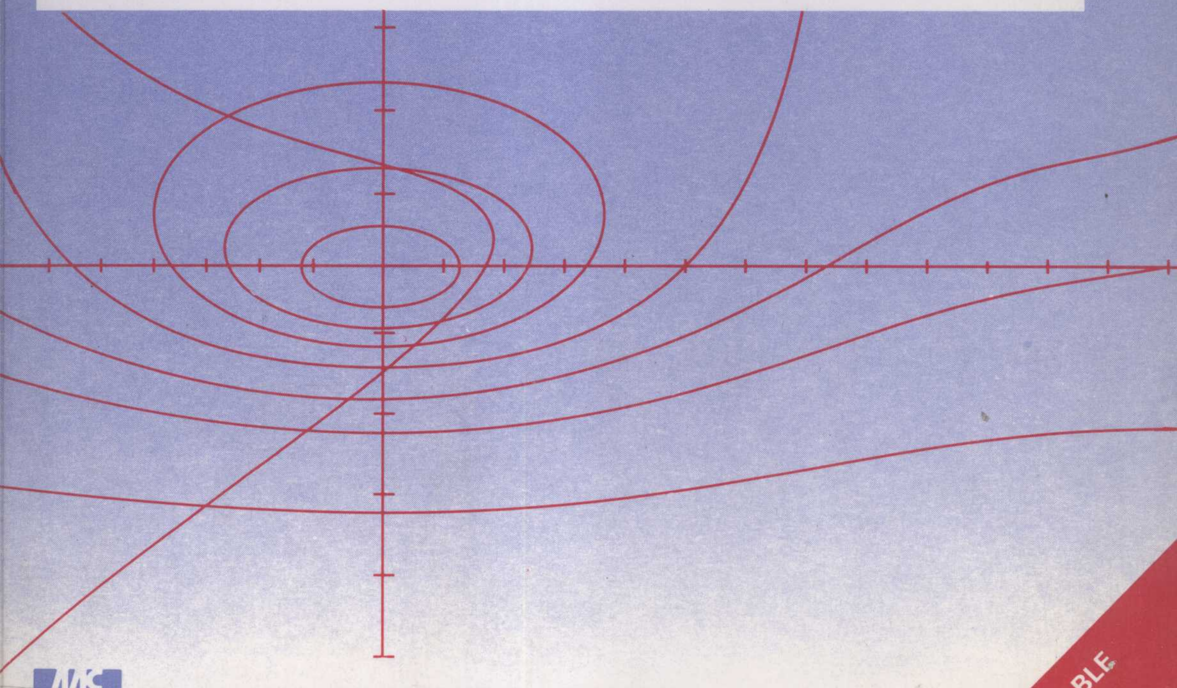
Control System Design and Simulation

JACK GOLTEN AND ANDY VERWER



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CONTROL SYSTEM DESIGN AND SIMULATION

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CONTROL SYSTEM DESIGN AND SIMULATION

In fond memory of Marcel and Jean

PREFACE

This book and accompanying computer software form a unit which is suitable as a course in feedback control systems on a wide range of degree level studies. The approach is based on student centred learning, where readers can try out various ideas and exercises on their own. This book is therefore also suitable as a 'teach yourself' text for individuals not pursuing a formal course.

The book emphasizes the sound grasp of principles, and has many examples of how to apply these principles to produce working designs that meet specifications. The mathematical content has been kept down to a minimum and where possible heuristic argument has been used rather than rigorous and over-facing analysis. Many of the exercises and problems are designed to encourage the reader to explore the subject area and in conjunction with the accompanying software will allow imaginative students to test and develop their knowledge. The case studies show how the design methods can be applied to practical problems.

The software supplied with the book (CODAS) is a special issue of a professional package (CODAS-II) with restricted features. The accompanying disk has all the capabilities of the full package except for the discrete time and nonlinear facilities, also the overall system is limited to fifth order. It allows most of the exercises and problems in the book on continuous time linear systems to be tackled and validated. The exercises and problems on discrete time and nonlinear systems in Chapters 8, 9 and 10 can be done with the full version of CODAS-II. A comprehensive manual for CODAS is supplied on the disk. The file README.DOC contains information on the supplied software and any updates.

CODAS-II (Control System Design and Simulation) is a fully integrated graphics-based package for designing and simulating feedback control systems. PCS is a package concerned exclusively with process control. CODAS-II (and to a lesser extent PCS) is the computational vehicle that is used to promote the ideas developed in this book. In addition to its use as a teaching aid, CODAS-II is a powerful tool for the practising control engineer and technician. All packages are written in efficient C programming language and run on fully IBM-compatible machines which are fitted with one of the standard graphics adaptors such as Hercules, CGA, EGA, VGA and others.

