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# Linear Control Systems Engineering

# 线性控制系统工程

Morris Driels

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## 本书特色

由Morris Driels编著的"Linear Control Systems Engineering"一书出版于1995年。本书的定位是要为机械工程、电机工程、电子工程、计算机工程等非控制工程专业的本科生提供一本内容适度、实用性强和学时较少的控制理论教材。内容覆盖了经典控制理论和现代控制理论的基础部分，方法包括了频率响应法、根轨迹法和状态空间法。本书已被美国多所知名大学采用作为电子工程等专业的本科层次的控制理论教材或主要教学参考书。

本书的主要特点是，从非控制工程专业本科生对控制理论的需求和教学学时相对要少的实情出发，在体系结构和内容安排上作了富有新意的改革。例如，破除章节式结构、设立专题；破除按一个结论结论引入例子的惯例，增加来自不同专业工程的研究案例。

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# Preface

Although I have been teaching linear control systems engineering to mechanical engineering undergraduate students for the last twenty years or so, I was never motivated to write a book on the subject until I had the opportunity to teach controls together with a first course in dynamics in the same academic quarter. This enabled me to directly compare the structure, style, and student use of the required texts in each subject. Such a comparison proved quite enlightening.

Both books had been around for more than a decade and had been through several editions. The controls book was, at the time, the best seller, as was the dynamics book. Their styles, however, were very different. The dynamics book was written in the following format:

- The subject matter was grouped into discrete amounts of material that could be comfortably covered in one lecture.
- Following this, two or three worked problems showed the student how this material is used to solve engineering problems.
- Finally, several homework problems were provided to enable the student to test his or her knowledge of the material.

The controls book was written in a more traditional style comprising chapters of around fifty pages followed by twenty or so problems.

In teaching both courses, it was apparent that the students made more use of the dynamics book; they were not overwhelmed by the amount of material covered in a class, and the abundance of solved and homework problems ensured a self-assessment of their understanding of the material and gave students a better perspective of the structure of the subject. From a professor's point of view, having the material already divided up into lecture-size pieces made the job of planning the course program much easier.

In this book, I have attempted to use the same philosophy as the dynamics books I have just described. I hope that the modular nature of the material will enable the book to be closely allied to the course of lectures, although there is still sufficient flexibility to allow the instructor the option of including additional topics or skipping over material he or she thinks the student already knows. Based on the student reviews of controls courses I have taught, the consensus on problem solving seems to be (a) there can never be too many solved problems and

(b) more detailed solutions to solved problems are welcome. I have attempted to address both these issues in this book. In particular, detailed solved problems are included at the end of each module so that the student may see the applicability of the material just covered. In order to provide students with an understanding of how control system analysis provides a basic tool in the design of complex engineering systems, I have also added several design case studies after Module 25. In many cases, these examples show alternative methods to achieve the required performance, and provide the student with a perspective of how the various analytical topics presented in the book may be used, combined, and applied to real engineering systems.

Originally, this book was intended primarily for undergraduate mechanical engineering students, although other engineering disciplines should find the material not too far from their own area. In most of these areas, a traditional systems stream would comprise:

- An introductory systems modeling course—sophomore level
- A linear controls systems course—junior level
- An advanced controls course—senior level

This book is aimed at the junior-level course and assumes the student is already familiar with systems modeling. Some material in this area is included in this book, but only to provide a smooth transition into controls rather than to teach techniques for modeling physical systems.

With regard to the issue of provision of software for the book, the objective has been to emphasize the fundamentals of control and not to become focused on computational techniques or tools. The student is encouraged to use whatever software is available to him or her, and where appropriate, examples have been given using FORTRAN, BASIC code, as well as proprietary packages such as MATLAB. For some of the problems in the text, involving laborious, though not difficult, manipulations, commercial packages such as MATLAB or MATRIX$_X$ are highly recommended.

