CONTROL SYSTEM PRINCIPLES AND DESIGN

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Preface

A teaching career that started in 1954 has allowed me to observe and participate in many developments in the field of control engineering. I feel this historical perspective provides a background particularly useful in evaluating alternative approaches and in creating a new control text at this time. In 1954, outside of electrical engineering, elective control courses were extremely rare and required undergraduate courses unheard of. At that time, the Ohio State Department of Mechanical Engineering instituted a required undergraduate course in control systems, which led in due course to the writing of my first textbook.* Over the years, I came to view the areas of system modeling, measurement, and control as a coherent body of knowledge of great utility in engineering practice and developed a total of eight courses (and seven associated laboratories) spanning the range from introductory (sophomore level) system dynamics courses (we require two), through separate required courses in measurement and control principles, to senior elective/beginning graduate courses in measurement system design and control system design, and ending finally with two graduate courses in system modeling and response. Texts† for all these courses were generated along the way, the present book being designed for the two control courses. (The first, 1962, control text was written for a required introductory course.)

Although enthusiasts like myself have for many years encouraged the introduction of required control courses into the mechanical engineering curriculum, and many schools have done this, the practice is not yet universal. It is hoped that the current national interest in industrial revitalization and productivity enhancement through application of flexible manufacturing systems, robotics, microprocessor-based controls, and computer-aided design and manufacturing will serve as a final push to make a required course in control as certain as a required course in thermodynamics. I have tried to design this new text to meet these needs in such a way that faculties will be encouraged to provide the needed curricular space for this important material. This is best done, I believe, by presenting control, not as a narrowly specialized mathematical exercise, but as a widely applied technology with close connections to, and important impacts on, many other areas of engineering design.

*E. O. Doebelin, *Dynamic Analysis and Feedback Control,* McGraw–Hill, 1962.

†E. O. Doebelin, *Measurement Systems,* McGraw–Hill, 1966, 1975, 1983; E. O. Doebelin, *System Dynamics,* Merrill, 1972; E. O. Doebelin, *System Modeling and Response,* Wiley, 1983.

Those familiar with my earlier works will find the same spirit has guided the present effort:

a. A balanced presentation of the mathematical and physical aspects of the subject.

b. Emphasis on time-tested approaches useful now and in the future in engineering practice.

c. A conscious and persistent effort to relate specialized topics to their proper role in the larger scene of engineering design.

d. Use of innumerable realistic application examples to develop hardware familiarity and an appreciation of the distinction between math models and real equipment, and to demonstrate the practical relevance of the methods being presented.

Although this philosophical attitude sets the tone of the work, technical and pedagogical details are also important. The book is designed, and has been used here at Ohio State, for both a required introductory course and a second, design-oriented elective course. It is thus suitable also for an elective course that is the student's first control course. The practical flavor of the text and its emphasis on careful and complete explanations should also make it appealing for self-study by practicing engineers needing information in the general area or on some specific topic. My earlier control text (1962) included considerable background material on system dynamics and this seems today to be still desirable since many schools do not yet require a separate system dynamics course. For those, such as my own students, who *do* have a good system dynamics preparation, this text material can be left for a quick outside-of-class review, giving more time to spend on strictly control topics. As for mathematical tools, I still find no real advantage to using the Laplace transform in an introductory required course, and leave this for the second course. I realize many prefer to use the Laplace transform from the outset, so have included this coverage early in the text for them. Since the Laplace transform is basically a means of evaluating the *response* of linear, constant-coefficient systems, the ready availability of digital simulation languages, which handle *all* kinds of systems (linear, nonlinear, time-varying, sampled-data, random inputs, etc.), makes using the Laplace transform less necessary for detailed performance calculations.

As in my 1962 book, nonlinear aspects of control systems, both intentional and parasitic, are considered an integral part of even an introductory course and are not to be left for a "second" course (which many students in a required first course would never take). This position may have been a little radical in 1962, but today, with digital simulation languages being widely available and inexpensive to use, there is no excuse for leaving students ignorant of nonlinear behavior. With regard to analytical techniques for nonlinear systems I present only the describing-function approach; other approaches have not demonstrated any great practical utility in design. Although there is a separate chapter on nonlinear systems, many nonlinear effects pertinent to control performance are also sprinkled throughout the text, where appropriate, and are treated using simulation.

The relative roles of "classical" and "modern" control theory in a text at this level is the subject of some controversy. Authors often allot each approach a roughly equal portion of space but then offer the student no real guidance as to the relative practical utility of each method. Since the provision of such guidance is, in my view, a major function of teachers and authors, I feel the need to provide in this text my best effort in that direction. In most current texts actual real-world applications of modern control, complete with hardware/software details, are almost never given, whereas it is easy to give hundreds such applications for classically designed systems. The reason for this is that the significant applications (and there are some very significant ones) of modern control are not only rare but are also complex and not easily explained. As long as this is the situation, I feel there is little justification for presenting modern control concepts in our first few control courses since one is unable to show students convincing evidence of their application, and most students at this level will never need these tools. Rather, we should reserve the presentation of modern control for advanced courses where significant applications can be shown and understood.

