Complex Digital Control Systems

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VNR VAN NOSTRAND REINHOLD COMPANY
NEW YORK CINCINNATI ATLANTA DALLAS SAN FRANCISCO
LONDON TORONTO MELBOURNE

Van Nostrand Reinhold Company Regional Offices:
New York Cincinnati Atlanta Dallas San Francisco

Van Nostrand Reinhold Company International Offices:
London Toronto Melbourne

Library of Congress Catalog Card Number: 78-26041
ISBN: 0-442-20110-9

Manufactured in the United States of America

Published by Van Nostrand Reinhold Company
135 West 50th Street, New York, N.Y. 10020

Published simultaneously in Canada by Van Nostrand Reinhold Ltd.

15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

Library of Congress Cataloging in Publication Data

Rao, Guthikonda V
Complex digital control systems.

Bibliography: p. 496
Includes index.
1. Digital control systems. I. Title.
TJ216.R36 629.8'3 78-26041
ISBN 0-442-20110-9

To
my sisters, Kanakrathnam and Dr. Subaima,
and grandpa Nandam Virswami

Preface

This tutorial control engineering book on the complex sampled-data/digital control systems, presently used in modern industrial applications, is primarily concerned with the study and exposition of the correlation between theory and technology at the juncture of the latest computerized industrial revolution. These applications belong to the category of broadcast high-quality quadruplex color videotape recorders, missile attitude control, automatic pilot, high-precision radar, TT&C (tracking, telemetry, and control of synchronous and interplanetary satellites), simulation and signal processing, manufacturing plant-automation, high-precision numerical machine control, etc. Automation, computation and control, and TDM (time-division multiplex) data storage and real-time data communications via synchronous satellites, fiber-optic optical communications, and microwave links are, all-in-all, the order of the day. There is a proliferation in developments in theory, components, and systems, and the book modestly aims at briefly acquainting the reader with the latest trends in the implementation of the modern control systems. A sophisticated multiloop interacting sampled-data control system is comprehensively analyzed at length to illustrate the extent of complexity encountered in some of the major applications in the field.

A brief survey of the theoretical aspects of analysis and synthesis in automatic control is presented in Chapter 1 under four different classifications for both continuous and digital control systems. (Most systems are actually hybrid in these respects, and *digital filters* are exclusively used for compensation in digital control systems.) These classifications are:

1. The frequency response techniques.
2. The statistical design technique.
3. Modern control theory with state-space techniques.
4. Miscellaneous techniques such as the extension of frequency response methods to nonlinear systems as quasi-linear approximations, graphical phase-plane tra-

jectories for display of transient response in low-order linear/nonlinear systems, Lyapounov's Second or Direct Method, and general ac carrier servo systems.

Chapter 2 is a comprehensive introduction to the complex digital control system referred to in Chapter 3. Actual worked-out examples in Chapter 3 illustrate the method of application of the various theoretical concepts in each classification to simple mathematical models, as far as the transfer functions or pulse-transfer functions go. Realistic, hard-to-derive, highly complex transfer functions are generally beyond practical consideration in the case of the more complex, multivariable physical control systems using the latest components. The simplified mathematical models used for analysis may be therefore more pertinent to the various subsystems or grossly approximated subloops in a modern control-system complex. The manner in which these examples are explained, as an illustration of the theoretical concept involved in each technique, is conducive to a rapid and meaningful understanding of the subject to the undergraduate or graduate student and the practical electrical engineer, because a physical image of a substantial control element with a certain function is immediately available as a reference in the complex sampled-data control system chosen for exposition in Chapters 2 and 4. It is generally anticipated in this context that the student and the practicing control engineer will have had some elementary knowledge in Laplace and Z-transforms, and differential and difference equations. At the same time, some insight into the heuristic methods normally resorted to in the laboratory for the successful implementation of these complex sampled-data control systems is provided by some of the theoretical examples chosen in this method of approach.

Most textbooks in the control engineering field usually devote extensive space to the peripheral mathematics related to the theoretical concepts, and give less importance to the applicability of the concept to some physical system, which is invariably nonlinear and thus unduly complex to solve for the *necessary and sufficient conditions of stability*. Some textbooks specialize and concentrate on a rigorous treatment of a few methods for a strictly limited range of applications. This control engineering book, on the other hand, attempts to introduce in principle the status of practically every classification of control technique and its applicability at the present time. It will therefore serve as an introduction to the comparative study of the various techniques, past and present. It will provide an overall perspective to establish guidelines by the examples chosen for a particular technique. Without this all-around theoretical orientation, the engineer working on a heuristic basis may perhaps waste time and effort on unrealizable objectives in his or her particular application. The latest achievements—in both theory and practice—in modern control systems should mutually contribute to one another by regular intercommunication and coordination as far as possible, instead of drifting further apart.

Chapter 4 introduces to the student and exponents of theory a typical example of a successful, modern, high-precision digital control system-complex, and its mostly unsolvable stability criterions as far as the theory is concerned. The technological sophistication of the control system and the closely related system electronics expose students of control theory to the physical reality of the control system, and give them a substantial impression of the elaborate electronics circuit design and signal processing involved in each and every feedback loop in the three interdependent sampled-data control systems of a high-quality quadruplex color videotape recorder. The *measure-and-optimize* technique introduced by the author for the stage-by-stage and loop-by-loop development of the interacting nonlinear digital control systems in the laboratory on a heuristic basis is considered appropriate for the following reasons. The development and design of the associated digital controllers are not along the lines of conventional *trial-and-error* technique usually employed in feedback control systems for the analysis and synthesis of suitable compensating networks to meet the requirements of parameters such as stability, bandwidth, noise immunity and gain. The measure-and-optimize technique is more in line with the developments and trends in the state-space techniques of modern control theory, where the measured variables through the various stages of the system for desired coefficients of the system equation, and the optimization of the system parameters for the desired performance-index share a prominent role. As an incidental development, a comprehensive, up-to-date background is presented on the technology of compatible color television since magnetic tape recording and color television are inseparable in modern telecasting.

