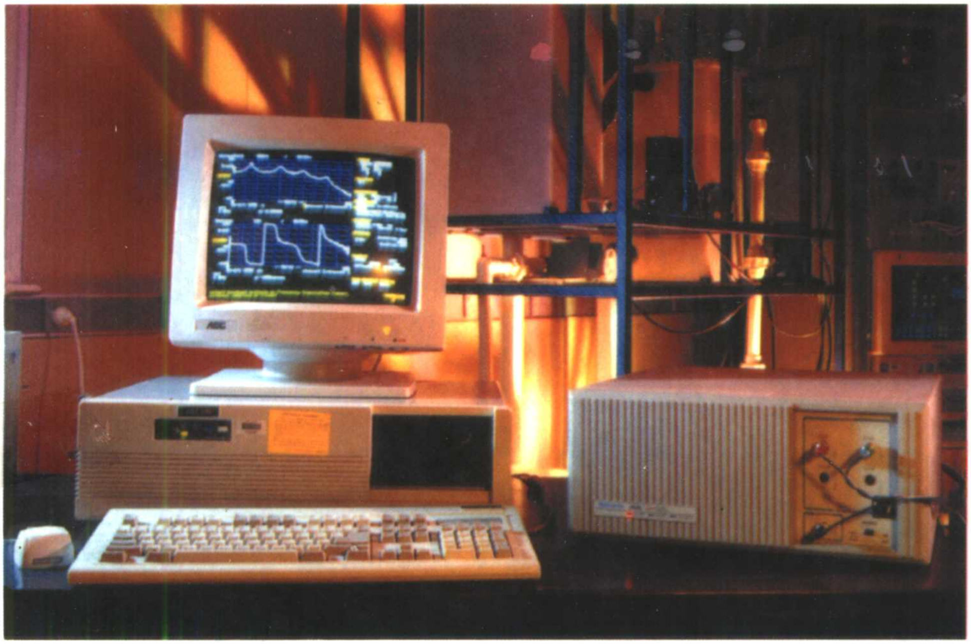
D K ANAND *and* R B ZMOOD

Introduction to CONTROL SYSTEMS

3rd Edition

控制系统导论

第 3 版



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Introduction to Control Systems

Third edition

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Preface

Since the printing of the first two editions, the use of computer software by students has become an important adjunct to the teaching and learning of control systems analysis. With this in mind the entire text has been enlarged and strengthened in the third edition. In addition an attempt has been made to broaden the scope of the book so that it is suitable for mechanical and electrical engineering students as well as for other students of control systems. This revision has been largely carried out by the second author.

The advent of the desk-top computer based computer aided design (CAD) tools has removed the need for repeated hand computations previously required in control system design. While this has forced a fundamental review of the material taught in control courses, it is our contention that many of the analytical and graphical tools, developed during the early days of the discipline are still important for developing an intuitive understanding, or a "mind's eye model", of system design. The computer simply removes the drudgery of applying them.

In reviewing the content of the earlier editions we have sought to arrive at a balance between the material which has pedagogical value and that which has proved useful to the authors in research and industrial practice. This has led to the deletion of some material, and the inclusion of much new material. In addition the order of the material has been altered to assist in the assimilation of important concepts. Class room experience has shown, for example, that when the dominant pole concept is introduced at the same time as the root locus analysis method for feedback systems students identify this idea with the analysis method, rather than accepting it as a separate concept. By presenting it divorced from the root locus method it has been found they more readily accept the generality of the idea.

In the early chapters considerable attention is given to introducing the many methods of mathematical modeling physical systems. To this end the concept of the system S is emphasized and the mathematical models are viewed as approximate but useful descriptions of the system. Their relative utilities depend upon the application in question. While very little motivation for the adoption of these models is given at this time the rapid progress in later chapters to their use in design is felt to satisfy the question of the student. Why all these models? Consistent with our focus on the central role of the system S, the presentation of the various models is carefully developed so as to show their interrelationships.

Apart from discussing steady state and transient performance measures and the sensitivity function, we have introduced unstructured robustness concepts for investigating the effect upon system operation of large changes in its parameters. As the parameters of all practical control systems vary over some non-infinitesimal but defined range the robustness approach has been assuming an ever more important role in system design. Although there is a rich collection of research results on system robustness our treatment of this field is necessarily brief.

It has long been felt by the authors that, while most introductory control system texts dwell on various design techniques such as root locus and other methods at length, they gloss over two of the most important aspects of control system design. These being control strategies and component sizing. While in some instances these are only of minor concern, in many cases they are of utmost importance. Wrong decisions on these matters during the early stages of a project can lead to poor system operation or even failure. In both cases it can be very costly to correct the situation at a later stage after an expensive plant or machine has been constructed. This cost can be measured both in time and money.

