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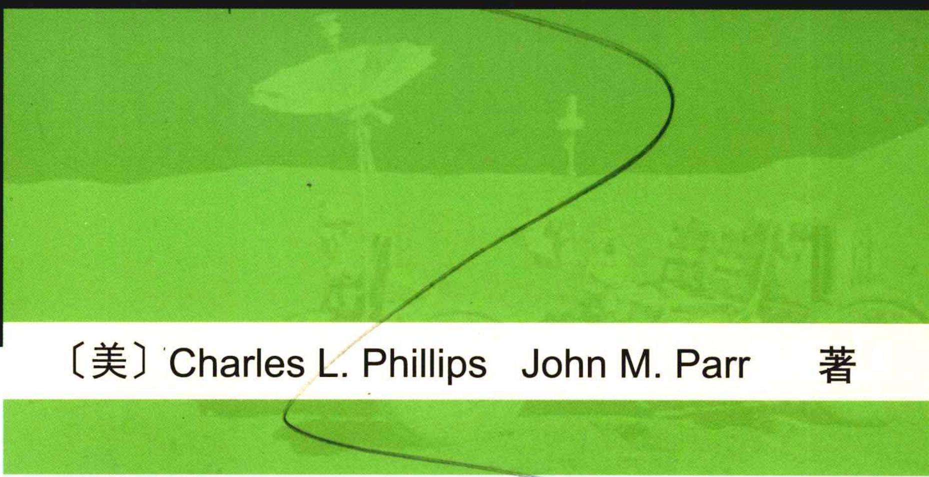
反馈控制系统

（第5版）

Feedback Control Systems (Fifth Edition)

（英文版）



〔美〕Charles L. Phillips　John M. Parr　著

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内 容 简 介

本书涵盖了自动化、电气工程及其自动化、机械工程及其自动化等本科专业中自动控制原理课程经典和现代部分的核心内容。主要包括反馈控制的基本概念、根据物理定律等建立控制对象模型、控制对象模型的状态空间表示、单输入单输出控制系统的响应特性和主要性能指标、非线性系统分析的描述函数法和相平面法等。本书作者具有十分丰富的教学经验，已出版过多本系统分析与设计方面的优秀教材。

本书可作为高等院校自动化、电气工程等相关专业的本科生教材，也可作为相关领域工程技术人员的参考书。

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Preface

The structure and philosophy of the previous editions of *Feedback Control Systems* remains unchanged in the fifth edition. However, the focus has been sharpened as a result of the experience using the first four editions and the reactions of colleagues who have taught from the book. Some explanations have been enhanced. Where appropriate, a number of examples have been improved. The majority of the end-of-chapter problems have been either altered or replaced.

The simulation program SIMULINK®, a block-diagram program to be used with MATLAB®, is introduced to illustrate the simulation of both continuous (analog) and discrete systems, and of nonlinear continuous systems. New capabilities of MATLAB have been added and many examples contain short MATLAB programs. In this fifth edition, the MATLAB programs given in the examples may be downloaded from the Companion Website http://www.pearsonhighered.com/phillips

This book is intended to be used primarily as a text for junior- and senior-level students in engineering curricula and for self-study by practicing engineers with little or no experience in control systems. For maximum benefits, the reader should have had some experience in linear system analysis.

The material of this book is organized into three principal areas: analog control systems, digital control systems, and nonlinear analog control systems. Chapter 1 presents a brief introduction and an outline of the text. In addition, some control systems are described to introduce the reader to typical applications. Next, a short history of feedback control systems is given. The mathematical models of some common components that appear in control systems are developed in Chapter 2.

Chapters 3 through 10 cover the analysis and design of linear analog systems; that is, control systems that contain no sampling. Chapter 2 develops the transfer-function model of linear analog systems, and Chapter 3 develops the state-variable model.

Chapter 4 covers typical responses of linear analog systems, including the concept of frequency response. Since many of the characteristics of closed-loop systems cannot be adequately explained without reference to frequency response, this concept is developed early in the book. The authors believe that the frequency-response concept ranks in importance with the time-response concept.

Important control-system characteristics are developed in Chapter 5. Some of the applications of closed-loop systems are evident from these characteristics. The concept of system stability is developed in Chapter 6 along with the Routh-Hurwitz stability criterion. Chapter 7 presents analysis and design by root-locus procedures, which are basically time-response procedures. The equally important frequency-response analysis and design procedures are presented in Chapters 8 and 9. Chapter 10 is devoted to modern control-system design. Pole-placement design is developed, and the design of state estimators is introduced.

