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# AUTOMATIC CONTROL SYSTEMS

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# Preface

Two kinds of automatic control systems—academic and real—exist, and they have almost nothing in common.

Academic control systems have ignored almost completely the physical limitations on the performance capabilities of actual systems and have concentrated largely on the application of "sophisticated" mathematical methods for analyzing the stability characteristics of complicated systems of differential equations that have practically nothing to do with any real problem. The unfortunate consequence of these misdirected efforts is that most of what has been taught under the guise of control systems is at best irrelevant to real control systems; in fact, much of it has been misleading to such an extent that not only was the optimum control algorithm missed, but more practical problems have been created than have been solved.

In the summer of 1969 the author had the good fortune to be confronted with the necessity of upgrading the performance capability of an automatic control system, originally barely stable and easily upset, to a level of accuracy and stability previously considered impossible. The immediate problem was solved by December 1970 with the installation of the prototype Pseudo-Derivative-Feedback (PDF) controller at the Lawrence Livermore Laboratory of the University of California, Livermore. Although the controller itself is a significant advancement in control system technology, of even greater importance is that during the process of working "hands on" with the hardware of the complex real system and trying to apply the knowledge and understanding gained over many years of academic endeavor—as both a student and a teacher—the author came to see clearly the distinction between academic and real systems.

In the intervening years the author has evolved a basically new philosophy related to automatic control systems, around three fundamental observations:

1. A control system is always concerned with supplying energy to something called the controlled system.
2. The response capabilities of the system are ultimately limited by the ability of what is called the final control elements to deliver energy to the controlled system.
3. The basic method for avoiding all operational problems with real automatic control systems is to insure that the final control elements are never asked to deliver energy at a rate faster than they can.

Stability is, of course, an absolute requirement. But, if one follows the philosophy, principles, and methods presented in this book, insuring stability will be found to be almost a trivial matter where real, or engineering, automatic control systems are concerned. In fact, all control systems are nonlinear—to widely varying degrees. Most serious operating problems with real systems occur when a system that has been considered to be linear is driven into a region of highly nonlinear operation. An engineer dares not let himself fall into the academic trap of considering linear and nonlinear control systems as if they were distinct, neatly separated subjects. In this book systems are classified primarily on the basis of the order of the controlled system. The effect of choosing a particular control algorithm on the performance characteristics of the control system is considered in turn for zeroth-, first-, second-, and, finally, *n*th-order controlled systems. Nonlinear and linear control algorithms are considered as they are applicable, with major emphasis on the relative merits of the various algorithms in terms of system performance, rather than on mathematical niceties. The effects of nonlinearities in the controlled systems are also considered, as applicable.

In practically all cases, the control engineer can make no changes in the controlled system. His procedure, then, breaks down into three major steps: (1) to select final control elements that can deliver energy to the controlled system at a rate sufficient to make it respond as desired, (2) to specify the optimum control algorithm that can make the most efficient use of the energy-delivering capability of the final control elements while providing the best possible performance characteristics for the control system, and (3) to tune the controller to fulfill the goals set forth in step 2 above.

The ultimate purpose of this book is to develop the theory and explain the implementation of the optimum controller for *all* controlled systems, the Super Intelligent Pseudo-Derivative-Feedback (PDF) controller. Considerable attention is given to tuning the controller; but, although the significance of the finite limitations on their energy-delivering capability is constantly kept in mind, almost no attention is given to selecting the best final control elements for a given situation.

For industrial purposes this book is complete, in that it contains all of the theory, mathematics, and principles for implementation necessary for optimal control of any and all controlled systems. In fact, two figures and one equation in Chapter 6 contain all the basic information anyone with even minimal background in automatic control systems needs to understand in order to design and operate systems for all possible situations with absolute confidence that their performance will be better than can be provided by any other approach. Except for the units and physical parameters with which one must work and the details of components most suitable in a given situation, trying to assign a control system to a specific field of engineering, such as mechanical, chemical, or electrical, is a waste of time. To paraphrase Gertrude Stein, a control system is a control system is a control system.

For educational purposes the book is also essentially complete. *But*, as has been made clear to the author during the past six years, *old ideas die hard*, and communicating with engineers and operators already in the field is at best difficult and at times almost impossible without some understanding of the obsolete and/or irrelevant concepts, mathematics, methods, and terminology related to traditional systems. Consequently, for some years to come it will be necessary to cover to a reasonable depth in the classroom or in the laboratory traditional methods of stability analysis, such as the root-locus and conformal mapping, and traditional control algorithms, such as proportional plus integral and PID (proportional plus integral plus error-rate). In his own teaching, the author handles this requirement by telling each class at the beginning of the term that about 60 percent of the material to be covered will be significant in relation to the design of automatic control systems and the remaining 40 percent will be irrelevant and misleading, when not actually wrong.