Finally, I must thank a great number of people who have helped me write this book. The staff at McGraw-Hill have made the production process as near enjoyable as any author could reasonably expect. My students and colleagues at Edinburgh University, University of Rhode Island, Texas A&M, and the Naval Postgraduate School all deserve mention for their enthusiasm in reviewing material, discussing problems, and generally supporting my efforts over a considerable number of years. Special mention is due to Alan Linnett, Fotis Papoulias, and Tony Healey. The following reviewers provided many helpful comments and suggestions: Larry Banta, West Virginia University; Neyram Hemati, Drexel University; David Hullendar, University of Texas at Arlington; Leo LaFrance, New Mexico State University; Ronald A. Perez, University of Wisconsin, Milwaukee; and Gary Young, Oklahoma State University. All errors in the text are mine. Finally, the most thanks are due to my wife, Jenny, and children, Joanne, Chris, and Fiona. They supplied endless encouragement, help, motivation, and the ability to view all of life's pleasures and disappointments in the correct perspective.

Morris Driels

# Contents

*CONTROL SYSTEM DESIGN: CASE STUDIES*

MODULE 1

# Introduction to Feedback Control

Feedback control systems are at work all around us. The study of control systems involves not so much the development of new engineering components or machines, but taking combinations of existing hardware to achieve a predetermined goal. A control *system* is the collection of components connected in such a way as to effect *control* over certain aspects of the domain in which the system operates. Control systems operate in almost every aspect of human activity, including walking, talking, and handling objects. In addition, control systems exist that require no human interaction, such as aircraft automatic pilots and automobile cruise control systems.

In dealing with control systems, particularly engineering control systems, we will deal with a variety of components, indicating that the subject is an interdisciplinary one. The control engineer needs a working knowledge of mechanics, electronics, electrical machines, fluid mechanics, thermodynamics, structures, material properties, and so on. Obviously not every control system contains elements from each of the above domains, but most useful control systems contain elements from more than one discipline.

Control system *analysis* involves the uniform treatment of different engineering components. What this means is that we try to represent the system elements in a common format and identify the connections between the elements in a similar way. When we do this, most control systems look the same in schematic form and lend themselves to common methods of analysis. This process usually involves a technique known as *block diagram representation,* discussed in Module 2, where each component is reduced to its basic function with one input variable and one output variable, the relationship between them known as a *transfer function.*

At this stage it is best to focus the discussion so far into a simple example. Suppose we attempt to analyze the mechanism at work when we adjust the water