Chapters 3 through 10 applies directly to analog control systems and Chapters 11 through 14 applies to digital control systems. Essentially all the analog analysis and design techniques of Chapters 3 through 9 are developed again for digital control systems. These topics include typical responses, characteristics, stability, root-locus analysis and design, and frequency-response analysis and design.

Nonlinear system analysis is presented in Chapter 15. These methods include the describing-function analysis, linearization, and the state-plane analysis.

Usually, nonlinear controls are not covered in introductory books in control. However, many of the important characteristics of physical systems cannot be explained on the basis of linear systems. For example, stability as a function of signal amplitude is one of the most common phenomena observed in closed-loop physical systems, and the describing function is included in Chapter 15 to offer an analysis procedure that explains this phenomenon. Lyapunov's first stability theorem is also presented to illustrate some of the pitfalls of linear system-stability analysis.

Many examples are given, with an effort to limit each example to illustrating only one concept. It is realized that in using this approach, many obvious and interesting characteristics of the systems of the examples are not mentioned; however, since this is a book for beginning students in feedback control, making the examples more complex would tend to add confusion.

In general, each chapter is organized such that the more advanced material is placed toward the end of the chapter. This placement is to allow the omission of this material by those instructors who wish to present a less intense course.

This book may be covered in its entirety as a three-hour one-semester course in analog control (Chapters 1 through 9), and a three-hour one-semester course in digital control and nonlinear control with an introduction to modern control (Chapters 10 through 15). The material may also be covered in two-quarter course sequence, with approximately five hours for each course. With the omission of appropriate material, the remaining material may be covered in courses with fewer credits. If a course in digital control is taught without the coverage of the first nine chapters, some of the material of the first nine chapters must be introduced; Chapters 11 through 13 rely on some of this material. An asterisk sign is used to mark the problems with answers given in Appendix E. A manual containing the solutions to all problems at the end of the chapters is available for teachers who have adopted the text for use in the classroom.

NEW TO THIS EDITION

The following improvements have been made to the fifth edition:

- More than 70 percent of the end-of-chapter problems are new or revised
- Additional examples
- Additional explanation of some concepts and procedures
- More extensive use of MATLAB in examples and problem sets
- Companion Website contains M-files
- A new Appendix that introduces control-system applications of MATLAB.
- A new Appendix with answers for selected end-of-chapter problems.
- The end-of-chapter problems are grouped into sets so that each set corresponds to a section of the chapter. In each set, at least one problem has its answer provided in Appendix E. Other problems in the set are based on the same concepts as the one with its answer given. This can provide immediate feedback to students in cases where the problems do not provide a second method of verification.
- A new chapter 14 on discrete-time pole assignment and state estimation has been added.

ACKNOWLEDGMENTS

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Thanks to Royce D. Harbor for his significant contributions to the first edition.

Finally, we express our gratitude and love for our families, without whom this undertaking would not have been possible.

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Contents

CHAPTER 1
Introduction

This book is concerned with the analysis and design of closed-loop control systems. In the *analysis* of closed-loop systems, we are given the system, and we wish to determine its characteristics or behavior. In the *design* of closed-loop systems, we specify the desired system characteristics or behavior, and we must configure or synthesize the closed-loop system so that it exhibits these desired qualities.

We define a closed-loop system as one in which certain of the system forcing signals (we call these *inputs*) are determined, at least in part, by certain of the responses of the system (we call these *outputs*). Hence, the system inputs are a function of the system outputs, and the system outputs are a function of the system inputs. A diagram representing the functional relationships in a closed-loop system is given in Figure 1.1.

An example of a closed-loop system is the temperature-control system in the home. For this system we wish to maintain, automatically, the temperature of the living space in the home at a desired value. To control any physical variable, which we usually call a *signal,* we must know the value of this variable; that is, we must measure this variable. We call the system for the measurement of a variable a *sensor,* as indicated in Figure 1.2. In a home temperature-control system, the sensor is a thermostat, which indicates a low temperature by closing an electrical switch and an acceptable temperature by opening the same switch. We define the *plant* of a control system as that part of the system to be controlled. It is assumed in this example that the temperature is increased by activating a gas furnace. Hence the plant input is the electrical signal that activates the furnace, and the plant output signal is the actual temperature of the living area. The plant is represented as shown in Figure 1.2. In the home-heating system, the output of each of the systems is connected to the input of the other to form the closed loop. However, in most closed-loop control systems, it is necessary to connect a third system into the loop to obtain satisfactory characteristics for the total system. This additional system is called a *compensator*, a *controller*, or simply a *filter.*

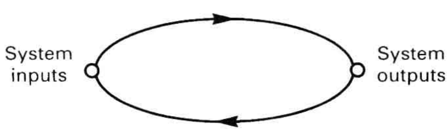


FIGURE 1.1
Closed-loop system.

