. *The analysis problem.* Here, we are given the input $u(t)$ and the system T and we are asked to *determine* the output $y(t)$.
2. *The synthesis problem.* Here, we are given the input $u(t)$ and the output $y(t)$ and we are asked to *design* the system T.
3. *The measurement problem.* Here, we are given the system T and the output $y(t)$ and we are asked to *measure* the input $u(t)$.

The control design problem does not belong to any of these three problems and is defined as follows.

Definition 1.3.1

Given the system T under control and its *desired response* $y(t)$, find an appropriate input signal $u(t)$, such that, when this signal is applied to system T, the output of the system to be the desired response $y(t)$. Here, this appropriate input signal $u(t)$ is called *control signal.*

From Definition 1.3.1 it appears that the control design problem is a signal synthesis problem: namely, the synthesis of the control signal $u(t)$. However, as it will be shown later in this section, in practice, the control design problem is reduced to that of designing a controller (see Definition 1.3.4).

Control systems can be divided into two categories: the *open-loop* and the *closed-loop* systems.

Definition 1.3.2

An open-loop system (Figure 1.4a) is a system whose input $u(t)$ does not depend on the output $y(t)$, i.e., $u(t)$ is not a function of $y(t)$.

Definition 1.3.3

A closed-loop system (Figure 1.4b) is a system whose input $u(t)$ depends on the output $y(t)$, i.e., $u(t)$ is a function of $y(t)$.

In control systems, the control signal $u(t)$ is not the output of a signal generator, but the output of another new additional component that we add to the