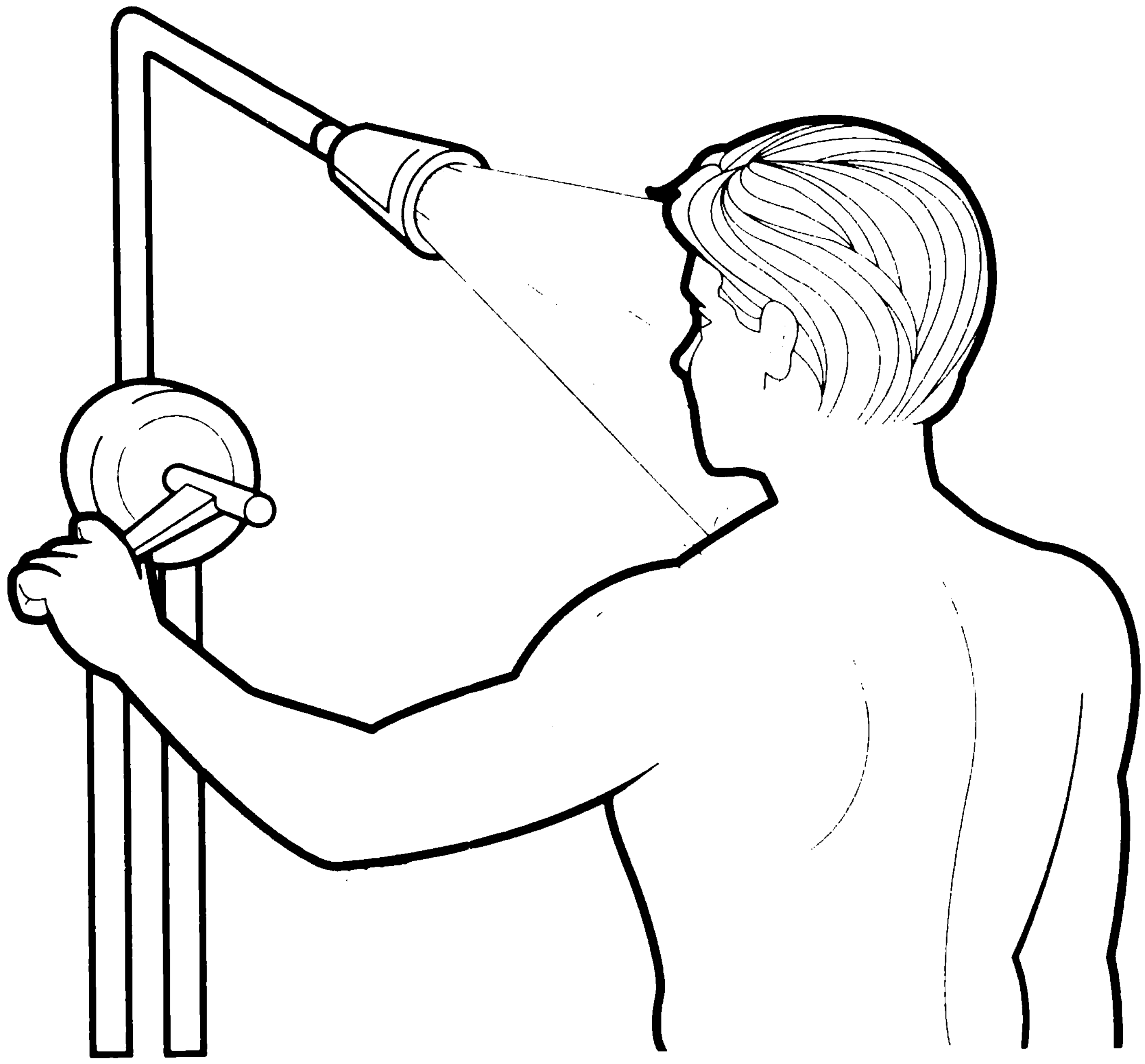

Fig. 1.1 Water temperature control system

temperature while taking a shower. The major components of the system are shown in Fig. 1.1. When we get into the shower, we have some idea of the water temperature we want. This temperature is not known in an absolute sense, such as 82 degrees, but qualitatively, such as cold, warm, or hot. Temperature sensors in our skin effectively measure the water temperature and convey the information to the brain, where it is compared to the water temperature we want. The brain computes the difference in terms of "too hot" or "too cold" and causes the hand muscles to manipulate the hot and cold mixer valve to reduce the temperature if it is too hot or increase the temperature if it is too cold. Once corrective action is taken, the process is repeated until the required water temperature is achieved.

The operation of the system and its major components are shown in Fig. 1.2. The boxes in the diagram represent processes that perform subtasks of the overall