The classical design techniques of the root locus and the frequency response methods involve sequentially adjusting the parameters of the assumed controller structures to determine if the performance specification is satisfied. These approaches involve a considerable amount of trial and error, as well as relying on designer inspiration for the selection of the appropriate controller structures. As an alternative approach we present here a state space pole placement design method where the performance specification leads systematically and directly to the controller design by a well defined numerical algorithm. State observers, which are needed to implement these designs, are also introduced, and it is shown how these designs are integrated to complete a total control system design.

The design methodologies discussed in earlier chapters of the book lead to controllers with fixed parameter settings. Adaptive control was developed for systems having large plant parameter changes where the controller settings are adjusted to accommodate these changes and so as to always give the desired performance. In the discussion only the basics of adaptive control are presented. Such important concepts as the certainty equivalence principle, model reference adaptive systems (MRAS), and self tuning regulators (STM) are introduced and applied to a number of examples of adaptive control systems.

The material in this book has been used in a variety of courses over the last twenty years by the authors, both at the University of Maryland, and the Royal Melbourne Institute of Technology (RMIT). At RMIT the material presented has been used as the basis for junior level and senior level courses in electrical engineering, each running over two semesters for $1\frac{1}{2}$ hours per week. At the University of Maryland both authors have covered the equivalent of Chapters 1 to 7 in a one semester course to mechanical engineering students taking their senior year. Other combinations of chapters could be easily be used as a basis for other courses. For example Chapters 1 to 4, 6, 7, 9 and 10 could be used as an introductory course on digital control systems. Apart from its use as an undergraduate text the book is well structured to be read by practicing engineers and applied scientists who need to utilize control techniques in their work.

A hallmark of earlier editions was the use of copious examples to illustrate the various concepts and techniques. This feature has been retained, with the range of problems in each chapter being greatly expanded, both in number and in spread of difficulty. To this end the teacher will find some problems are elementary exercises, some are challenging even to good students, some are open-ended, and some are design-oriented. These latter problems are intended to encourage the student to approach control design problems from a holistic or integrated point of view. As well they illustrate the power of computer analysis for control system design. Cautious selection of problems, suited to the audience who are using the book, will need to be exercised.

In carrying out a task of this magnitude many people, some of them unknowingly, have contributed to its success. First of all there are the many students who have suffered through our trying to get the presentation right. Then there are our colleagues with whom we have discussed the finer points of presentation. Dr. G. Feng of the University of New South Wales deserves special mention for it was he who wrote the first draft of Chapter 13. Also Dr. T. Vinayagalingam of RMIT critically read the complete manuscript and offered many suggestions for improvement of presentation. Mr. T. Bergin has read and critiqued some of the key chapters, while Daniel Zmood, the son of the second author, read many of the sections from a student perspective and made useful suggestions for clarifying the text. Ms R. Luxa painstakingly typed the entire manuscript from the handwritten notes and Mr R. Wang drew many of the figures. To all we express our thanks. Finally to our wives Asha and Devorah, and to our families, who at various times saw us disappear for long hours to write the manuscript

we express our gratitude. Their forbearance is much appreciated.

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Contents

Chapter 1

Introduction

1.1 Historical Perspective

The desire to control the forces of nature has been with man since early civilizations. Although many examples of control systems existed in early times, it was not until the mid-eighteenth century that several steam operated control devices appeared. This was the time of the steam engine, and perhaps the most noteworthy invention was the speed control flyball governor invented by James Watt.

Around the beginning of the twentieth century much of the work in control systems was being done in the power generation and the chemical processing industry. Also by this time, the concept of the autopilot for airplanes was being developed.

The period beginning about twenty-five years before World War Two saw rapid advances in electronics and especially in circuit theory, aided by the now classical work of Nyquist in the area of stability theory. The requirements of sophisticated weapon systems, submarines, aircraft and the like gave new impetus to the work in control systems before and after the war. The advent of the analog computer coupled with advances in electronics saw the beginning of the establishment of control systems as a science. By the mid-fifties, the progress in digital computers had given engineers a new tool that greatly enhanced their capability to study large and complex systems. The availability of computers also opened the era of data-logging, computer control, and the state space or modern method of analysis.

The Russian sputnik ushered in the space race which led to large governmental expenditures on the U.S. space program as well as on the devel-

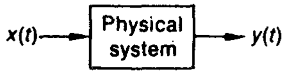

Figure 1.1: A physical system

opment of advanced military hardware. During this time, electronic circuits became miniaturized and large sophisticated systems could be put together very compactly thereby allowing a computational and control advantage coupled with systems of small physical dimensions. We were now capable of designing and flying minicomputers and landing men on the moon. The post sputnik age saw much effort in system optimization and adaptive systems.

Finally, the refinement of the micro chip and related computer developments has created an explosion in computational capability and computer-controlled devices. This has led to many innovative techniques in manufacturing methods, such as computer-aided design and manufacturing, and the possibility of unprecedented increases in industrial productivity via the use of computer-controlled machinery, manipulators and robotics.