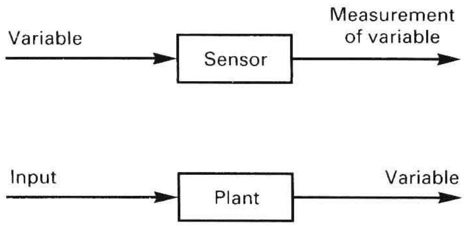


FIGURE 1.2
Control-system components.

The usual form of a single-loop closed-loop control system is given in Figure 1.3. The system input is a reference signal; usually we want the system output to be equal to this input. In the home temperature-control system, this input is the setting of the thermostat. If we want to change the temperature, we change the system input. The system output is measured by the sensor, and this measured value is compared with (subtracted from) the input. This difference signal is called the *error signal,* or simply the error. If the output is equal to the input, this error signal is zero, and the plant output remains at its current value. If the error is not zero, in a properly designed system the error signal causes a response in the plant such that the magnitude of the error is reduced. The compensator is a filter for the error signal, since usually satisfactory operation does not occur if the error signal is applied directly to the plant.

Control systems are sometimes divided into two classes. If the object of the control system is to maintain a physical variable at some constant value in the presence of disturbances, we call this system a *regulator.* One example of a regulator control system is the speed-control system on the ac power generators of power utility companies. The purpose of this control system is to maintain the speed of the generators at the constant value that results in the generated voltage having a frequency of 60 Hz in the presence of varying electrical power loads. Another example of a regulator control system is the biological system that maintains the temperature of the human body at approximately 98.6°F in an environment that usually has a different temperature.

The second class of control systems is the *servomechanism.* Although this term was originally applied to a system that controlled a mechanical position or motion, it is now often used to describe a control system in which a physical variable is required to follow, or track, some desired time function. An example of this type of system is an automatic aircraft landing system, in which the aircraft follows a ramp to the desired touchdown point. A second example is the control systems of a robot, in which the robot hand is made to follow some desired path in space.

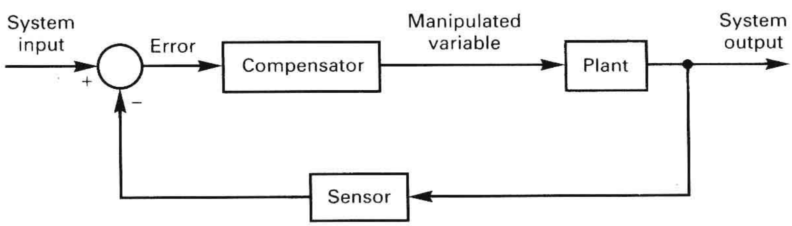


FIGURE 1.3
Closed-loop control system.

The preceding is a very simplified discussion of a closed-loop control system. The remainder of this book improves upon this description. In order to perform either mathematical analysis or design, it is necessary that we have a mathematical relationship between the input and the output for each of the blocks in the control system of Figure 1.3. The purpose of Chapter 2 is to develop these functional relationships for some common physical systems. Chapter 3 presents a different method of expressing these functional relationships.

We examine typical responses that occur in control systems in Chapter 4 and look at control-system specifications in Chapter 5. Chapter 6 presents concepts and some analysis techniques for system stability. The root locus, one of the principal methods of analysis and design, is developed in Chapter 7. Chapters 8 and 9 present a second principal analysis and design method, the frequency response. Chapter 10 presents an introduction to a different method of design of control systems, which is classified as a modern control procedure.

In Chapters 2 through 9, it is assumed that no system signals appear in sampled form and in particular that no digital computers are used in the control of the system. The systems considered in these chapters are called *analog* systems, *continuous-data* systems, or *continuous-time* systems. Chapters 11 through 13 consider systems in which sampling does occur, and these systems are called *sampled-data* systems. If a digital computer is used in the control of these systems, the systems are then called *digital* control systems. The terms *discrete-time* systems or simply *discrete* systems are also used to refer to sampled-data systems and digital control systems.

In Chapters 2 through 13, all systems are assumed to be linear (linearity is defined in Chapter 2). However, physical systems are not linear, and in general, nonlinear systems are difficult to analyze or design. Throughout this book, we discuss the problems of the inaccurate representations in the functional relationships that we use to model physical systems. However, for some physical systems, the linear model is not sufficiently accurate, and nonlinearities must be added to the system model to improve the accuracy of these functional relationships. We consider some common nonlinearities and some properties and analysis methods for nonlinear systems in Chapter 15.