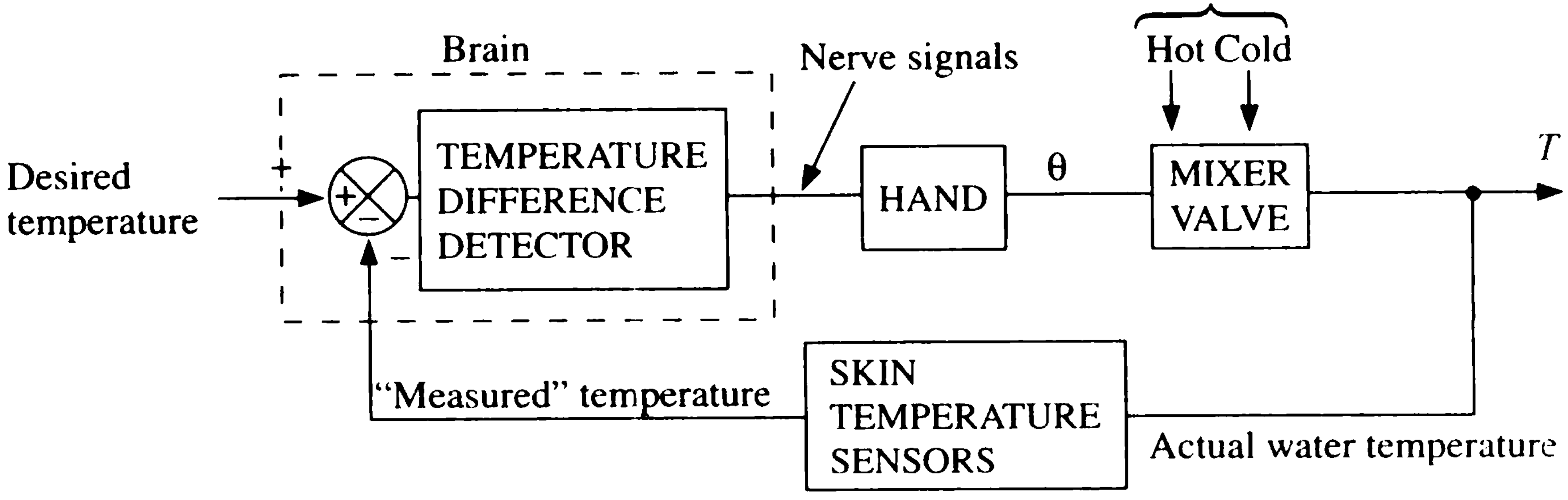

Fig. 1.2 System representation of temperature control

objective, such as measure the water temperature or actuate (move) the mixer valve. Such boxes transfer the input variable to the output variable by means of the transfer function mentioned previously. Some transfer functions are easily calculated, such as the mixer valve. This element has the valve handle angle $\theta$ as input variable and water temperature $T$ as output variable. Making assumptions regarding the linearity of the valve might lead to the relationship

$$T = K_T\theta \tag{1.1}$$

where $K_T$ may be defined as the valve temperature constant. Other transfer functions, such as the relationship between the nerve signals passing between the brain and the hand and the rotation of the mixer handle, will be much more difficult to represent in simple mathematical form.

The system described above will now be represented in the somewhat abstract form shown in Fig. 1.3. The purpose of doing this is because most control systems can be represented in the form of Fig. 1.3, and so analytical methods developed for use on this system will be applicable to most control problems without reference to the physical embodiment of the various elements. Shown in Fig. 1.3 is some of the terminology used throughout the book. Generally the plant represents the major component that is being controlled, and its transfer function is usually fixed. The controller is a component that the engineer designs using techniques outlined later in the book, so that the "best" performance may be obtained from the overall system. The feedback path is a critical part of the system and indicates how the output variable of interest from the plant (temperature in this case) is measured and fed back to be compared with the desired value. The magnitude of the error causes changes in the input to the plant, resulting in further changes in the output.

In the simplest controller design, the output is made proportional to the input. In our example, if the water temperature is far too cold, then the mixer handle is turned to maximize the hot-water content downstream of the valve. As the water temperature approaches the required value, smaller changes in the handle position occur. When the water is at the desired temperature, the two inputs to the differencing junction are equal and the output is zero, as is the output of the controller. The plant is therefore unperturbed and the whole system is in equilibrium.

The water temperature control system described above has a human as part of the control loop. For the immediate future, many control systems will continue