CODAS-II provides time domain, frequency domain and root locus environments for the design and simulation of single-input/single-output control systems. The plant and controller dynamics are defined in terms of transfer functions and optional transport delay can be included. CODAS-II can cater for continuous and discrete time systems and can include nonlinear elements which are defined using an interactive editor. CODAS-II is designed to facilitate rapid user interaction and promote 'what if?' experimentation. The techniques described in this book are not exclusive to CODAS-II; certainly other packages do exist on which many or all of the exercises can be done and many of the techniques can be tried.

Often in the past, control engineering text books developed designs that were not or could not easily be tested. CODAS-II is a hard task master because for every design and design technique there is instant verification and there is no room for hopeful intent. Using CODAS-II often shatters preconceived views and challenges former fondly-held beliefs.

Even though the book is heavily based on computer-aided design, the design methods used are mainly classical. There is an introduction to state space but on the whole the classical methods of s-plane, z-plane and frequency domain have been used because they have an intuitive appeal which is generally lost in state space representations. State space methods come into their own when dealing with multi-variable systems and in optimal control problems; both of which are outside the scope of this book.

The reader should be familiar with complex numbers and their use for vector manipulation. A knowledge of elementary calculus is required and some familiarity with simple differential equations is useful but not essential. It is expected that the reader is sufficiently familiar with the MS–DOS operating system to run programs and manipulate and examine files.

The book begins with an introduction to feedback control systems and modelling in Chapters 1 and 2. Chapter 3 deals with the transient and steady-state responses of open-loop systems. The correlation between transient response and s-plane diagram is explored. First- and second-order dynamics are covered in detail as well as the effects of additional poles and zeros. Closed-loop systems are introduced towards the end of Chapter 3 where steady-state performance is covered. In Chapters 4 and 5 frequency domain methods are developed. Chapter 4 concentrates primarily on open-loop systems whereas Chapter 5 deals with the design of closed-loop systems using frequency domain techniques. Some new, or at least revised design techniques using the 'D' contour are covered here.

Chapter 6 returns to the s-plane and examines root locus and root contours as design techniques. Two full case studies are included which look at the design of control systems for two very different applications. Chapter 7 deals with process control and the tuning of three-term controllers. A thorough evaluation of popular tuning techniques is included. Chapters 8 and 9 deal with discrete time and computer control systems. Chapter 8 examines industrial control computer hardware and software and covers the analytical techniques required for discrete time system analysis. Chapter 9 develops design methods for discrete time controllers and filters. Practical aspects, including sample rate selection, anti-aliasing filters and quantization are also dealt with. A comprehensive case study concludes this chapter. The final chapter looks at nonlinear control systems using perturbation methods and describing functions.

We would like to acknowledge the support given to us by the Department of Mechanical Engineering, Design and Manufacture; Manchester Polytechnic. We also thank all the students over the years who have acted as guinea pigs in helping to develop our computer-aided design and simulation approach to teaching control engineering.

Jack Golten
Andy Verwer

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CHAPTER

ONE

INTRODUCTION TO CONTROL SYSTEMS

1.1 INTRODUCTION

The automatic control of machines and processes is fundamental to the successful operation of modern industry. Modern manufacturing, processing and transportation systems are heavily dependent on automatic control systems. The benefits of automatic control include more consistent operation, greater safety for the process or machine and operating personnel and reduced operating costs due to improved utilization and reduction in manpower requirements.

The need for automatic control continues to grow in terms of the range of applications and performance requirements. The development of high performance civil and military aircraft, missile technology and space vehicles has placed great demands on the speed and accuracy of attitude control systems. In manufacturing, the developing use of robots and automated production has further increased the need for reliable, high performance control systems. In the process industry, stricter requirements for product quality, energy efficiency and pollution levels place tighter limits on process control systems.

The reducing cost and increased performance of digital computers has had a significant impact on the way control systems are designed and implemented. Powerful mini- and microcomputers with superb graphics capabilities are readily available for designing and simulating control systems. Computers are also widely used for implementing automatic control in an increasing variety of industrial and domestic applications. Even mass-produced consumer products can include powerful microprocessor systems to monitor and control the system. For example, the average music centre or video camera contains more computing power and automatic control than a typical engineering laboratory of the mid 1960s.