Today control systems is a science; but with the art still playing an important role. Much mathematical sophistication has been achieved with considerable interest in the application of advanced mathematical methods to the solution of ever more demanding control system problems. The modern approach, having been established as a science, is being applied not only to traditional engineering control systems, but to newer fields like urban studies, economics, transportation, medicine, energy systems, and a host of fields which are generating similar problems that affect modern man.

1.2 Basic Concepts

Control system analysis is concerned with the study of the behavior of dynamic systems. The analysis relies upon the fundamentals of system theory where the governing differential equations assume a **cause-effect (causal)** relationship. A physical system may be represented as shown in Fig. 1-1, where the excitation or **input** is $x(t)$ and the response or **output** is $y(t)$. A simple control system is shown in Fig. 1-2. Here the output is compared to the input signal, and the difference of these two signals becomes the excitation to the physical system, and we speak of the control

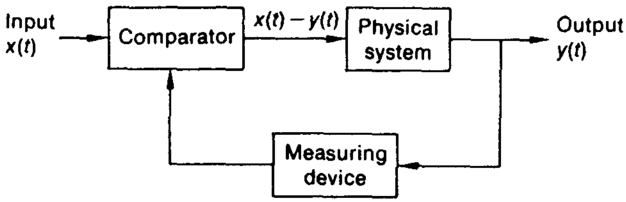

Figure 1.2: A simple control system

system as having **feedback**. The **analysis** of a control system, such as described in Fig. 1-2, involves the determination of $y(t)$ given the input and the characteristics of the system. On the other hand, if the input and output are specified and we wish to design the system characteristics, then this is known as **synthesis**.

A generalized control system is shown in Fig. 1-3. The **reference** or **input variables** $r_1, r_2, \ldots, r_m$ are applied to the **comparator** or **controller**. The **output variables** are $c_1, c_2, \ldots, c_n$. The signals $e_1, e_2, \ldots, e_p$ are **actuating** or **control variables** which are applied by the controller to the system or **plant**. The plant is also subjected to **disturbance inputs** $u_1, u_2, \ldots, u_q$. If the output variable is not measured and fed back to the controller, then the total system consisting of the controller and plant is an **open loop system**. If the output is fed back, then the system is a **closed loop system**.

1.3 Systems Description

Because control systems occur so frequently in our lives, their study is quite important. Generally, a control system is composed of several subsystems connected in such a way as to yield the proper cause-effect relationship. Since the various subsystems can be electrical, mechanical, pneumatic, biological, etc., the complete description of the entire system requires the understanding of fundamental relationships in many different disciplines. Fortunately, the similarity in the dynamic behavior of different physical systems makes this task easier and more interesting.

As an example of a control system consider the simplified version of the attitude control of a spacecraft illustrated in Fig. 1-4. We wish the satellite to have some specific attitude relative to an inertial coordinate system. The actual attitude is measured by an attitude sensor on board the satellite. If the desired and actual attitudes are not the same, then

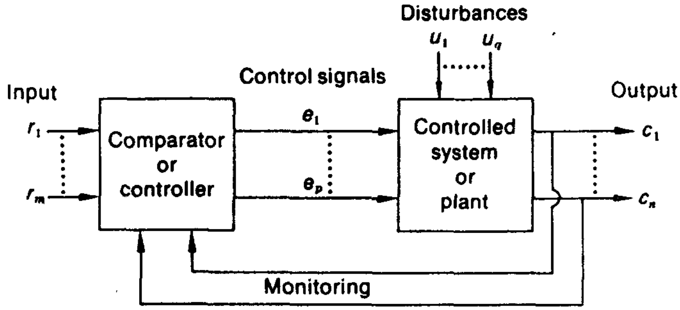

Figure 1.3: A general control system

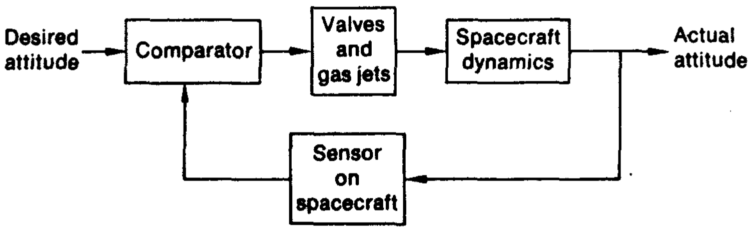

Figure 1.4: Control of satellite attitude

the comparator sends a signal to the valves which open and cause gas jet firings. These jet firings give the necessary corrective signal to the satellite dynamics thereby bringing it under control. A control system represented this way is said to be represented by **block diagrams**. Such a representation helps in the partitioning of a large system into subsystems. This allows each subsystem to be studied individually, and the interactions between the various subsystems to be studied at a later time.

If we have many inputs and outputs that are monitored and controlled, the block diagram appears as illustrated in Fig. 1-5. Systems where several variables are monitored and controlled are called **multivariable** systems. Examples of multivariable systems are found in chemical processing, guidance and control of space vehicles, the national economy, urban housing growth patterns, the postal service, and a host of other social and urban problems.

As another example consider the system shown in Fig. 1-6. The figure