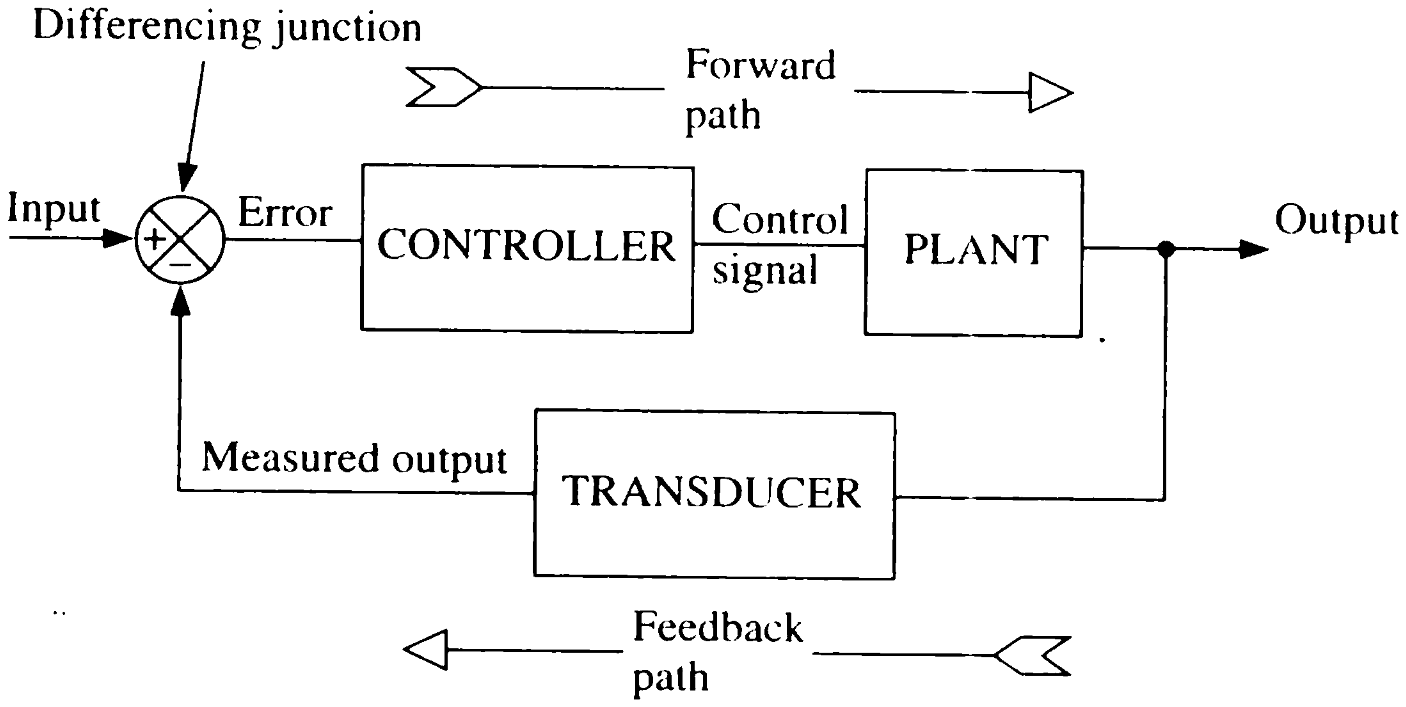

**Fig. 1.3** Generalized feedback control system

to have human computational and reasoning capability as part of the system since computers and actuation hardware do not have the performance to provide a practical substitute. Such systems will include driving an automobile in heavy traffic, performing surgery on humans, playing a game of tennis, or performing classical music on a concert piano. There are, however, a vast number of situations where the human has been replaced in the control loop, resulting in an *automatic* control system. In the water temperature control problem, a temperature sensor placed in the mixer valve delivery pipe could generate a voltage proportional to the temperature, which is compared with that set by a potentiometer. The difference, or error, drives a motor that rotates the mixer handle, enabling the human operator to simply dial the temperature required and leave the rest to the control system. Such a system is shown in physical form in Fig. 1.4 and in block diagram form in Fig. 1.5.