At the risk of alienating some potential users of this book, I have therefore opted for a concentration on classical methods, augmented with computer simulation. As one who was present during the creation and development of modern control theory, I find it necessary to emphasize that the theory is now 30 years old and there has been ample time and more than ample effort expended on its application for some judgements to be reached on its utility. Lack of on-line computing power, sometimes claimed as a main reason for a dearth of applications, becomes a less convincing argument with the appearance of each new generation of microcomputers. My own conclusion is that modern control theory certainly is a suitable subject for advanced courses and research in the control field, and that a few very significant applications have been made, but that the vast majority of practical control system designs are satisfactorily worked out using classical analytical methods augmented by computer simulation and experimental development. It is also important to note that this situation is not about to change. Some proponents of modern control approaches have over the years fostered the impression that classical methods would "shortly" be superseded, thus it was necessary to prepare students for this revolution by replacing classical methods with "modern." I believe enough time has passed to make it safe to reject this view and restore in academic circles the view that classical methods (augmented with simulation) are the analytical methods of choice in most system design work.

A "modern" development that I feel is really more significant to practical design work is the wide availability and low cost of general-purpose digital simulation languages (such as CSMP and ACSL) for computer-aided design. These are of course used for many noncontrol purposes but their application in the control field is changing design procedures in important ways. These highlevel languages are very easy to learn and use and they apply to every kind of control system, including new concepts or combinations that a designer might daily conceive for specific applications. Since digital computers are being used more and more as system controllers, a digital simulation of a proposed new control system design also begins to look more and more like the actual system itself, making the transition from design calculations to operating hardware/software much more direct and rapid. Simulation studies without an adequate theoretical background can of course become aimless gropings and extremely wasteful of computer resources; however it is equally short-sighted to overlook the potential for replacing tedious and approximate analytical procedures with straightforward and accurate numerical evaluations. A good example here is the classical gain-setting procedures (Nichols charts, root locus, etc.) for linear systems. This book still explains these methods since they give a general understanding of the effects of design changes, in addition to providing a specific numerical result. I also, however, immediately show how easy it is to run a CSMP simulation with gain as a multivalued parameter to explore its effect and make a choice. Every other aspect of design can be similarly and efficiently explored with these simulation tools. Nonlinear and/or time-varying effects that defy analytical treatment are readily evaluated. These simulation tools are felt to be such an important accessory to the basic analytical methods that they are used heavily throughout the text. Although a practical designer is handicapped without access to such tools, and students definitely benefit from their hands-on use, the text examples are presented in such a way that readers get a large share of the benefits even though they may not have personal access to a simulation facility.

In addition to computer-aided design, the other main impact of computer technology on control is of course the use of digital computers as "components" (generally controllers) in operating control systems. Although many control specialists will want to take one or two courses devoted specifically to digital control systems, a quite useful capability in this area can be developed with a more modest effort. I have tried to provide such a treatment in Chapter 14. This chapter contains a condensed treatment of basic analytical methods, but (perhaps more importantly) explains in considerable detail how many digital systems can be understood, analyzed, designed, and applied using the basic methods for continuous systems developed earlier in the text. Simulation methods are again helpful in reaching these goals.

At this point, it is appropriate to go systematically through the chapters in sequence, giving advice (to those desiring it) on the selection of topics for certain types of courses. Our own curriculum has a required first course that concentrates on basic principles and develops some modest design competence, using a format of three hours of lecture and two hours of lab per week, for one quarter (about ten weeks), in the senior year. Students have had two system dynamics courses (three hours of lecture and two hours of lab each) at sophomore/junior level and a measurement systems course (one hour of lecture and four hours of lab) at senior level. The second control course extends in breadth and depth from the first, is a combined senior-elective and beginning-graduate course, and uses a three hour lecture and two hours of lab format. Its specific purpose is to prepare students for practical control system design in industry. The two courses together would cover essentially everything in the book.

Chapter 1, the introductory chapter, is much longer than most introductions since instead of just introducing the basic feedback principle it also gives an overview of all the important applications areas and all the basic categories of control systems. This is necessary if we want students to see control not just as another narrow topic but as a pervasive influence throughout engineering design, with a highly developed hierarchy of concepts and methods. Most of this chapter can be left for outside reading, with class discussion concentrating on Sections 1.3 and 1.4. We would assign the entire chapter for detailed reading in our first course and have students quickly review it at the beginning of the second course.