1.2 BASIC CONTROL SYSTEM TERMINOLOGY

A *control system* consists of a *controller* and a *plant*. We use the general term plant to describe the machine, vehicle or process which is being controlled. The controller can

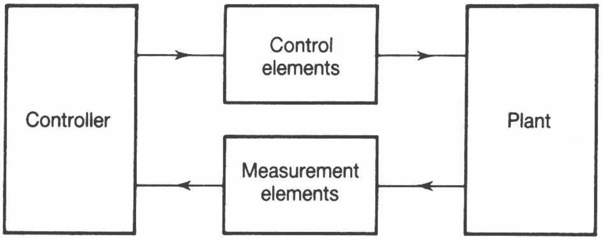

Figure 1.1 A general control system

be a person, in which case we have a *manual control system*. Alternatively, in an *automatic control system* the controller is a device, electronic circuit, computer, or mechanical linkage, etc. Figure 1.1 shows the general arrangement.

The interface between the plant and the controller requires actuators (*control elements*) to provide the control action. In addition instrumentation, detectors and sensors (*measurement elements*) are needed to provide information about the plant status to the controller. The information passing between the controller and the plant is in the form of *signals*. These signals can be very diverse, for example electrical, pneumatic or mechanical, etc. The term 'transmitter' is commonly used to describe the measurement element in a process control system because the transmitter sends an electrical or pneumatic signal representing the measured value to the controller.

Controllers are usually implemented electronically, either using analogue circuits or a digital computer (microprocessor). Pneumatic and hydraulic controllers are also to be found. Actuators are commonly pneumatic, electric or hydraulic depending on the application and power level required.

The behaviour and performance of a control system depends on the interaction of all the elements. The individual components cannot generally be considered in isolation. The plant itself is probably the most important element in any control system; the best controller in the world cannot make an inadequate plant operate well.

Feedback

In everyday life, feedback occurs when we are made aware of the consequences of our actions. Feedback is so natural that we take it for granted. Imagine trying to accomplish the simplest of tasks without feedback, for example, trying to walk without visual feedback. Feedback not only gives verification of our actions: it allows us to cope with a changing environment by adjusting our actions in the presence of unforeseen events and changing conditions.

Feedback has similar advantages when applied to automatic control. Feedback occurs in automatic control systems when the control action depends upon the measured state of the machine or process being controlled. Feedback gives an automatic control system the ability to deal with unexpected disturbances and changes in the plant behaviour.

Sequential and Quantitative Control Systems

A *sequential control system* involves *logic control functions*. The sensors monitoring the plant provide switched outputs which produce only on/off signals. For example an automatic door may be fitted with limit switches to detect the position of the door and an infrared detector with a switched output to sense an approaching person. The control function involves the use of logical rules so that the actuators operate in the correct sequence and at the correct time. Sequential control systems are common in factory automation, automatic warehouses and the control of batch operations. The design of sequential control systems involves problems in logic and is not covered in this book.

The objectives of a *quantitative control system* are different. This type of control system is concerned with controlling the actual value of some plant quantity. Measurement elements provide quantitative information to the controller rather than just on/off signals. The division between sequential control and quantitative control can be vague and some systems can be considered in both ways.

As an example, a modern automatic washing machine clearly involves sequential control to switch the various solenoid valves and pumps on and off in the required progression for the selected wash program. Quantitative control is used for the wash drum rotational speed. Here the actual drum speed is measured and controlled by altering the power delivered to the motor. A less clear example is the thermostatic control of wash temperature. The thermostat switches the heater element on and off depending on whether the wash temperature is too low or too high. The control signal is clearly on/off but since it is the actual value of the temperature which is important the system can also be considered as quantitative.

The behaviour of a quantitative control system depends fundamentally on the rate and extent to which the plant responds to the control action. Such *dynamic* behaviour is difficult to predict and the design of quantitative control systems to achieve acceptable response is no trivial matter. This book is concerned with the behaviour and design of quantitative control systems.

1.3 OBJECTIVES OF AUTOMATIC CONTROL SYSTEMS

Regulation

A control system for maintaining the plant output constant at the desired value in the presence of external disturbances is called a *regulator*. Disturbances will cause the plant output to deviate and the regulator must apply control action or *control effort* to attempt to maintain the plant output at the reference value with the minimum of error. Feedback is fundamental to regulation because only feedback can provide information about the actual plant output. A good regulator will minimize the effects of disturbances on the plant output.