So far, we have only discussed closed-loop control systems, but many objectives may be accomplished using open-loop systems. By definition, these are systems that do not measure and feed back the physical variable of interest. To examine the operation of an open-loop system, consider the shower temperature problem again. If we know the input hot- and cold-water temperatures and the mixer valve characteristics, it is possible to set the mixer valve angle $\theta$ to give us the exact water temperature we desire. Such a system may be represented in

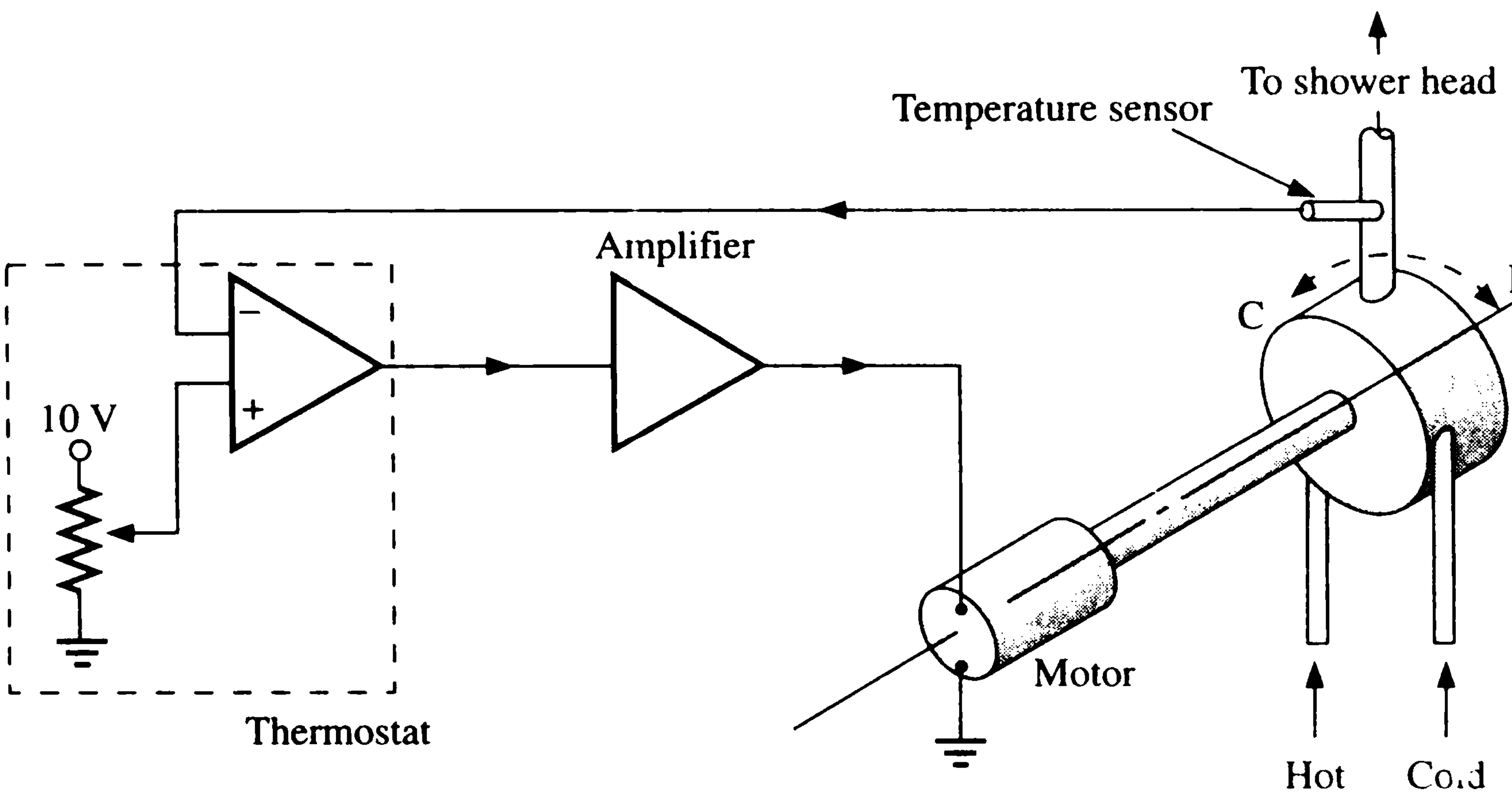

**Fig. 1.4** Automatic water temperature control system

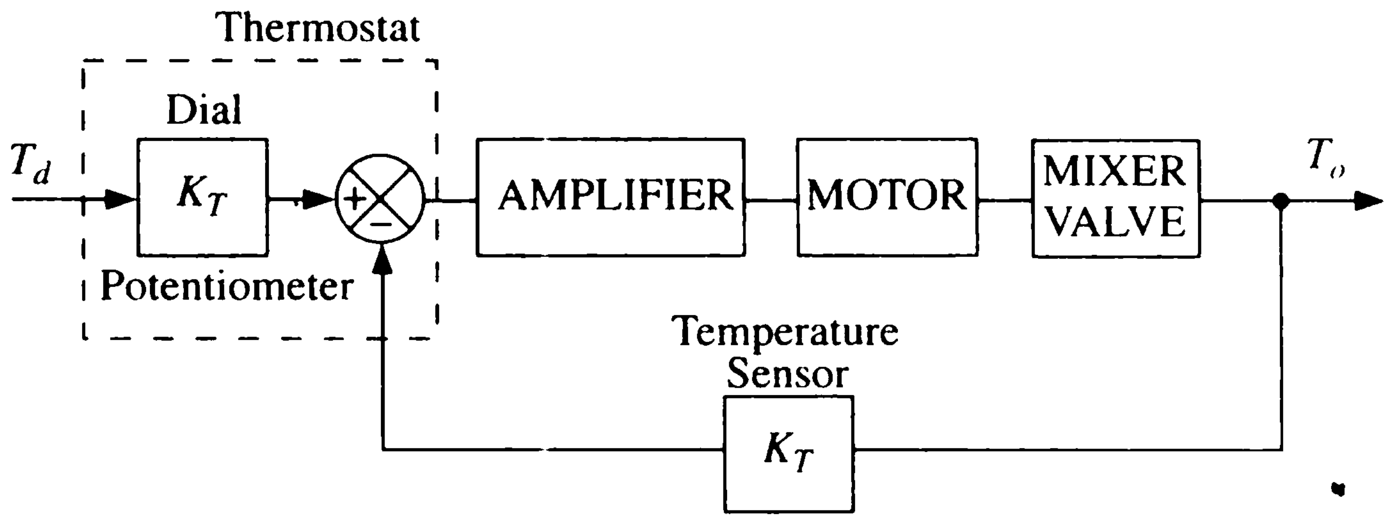