Chapter 2 combines some mathematical background with physical system modeling. Our first course would skip the Laplace transform material; our second course would cover it *quickly*. Due to our students' extensive system dynamics background, Chapter 2 would be left mainly for a quick review. Some class time would be spent on the hydraulic servo components, their digital simulation, and on dead-time effects. Chapter 3 is very design oriented and would not be given thorough treatment in our first course and covered in detail in the second. Chapter 4 would be covered in our first course, with particular emphasis on the programmable logic controller, the most widely used device in factory automation. Chapters 5, 6, and 7 would all be covered in detail in our first course.

In Chapter 8 the first course would cover the basic describing function method, apply it to on–off controllers, and check it with digital simulation. The rest of the chapter would be covered in the second course. Sections 9.1 to 9.4 plus the unity-feedback part of Section 9.6 and all of Section 9.7 would be covered in the first course, the rest of Chapter 9 in the second. In Chapter 10, Sections 10.1 to 10.4 are included in the first course, 10.5 to 10.7 in the second. Sections 11.1 to 11.4 would be covered in the first course, 11.5 to 11.7 in the second. In Chapter 12, ideal PI, PD, and PID modes are discussed in the first course, leaving most of the chapter for the second. Chapters 13 and 15 are reserved entirely for the second course; whereas Sections 14.1 to 14.3 are covered in the first course, and 14.4 to 14.6 in the second.

The intelligent design and use of control systems requires that one have:

a. Knowledge of the basic configurations (modes of control) that have been devised and the characteristic performance features of each. This allows one to initially select one or more alternative design concepts that have potential for success.

b. Familiarity with available hardware so that commercially available components to implement the design concepts can be selected.

c. Competence in modeling of physical systems with suitable equations, using judicious assumptions.

d. Facility in the use of analytical, simulation, and experimental techniques for determination of system response and suggesting design changes.

This text provides an integrated treatment of all these aspects of control engineering and thus prepares the student for early productivity upon entering industrial practice. I have attempted to make the coverage of item "a" particularly complete since this storehouse of basic ideas is what one draws on when conceiving a design for a new application. The vast majority of practical systems are designed in this way rather than by some mathematical synthesis procedure. The list of topics includes not only fundamental control modes such as on–off, proportional, integral, derivative, phase lead, phase lag, lead/lag, and cancellation compensation, but also more specialized schemes such as command and disturbance feedforward, cascade control, state-variable feedback, reset-windup compensation, Smith predictors and sampling controllers for dead-time process, phase-lock servos, intentional nonlinearities such as mode switching for conditional stability/saturation problems, adaptive-gain proportional controllers, square-root velocity servos, secondary feedback in on–off thermostats, open-loop digital control using digital actuators (step motors, etc.), and noninteracting control for multivariable processes. Many of these specialized (but important) topics are difficult to present convincingly since their nonlinearity or other complications frustrate analytical treatment; however digital simulation easily reveals their features and also provides a practical design capability.

In closing, I would like to acknowledge the support of the Department of Mechanical Engineering at Ohio State in providing assistance in manuscript preparation. Typing was capably performed by Elizabeth Fisher and Barbara Dolatabady.

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CHAPTER 1
Introduction

1.1 ROLE OF CONTROL SYSTEMS IN ENGINEERING DESIGN

Engineering students might find themselves using this book in various contexts. At my school it is used for two courses. The first is a senior-level course that is required of all mechanical engineering students. My philosophy for such a course emphasizes breadth, practicality, and concentration on fundamental principles. The major design techniques can be introduced and illustrated, however restrictions of time will ordinarily limit the development of design competence to a modest level. I believe this is a proper compromise for such a group of students since most of them will not become control specialists and this will be their "one and only" control course. Since I feel such a course should be required in *every* mechanical engineering curriculum (and most other engineering curricula also) and since this goal has not yet been attained, this section will present arguments for this viewpoint. These arguments serve to illuminate the important role played by control systems in almost every area of engineering design and are thus of particular significance to students who do not consider themselves control specialists and may "need convincing" that this is an area of study worthy of their time.

The book also includes material at a level (and in a quantity) suitable for a control specialist course emphasizing design. Such a specialist course would normally be elective rather than required, but could be either a "first" or "second" control course. Our course is used as a senior elective by undergraduates and as a graduate course by beginning graduate students. For graduate students coming from our undergraduate program, this would be a second course; however, graduate students from "outside" might take it as their first control course. Thus introductory material such as that in this section is still appropriate, though it might be left for background reading rather than class discussion. Finally, the text is intended to be useful for those practicing engineers whose academic training did not include control studies but who encounter assignments that require self-study of specific topics in the field. This group of readers is, of course, brought to the text by the greatest possible incentive, a current and pressing practical need, and thus the motivational aspect of this chapter is of secondary significance to them.