The technological exposition of the system chosen is profusely illustrated with detailed block diagrams from both electronics and control engineering aspects. The theoretical representation and interpretation of the complex interacting digital control systems of the quadruplex color videotape recorder will provide a direct channel of communication between theory and practice to avoid possible controversy. In high-precision nonlinear control systems, the loop-by-loop compression of the performance-index (the limit-cycle or residual phase-jitter of a nonlinear control system) on an automatic adaptive basis, by interloop transfer from the lower to the higher rates of sampling, may be perhaps a revealing example for introduction in a control engineering textbook. With the staggered higher rates of sampling used in the recorder, the system organizes itself toward self-optimization in terms of nanosecond control-timing patterns in arriving at the final result, viz., the reproduction of true color from videotape within an undetectable $\pm 2.5°$ phase-jitter at the color-subcarrier frequency of 3.579545 MHz in approximately 2 sec when the start push-button is pressed. The performance-index is of course entirely beyond the scope of a continuous feedback control system; this is how the modern digital control systems have revolutionized the accomplishments in the control field as far as the accuracy is concerned.

Along with the latest revolution of the silicon monolithic large-scale integration in microelectronics, complex digital control systems are just about to take a new turn altogether. In view of this timely development, Chapter 5 is devoted to the application of microprocessors and solid-state RAM and ROM memories to digital control systems. By employing auxiliary BIFET and BIMOS analog-to-digital and digital-to-analog LSI converter chips (built-in or external), the low-cost microcomputers are all set to play a major role, in conjunction with LSI digital filters, in simplifying the processing of present and future digital control systems as an alternative approach (and in displacing some of the former techniques).

Three appendixes, on the subjects of the local-oscillator frequency synthesis, the high-speed phase-lock loop, and some basic concepts of feedback control systems, present a useful supplement to the subject under consideration. The last two appendixes are incidental to the subject of the book.

The author extends his sincere appreciation to professor Cornelius N. Weygandt of the University of Pennsylvania and A. C. Luther, Jr., Chief Engineer, Broadcast & Communications Division, Radio Corporation of America, Camden, New Jersey for their continuous interest and encouragement during the early stage of this project. Thanks to Maxine Moore of AMECOM (Litton Systems, Inc.) and Margaret Pitchalonis of the Moore School of Electrical Engineering for typing the manuscript in record time. Grateful acknowledgments are due to the many authors who originally published the information (which is summarized in Chapters 1 and 5) in the voluminous literature on the subjects surveyed. The bibliography gives a partial list of these authors and their works.

The author considers himself fortunate to have been a member of the RCA team responsible for the development and design of the *first* broadcast solid-state quadruplex color videotape recorder in the world market.

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Introduction

The author admires the influence of students, control engineers, and control theorists (of a diversity of backgrounds in physical sciences and humanities) who exult in open, enlightened, tolerant, flexible, and harmonious communication with one another. In the theoretical and technological context of the book, the author understands that validated theory and *de facto* successful technological practice—via short-term heuristic and/or long-term computer simulation techniques—contribute to one another to assure optimal results when sheer complexity is encountered in systems.

The 10-billion neuron masterpiece of evolution, the human brain, and its neural communications supernetwork and the physiological glandular hormones and enzymes, form the most complex bioelectrochemical digital feedback control system in nature. As a parallel state-of-the-art achievement, 1 to 10 million functional building blocks of microelectronics will soon be incorporated on a minute chip as a result of creative research and development in modern science and technology. High-technology very-large-scale integration (VLSI) currently fabricates 100,000 functions on a silicon monolithic microcomputer chip!

The free individual's self-realization via persistent experimentation, that the brain-complex can be self-controlled and optimized in performance (or behavior) by positive constructive education and training via audio and visual aids and hence by strength of character, is the vital step toward achieving long-term stability in thought and/or action, as a precondition to inner psychological tranquility. Self-discipline with a broad perspective (as opposed to excesses of gain or unrestrained greed) is a simulation equivalent to the negative-feedback control systems of a stable and effective broad-band system organization. In particular, the unpredictable instigator of problems is the addictive life-style of indulging in drug- and alcohol-induced "highs" that intermittently interfere with the normal gain and sensitivity of the metabolism, which is both involuntarily and voluntarily (through learning and/or iterative programming) controlled by complex and fragile bioelectrochemical processes in the system-architecture of the brain. It is synonymous with disturbing the most important parameter "gain" of an otherwise optimally stable combined analog and digital feedback control system.

Constructive guidelines, based on an intelligent and tenacious effort along the *automatic* stabilized patterns in the brain and its network, merge to insure survivability, health, and happiness of the optimistic, secure individual in a sociological environment for ultimately maintaining peace on an expanding global scale. Peace, as a close parallel to stability in a nonlinear control system, is a continually converging process from a collective conglomerate made up of self-disciplined individuals in the body politic. "Blessed are the peacemakers" who righteously strive for the emergence and establishment of unity of purpose in life amid natural diversity of backgrounds. "They shall be called the children of God" (or, in classic Sanskrit, the *brahmanas*). As far as the memory and development of the cerebral cortex are concerned, there is no virtue that supersedes the acquisition of a broad spectrum of constructive knowledge that enhances a well-adjusted day-to-day participation of the individual in a harmonious community.

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