**Fig. 1.5** Block diagram of automatic temperature control system

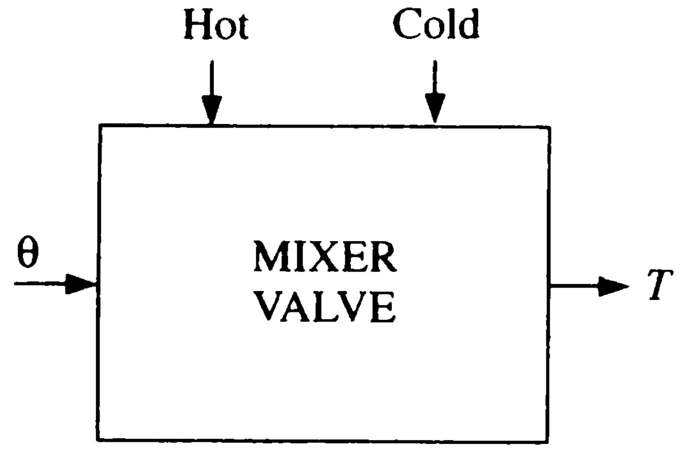

**Fig. 1.6** Open-loop water temperature control system

block diagram form in Fig. 1.6. Clearly this is much simpler than a closed-loop control system and consequently is less expensive, since no temperature sensor or comparator is needed, as in the case of the automated system shown in Fig. 1.4. This is the main advantage of open-loop systems compared to closed-loop systems. A major disadvantage of open-loop systems is the need to know an accurate model of the individual components making up the system so that the input may be set appropriately. Consider that the closed-loop system will work whether we know, for example, the transfer function of the mixing valve or not.