I now wish to justify both required and elective courses in control by demonstrating the widespread and significant impact of control concepts on many aspects of engineering, at the same time laying the foundation for the specific technical developments that come later in the text. I will show that all types of engineered products and services are tending to depend more and more on associated control systems for their optimum functioning. In contrast with earlier years, these control systems are increasingly considered to be an integral part of the overall system rather than afterthought "add-ons." Although the "invention" of such overall systems does not necessarily require the talents of a control specialist, it is unlikely to be created by someone totally ignorant of control principles. That is, there needs to be a melding of control basics with the engineering lore of the specific product area. Recognition of this need is the basis of my conviction that required courses in control are easily justified in today's curricula.

Although the above argument is sufficient, even further benefits accrue when a required control course is instituted. Students completing such a course will be in a good position to decide whether their talents and interests lie in this area, making the choice whether to continue with an elective course more rational, and allowing the elective course to be of sufficient breadth and depth to develop a practical level of design competence. When control courses are taught with a heavy hardware emphasis (as this text encourages), they become particularly good capstone design courses in a curriculum since they require the application and integration of many previously developed subject areas such as applied mathematics, computer-aided design, electronics, system dynamics, hydraulics, pneumatics, measurement systems, and the like. Finally, some of the techniques taught in control courses turn out to have important application in non-control-contexts.[1] For example, the design of hydrostatic fluid bearings is not conventionally considered to be a part of control, yet the dynamic instabilities of such bearings are studied with the same techniques developed for stability considerations in control system courses. A similar situation exists for machine tool chatter, combustion oscillations, and, in fact, all self-excited oscillatory phenomena.

We have up to this point been using the words *control* and *control system* as if the reader perfectly understood their meaning. Although individual readers may indeed have rather specific meanings in mind, I cannot leave such fundamental issues to chance and now proceed to develop some definitions systematically. It may be helpful to categorize some of the many applications of control systems according to the type of device being controlled, one possible listing being as follows.

Energy Sources Nuclear and fossil-fueled steam power plants, internal combustion engines and turbines, hydroelectric power plants, wind turbines, solar power plants.

Materials Production Facilities Open-hearth furnaces, rolling mills, petrochemical plants, cement plants, lumber mills.

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[1]K. N. Chen et al., A System Approach to the Dynamic Characteristics of Hydrostatic Bearings Used on Machine Tools, *Int. J. Mach Tool Des. Res.* Vol. 20, pp. 287–297; S. A. Jaliwala et al., An Application of Control Theory to Optimize Automotive Cam Design, ASME Paper 80-DGP-13, 1980.

Vehicles and Transport Systems Railways, aircraft, spacecraft, ships, automobiles, pipelines, conveyors, elevators.

Construction Equipment Excavators, graders, tile-laying machines, tunneling machines, cranes.

Manufacturing Equipment Machine tools, industrial robots, foundry equipment, forging and stamping presses, assembly machines, automatic test equipment, plastic molding presses, textile machinery, packaging machines, heating, ventilating, and air conditioning system.

Agricultural Equipment Tillage, planting, and cultivation machines, spraying equipment, harvesters, environmental control equipment.

Consumer Goods, Appliances Refrigerators, washing machines, ranges, water softeners, furnaces, mixers and blenders, cameras, sewing machines.

Computers and Peripherals Analog, digital, and hybrid computers, tape drives, disk drives, printers, card and tape punches, plotters.

Weapon Systems Missiles, launchers, tracking systems, submarines, torpedoes, hydrofoil craft, tanks.

Communications Videotape recorders/reproducers, copying machines, printing presses.

Measurement Systems Servomanometers, hot-wire anemometers, servo accelerometers, pen, optical, thermal, and electrostatic recorders.

Medical Equipment Heart and lung machines, dialysis machines, pacemakers, artificial hearts, prosthetic devices.

This list is not exhaustive, yet it seems to show that "everything" needs a control system. Our definition of control is at this point intentionally broad enough to encourage exactly such a viewpoint. Section 1.2 will try to bring some focus to this somewhat diffuse picture by separating control systems into functional types.

In each of the above-listed applications there is some "device to be controlled" which often has a use aside from any associated control system. In control parlance this entity is given various names: *process, plant,* and *controlled system* being perhaps the most common, my preference being *process*. As seen in Fig. 1.1, process *inputs* are flows of energy and/or material that cause the process to react or respond. Mathematically, inputs are considered to be known or assumed and are classified into *manipulated inputs* (subject to our control) and *disturbance inputs* (undesirable and unavoidable effects beyond our control). If a process needs a control system it may be because of the presence of significant disturbance inputs. If we decide to implement a control system we must be sufficiently clever in our management of the manipulated inputs so as to counteract the effects of the disturbances. This implies that there are some *response variables* associated with the process, which we require to behave in some specified fashion. At this point we note that to cause a desired process response,