In the analysis of linear systems, we use the Laplace transform for analog systems and the z-transform for discrete systems. Appendix B presents the concepts and procedures of the Laplace transform, and the z-transform is covered in Chapter 11. Next, the control problem is presented, and then some control systems are discussed.

1.1 THE CONTROL PROBLEM

We may state the control problem as follows. A physical system or process is to be accurately controlled through closed-loop, or feedback, operation. An output variable, called the response, is adjusted as required by the error signal. This error signal is the difference between the system response, as measured by a sensor, and the reference signal, which represents the desired system response.

Generally, a controller, or compensator, is required to filter the error signal in order that certain control criteria, or specifications, be satisfied. These criteria may involve, but not be limited to:

1. Disturbance rejection
2. Steady-state errors

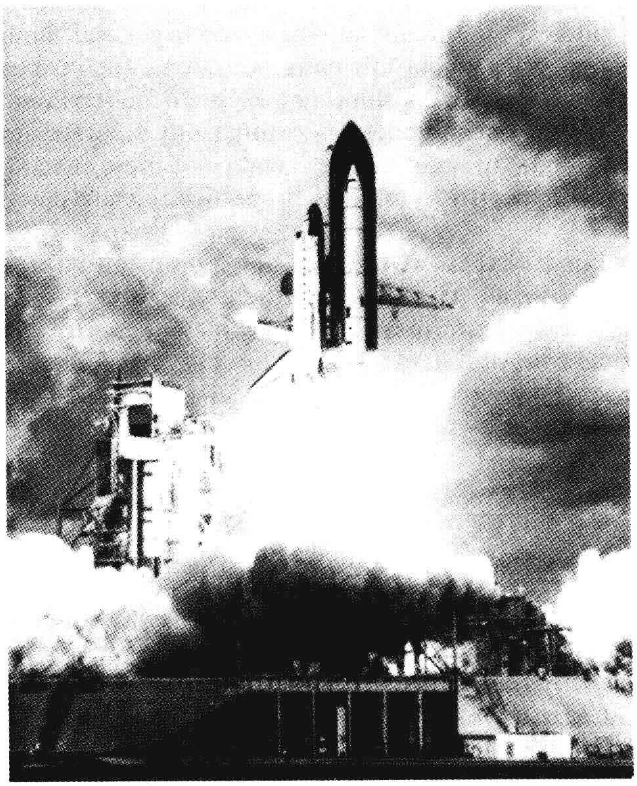
3. Transient response characteristics
4. Sensitivity to parameter changes in the plant

Solving in control problem generally involves

1. Choosing sensors to measure the plant output
2. Choosing actuators to drive the plant
3. Developing the plant, actuator, and sensor equations (models)
4. Designing the controller based on the models developed and the control criteria
5. Evaluating the design analytically, by simulation, and finally, by testing the physical system
6. If the physical tests are unsatisfactory, iterating these steps

Because of inaccuracies in the models, the first tests on the physical control system are usually not satisfactory. The controls engineer must then iterate this design procedure, using all tools available, to improve the system. Generally, intuition, developed while experimenting with the physical system, plays an important part in the design process.

The relationship of mathematical analysis and design to physical-system design procedures is depicted in Figure 1.4 [1]. In this book, all phases shown in the figure are discussed, but



NASA space shuttle launch. (Courtesy of NASA.)

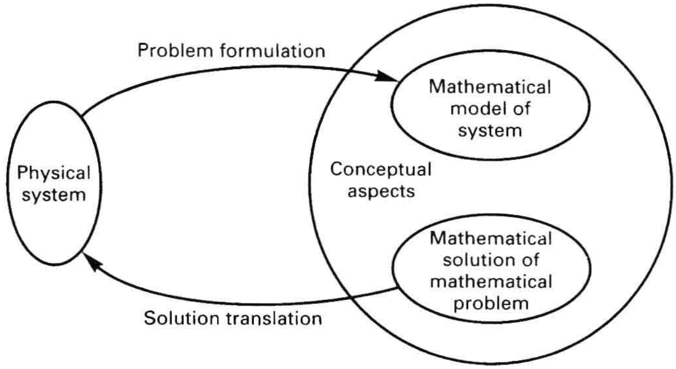


FIGURE 1.4
Mathematical solution of physical problems.

the emphasis is necessarily on the conceptual part of the procedures—that is, the application of mathematical concepts to mathematical models. In practical design situations, however, the major difficulties are in formulating the problem mathematically and in translating the mathematical solution back to the physical world. As stated earlier, many iterations of the procedures shown in Figure 1.4 are usually required in practical situations.