Readers familiar with existing books on control systems will quickly note the absence of any reference to Laplace transforms. The reason is simple: with respect to control systems, the Laplace transformation is only another method for solving a limited class of differential equations. As will be seen, all the information that can be obtained by the use of Laplace transforms can be obtained just as readily and with much greater insight into the real problem by using ordinary differential equations and the complex rotating vector representation for sinusoidally varying quantities. The apparent justifications for past use of Laplace transforms were (a) it was a good way to keep students occupied in an intellectually stimulating way for quite a period of time, and (b) it established a jargon for the fraternity while effectively sophisticating—in the true dictionary definition of the word—a basically simple field of study into one that was awe-inspiring to the unknowing. To interpose the requirement of learning a new method for solving differential equations between the equations and an understanding of what is happening is inexcusable.

For a course in automatic control systems to be more than a challenging exercise in mathematical manipulations of dubious academic value, the maximum possible contact with real components and systems must be provided in the laboratory. In the author's laboratory, small (10-amplifier) instructional-type analog computers are used extensively as (a) sources of operational amplifiers for building up the control algorithms for use in conjunction with real final control elements and real controlled systems, and (b) sources of building blocks for simulating complete control systems. The major thrust of the laboratory effort is to let the students prove to themselves the validity of the statements in this book and to discover the serious limitations of all traditional control algorithms.

Work in the laboratory is by far the most important part of the course taught by the author, and the time is split roughly into three equal parts paralleling the structure of this book: the control of a zeroth-order, a first-order, and a second-order controlled system. A small dc amplifier with miserable performance characteristics (i.e., highly nonlinear and with relatively high output impedance) serves as a beautiful example of final control elements that do not perform satisfactorily as an open-loop system and, therefore, should be treated as a zeroth-order controlled system in an automatic control system. In this case the control algorithms considered are proportional and integral. Computer simulation of the amplifier and operation with the real amplifier under load are both performed. The improvement in performance capabilities when Intelligent integral control is used is rather impressive—the amplifier then has zero output impedance (at zero frequency) and as good a frequency response as is possible with proportional control *and real components.*

A small permanent-magnet dc motor with a gear reduction unit and a potentiometer is found to approximate closely the basic first-order controlled system when the controlled variable is the angular position and the measure of the rate of energy delivery is the voltage supplied to the motor. In addition, this system introduces students to the serious problems resulting from the ever-present Coulomb damping and backlash in gear trains in real systems. All investigations in this case are done with the real controlled system, and proportional, proportional plus integral, and PDF control algorithms are used.

Because of lack of class time and the absence of a reasonable approximation to the basic second-order controlled system, simulation on the analog computer is used exclusively to investigate the relative performance of systems with the following control algorithms: proportional plus error-rate, proportional plus derivative-feedback, proportional plus integral plus error-rate (PID), proportional plus integral plus derivative-feedback, and PDF control.

The reader will notice the presence of very few problems and the almost complete absence of the types of problems found in other texts. The reason is simply that since the development presented in this text leads to a single equation and two figures in Chapter 6 that effectively cover all possible situations, there is no justification for making students play the usual academic games with block diagrams of hypothetical systems that are unrelated to reality. The slight improvement in manipulative skills is far outweighed by the ill effects of the forced separation from the real world. In addition, simple exercises in plugging numbers into the equations in the text cannot be justified, because real systems, which are not so contrived as to be trivial, cannot be truly represented by transfer functions—they can only be approximated by such functions. To the maximum extent possible, students should be faced with this fact of life and its consequences in the process of working with real components and systems in the laboratory. Of particular importance will be the discovery that PDF control is extremely tolerant of even gross approximations and, therefore, our inability to model the system exactly will be of relatively little consequence in a real situation.

The author assigns no homework in his course. The students are responsible for three laboratory reports, each covering the control of one of the basic controlled systems; and there is a final examination that has as its goal separating those who really understand what a control system is from those who are primarily good at following instructions. The course is an elective, and all of our own students have already been introduced to automatic control systems and PDF control as a part of a required course in dynamics of machinery.