Another advantage of closed-loop systems over open-loop systems is their ability to recover from external, unwanted disturbances. A common situation occurs in the shower when someone flushes a toilet, reducing the supply of cold water to the mixing valve, resulting in a rapid increase in water temperature. If the system is open loop, the mixing valve cannot be adjusted in response to the rapid temperature rise; otherwise it becomes a closed-loop system. All we can do is wait until the toilet has filled up, and the initial cold-water flow is restored. This recovery is shown in Fig. 1.7. On the other hand, if the person in the shower operates the mixer valve in a closed-loop mode, less hot and more cold water may be mixed, producing the correct temperature much faster, again as shown in Fig. 1.7. As the toilet fills up, continual adjustment of the mixer valve is required since a decreasing temperature will be sensed, but the user will experience a reasonably constant water temperature. Once the toilet has refilled and the initial water flow conditions have been restored, the mixer valve is in its original position, and no further adjustments are necessary. It may be concluded, therefore, that

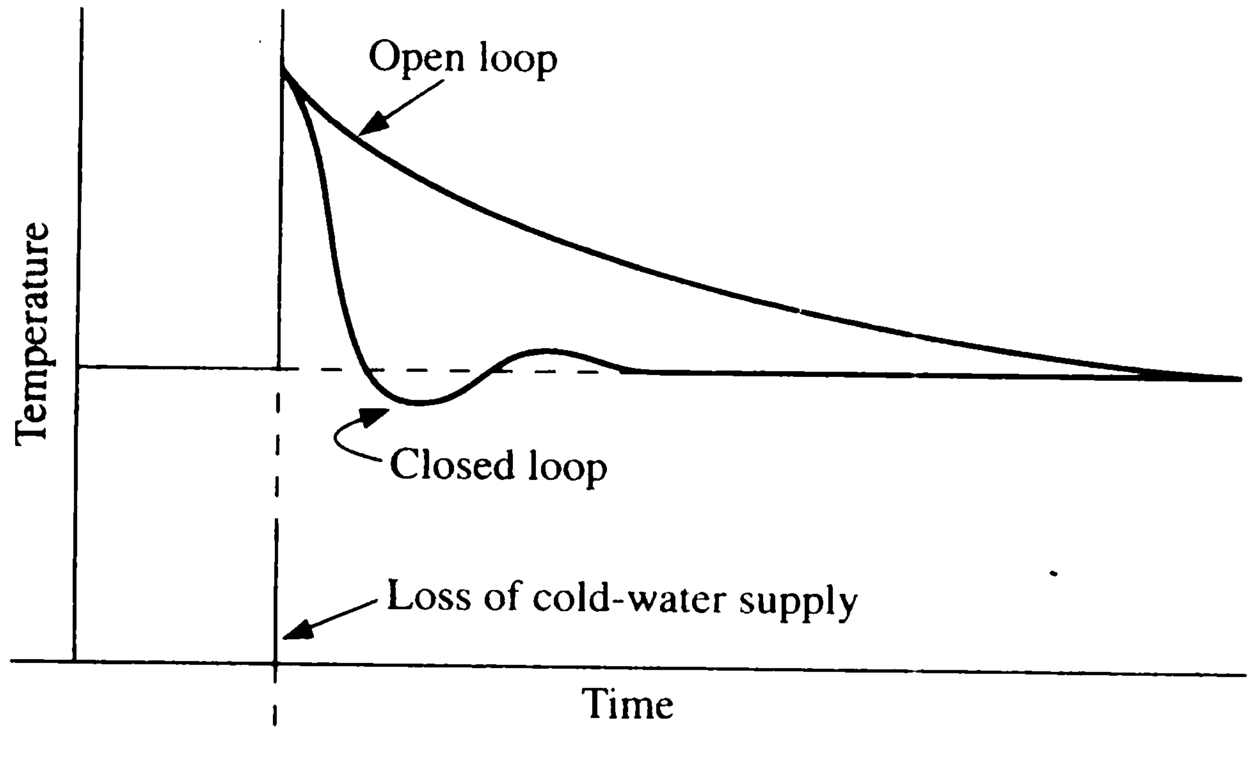

**Fig. 1.7** Temperature recovery from external disturbance