Trajectory Following

Quite often a control system is required to make the plant output follow a certain profile or trajectory. A *servo system* is a control system specifically designed to follow a changing reference value. The servo problem, as it is called, is of major concern in transportation, defence and manufacturing systems. The servo must apply control effort to make the plant output follow the desired path with the minimum of error.

It is clear that the regulation and servo problems are very similar and indeed many control systems give good regulation against disturbances and close following of a changing reference.

1.4 CONTROL STRATEGIES

In order to examine some different control strategies let us consider a simple level control problem. Figure 1.2 shows a tank holding liquid for feeding some process. The process being supplied requires a constant head feed and so a control system is required to keep the tank level constant at some reference level. A valve is located in the tank inlet to alter or modulate the flow rate.

Open-loop Control

The simplest strategy is to have a dial on the inlet valve. By experiment the valve can be moved to different positions and a note made of the dial position and the corresponding level in the vessel. The dial can be calibrated in 'metres'. Thus if it is decided to operate at a different level, the valve can be moved to the corresponding position on the dial. This strategy is termed open-loop control. Open-loop control is simple and will work well provided there is no change in the flow of liquid from the vessel and all other parameters affecting the level in the vessel remain constant.

Feedforward Control

The major cause of disturbances affecting the tank level is likely to be changes in the tank outflow rate. An increased outflow will cause the level to drop. A more sophisticated strategy is to use a set of calibrations over a number of outflow rates. By monitoring the outflow rate when the plant is in operation, the correct position of the valve can

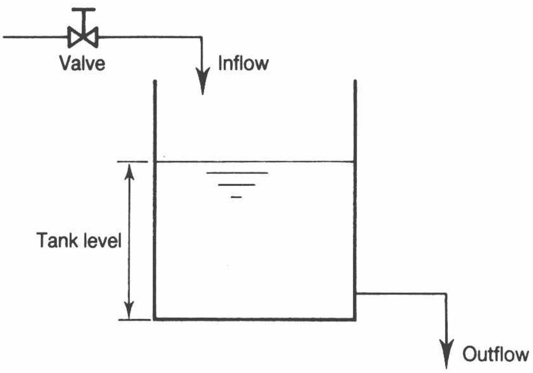

Figure 1.2 Example plant for level control

be determined by examining the calibration curve for the new flow and then opening or closing the inlet valve accordingly. This strategy is termed feedforward control.

Feedforward control requires a set of calibration curves or a *model* of the relationship between the valve position, outflow and level. The relationship can be obtained experimentally by measuring the level for various outflow rates and inlet valve positions. Alternatively the model can be formulated from a theoretical analysis of the tank. Another consequence of this strategy is that a measurement of the outlet flow rate is required to calculate the necessary change in the position of the inlet valve.

Feedforward control is an improvement over simple open-loop control. But it only caters for the one variable which is being monitored (in this case the outflow) and relies on a good model of the plant. If the model is inaccurate or the behaviour of the system varies with time then the feedforward strategy may not work too well. Disturbances can originate from many causes which may not be included in the model, or are not monitored. For example, the supply pressure upstream of the inlet valve may change or the density of the liquid could alter. These variations will cause the relationship between inlet valve position and tank inflow to change and so the tank level will be incorrect. The feedforward strategy will not correct for these factors.

Feedback Control

Rather than adding more feedforward measurements to compensate for these other factors, the obvious solution to maintain the level in the vessel is to monitor the level itself and adjust the inlet valve if the level deviates from the desired value. Such a *feedback* strategy is *error driven* in that the control effort is a function of the difference between the required level and actual level. The relationship between the error and the control effort is called the *control law*. Feedback control, unlike feedforward, can give regulation against unmeasured or unmodelled disturbances.

On/Off Feedback Control

The simplest method of monitoring the level is by means of a level switch (float switch). The level switch is mounted in the tank at the desired level. The switch produces a binary (on/off) signal that indicates whether the level is above or below the required value. The signal can be used to operate the inlet valve directly. When the level is above the reference the inlet valve is closed and when below it is opened. The control law in on/off control therefore switches the control effort between extremes depending on the sign of the error.

On/off control certainly overcomes the criticisms of the open-loop and feedforward strategies. Whatever the cause of the change in level, if the deviation in the level is large enough to activate the switch then control action will be applied to correct the situation. The required level (reference) in this simple scheme is determined by the position of the level switch on the tank. On/off control requires only very simple equipment in the form of level switches and a simple solenoid type actuator to open or shut the valve.

There are several problems with on/off control. One problem concerns the violent fluctuations in inlet flow as the valve switches between fully open and fully shut. These flow changes may appear as a significant disturbance to any process feeding the tank.