Depending on the system and the experience of the designer, some of the steps listed earlier may be omitted. In particular, many control systems are implemented by choosing standard forms of controllers and experimentally determining the parameters of the controller by following a specified step-by-step procedure with the physical system; no mathematical models are developed. This type of procedure works very well for certain control systems. For other systems, however, it does not. For example, a control system for a space vehicle obviously cannot be designed in this manner; the control system must respond in a satisfactory manner the first time that it is activated.

In this book, mathematical procedures are developed for the analysis and design of control systems. The actual techniques may or may not be of value in the design of a particular control system. However, standard controllers are utilized in the developments in this book. Thus, the analytical procedures develop the concepts of control-system design and indicate the application of each of the standard controllers.

1.2 EXAMPLES OF CONTROL SYSTEMS

In this section, some physical control systems are described to acquaint the reader with these types of systems. In addition, the various physical components that make up control systems will become more evident.

1.2.1 Aircraft Landing Systems

The first example of a closed-loop control system is the case of a pilot landing an aircraft. The pilot has three basic tasks. First, the aircraft must approach the airfield along the extended centerline of the runway. This approach is depicted in Figure 1.5. Also shown in this figure is the

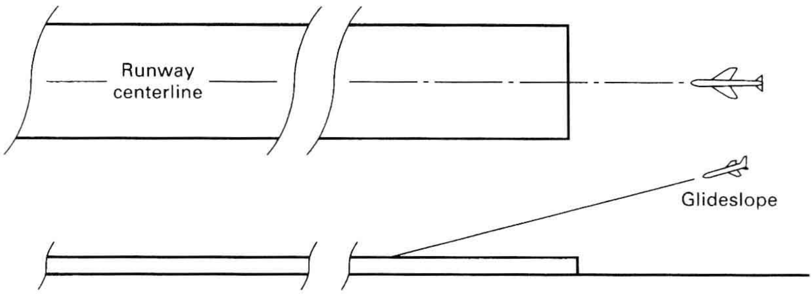


FIGURE 1.5
Landing an aircraft.

second task of maintaining the aircraft on the correct glideslope. The third task is that of maintaining the correct speed.

We will consider only the problem of keeping the aircraft on the extended centerline of the runway (controlling the aircraft's lateral position). A block diagram of the system, of the type of Figure 1.3, is given in Figure 1.6. It is assumed that the lateral position of the aircraft is controlled by the ailerons, the control surfaces near the tip of each wing. Actually, the rudder is also used to control the lateral position, but for simplicity we will consider only the ailerons. The ailerons, along with the mechanisms for varying their angle, form the actuator of the control system.

For this control system, a number of sensors are used by the pilot to determine the lateral position of the aircraft. The pilot has certain instrument readings available in the cockpit. In addition, usually the pilot can see the runway, which indicates the position of the aircraft relative to the runway. Hence, the pilot has indications of the lateral position of the aircraft and also knows the desired lateral position. He/she manipulates the ailerons in an effort to bring the aircraft to the desired lateral position. For a control system, we usually call the difference between the desired position and the actual position the *system error.*

The remaining block in Figure 1.6 is the compensator. For this system the compensation function is performed by the pilot, who also performs part of the sensing function and the manipulation of the control surfaces. Given the position and the attitude of the aircraft,

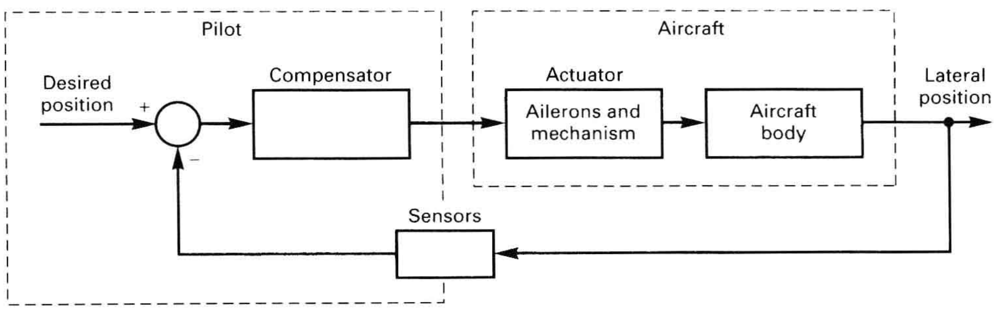


FIGURE 1.6
Aircraft landing system.