Applications of Adaptive Control

Edited by

Kumpati S. Narendra
Richard V. Monopoli

TP273.2
N1
8264517
E8264517
TP27-53
A.552
1979

APPLICATIONS OF ADAPTIVE CONTROL

edited by

Kumpati S. Narendra
Department of Engineering and Applied Science
Yale University
New Haven, Connecticut

Richard V. Monopoli
Electrical and Computer Engineering Department
University of Massachusetts
Amherst, Massachusetts

1980
ACADEMIC PRESS
A Subsidiary of Harcourt Brace Jovanovich, Publishers
New York London Toronto Sydney San Francisco

COPYRIGHT © 1980, BY ACADEMIC PRESS, INC.
ALL RIGHTS RESERVED.
NO PART OF THIS PUBLICATION MAY BE REPRODUCED OR
TRANSMITTED IN ANY FORM OR BY ANY MEANS, ELECTRONIC
OR MECHANICAL, INCLUDING PHOTOCOPY, RECORDING, OR ANY
INFORMATION STORAGE AND RETRIEVAL SYSTEM, WITHOUT
PERMISSION IN WRITING FROM THE PUBLISHER.

ACADEMIC PRESS, INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS, INC. (LONDON) LTD.
24/28 Oval Road, London NW1 7DX

Library of Congress Cataloging in Publication Data

International Workshop on Applications of Adaptive
Control, Yale University, 1979.
Applications of adaptive control.

1. Adaptive control systems—Congresses. I. Narendra, Kumpati S. II. Monopoli, Richard Vito,
Date III. Title.
TJ217.I59 1979 629.8′36 80-18879
ISBN 0-12-514060-6

PRINTED IN THE UNITED STATES OF AMERICA

80 81 82 83 9 8 7 6 5 4 3 2 1

Applications of Adaptive Control

ACADEMIC PRESS RAPID MANUSCRIPT REPRODUCTION

Papers included in this book were presented at
the *International Workshop on Applications of Adaptive Control*
held at Yale University, August 23–25, 1979.

此为试读，需要完整PDF请访问：www.ertongbook.com

Contributors

Numbers in parentheses indicate the pages on which the authors' contributions begin.

K. J. Åström (1), Department of Automatic Control, Lund Institute of Technology, Lund Sweden

Mark J. Balas, (313), Electrical and Systems Engineering Department, Rensselaer Polytechnic Institute, Troy, New York

Pierre R. Bélanger (345), Department of Electrical Engineering, McGill University, Montreal, Quebec, Canada

R. H. Borcherts (491), Engineering and Research Staff, Ford Motor Company, Dearborn, Michigan

Z. Csaszar (367), Research Group for Automation Control, Research and Design Institute for Silicate Industry, Budapest, Hungary

N. Czeiner (367), Research Group for Automation Control, Research and Design Institute for Silicate Industry, Budapest, Hungary

John S. Eterno (193), Scientific Systems, Inc., Cambridge, Massachusetts

A. Feher (367), Research Group for Automation Control, Research and Design Institute for Silicate Industry, Budapest, Hungary

D. G. Fisher (379), Department of Chemical Engineering, University of Alberta, Edmonton, Alberta, Canada

Sadashiva S. Godbole (193), The Babcock and Wilcox Company, Lynchburg Research Center, Lynchburg, Virginia

R. L. Gutmann (423), Boeing Company, Seattle, Washington

R. Haber (367), Department of Atuomation, Technical University of Budapest, Hungary

S. I. Haque (397), Intermetrics, Inc., Cambridge, Massachusetts

J. Hetthéssy (367), Department of Automation, Technical University of Budapest, Hungary

H. G. Hopkins (491), Engineering and Research Staff, Ford Motor Company, Dearborn, Michigan

E. Irving (221), Automatic Control Division, Direction des Etudes et Recherches, Electricité de France, Clamart, France

C. Richard Johnson, Jr. (313), Department of Electrical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia

R. M. Johnstone (379), Department of Chemical Engineering, University of Alberta, Edmonton, Alberta, Canada

L. Keviczky (367), Department of Automation, Technical University of Budapest, Hungary

A. Kovács (367), Department of Automation, Technical University of Budapest, Hungary

Gerhard Kreisselmeier (269), DFVLR-Institut fuer Dynamik der Flugsysteme, Oberpfaffenhofen, Federal Republic of Germany

Yuan-Hao Lin (69), Department of Engineering and Applied Science, Yale University, New Haven, Connecticut

Raman K. Mehra (193), Scientific Systems, Inc., Cambridge, Massachusetts

R. V. Monopoli (397, 423), Department of Electrical and Computer Engineering, University of Massachusetts, Amherst, Massachusetts

R. L. Morris[1] (453), Carnegie Institute of Technology, Carnegie-Mellon University, Pittsburgh, Pennsylvania

Kumpati S. Narendra (69), Department of Engineering and Applied Science, Yale University, New Haven, Connecticut

C. P. Neuman (453), Carnegie Institute of Technology, Carnegie-Mellon University, Pittsburgh, Pennsylvania

N. L. Owsley (131), Naval Underwater Systems Center, New London, Connecticut

E. G. Rynaski (245), Advanced Technology Center, Calspan Corporation, Buffalo, New York

E. H. Satorius[2] (165), Naval Ocean Systems Center, San Diego, California

Chr. Schmid (509), Department of Electrical Engineering, Ruhr-University Bochum, Germany

S. L. Shah (379), Department of Chemical Engineering, University of Alberta, Edmonton, Alberta, Canada

M. J. Shensa (165), Hydrotronics, Inc., San Diego, California

Gunter Stein (291), Honeywell Systems and Research Center and Massachusetts Institute of Technology, Cambridge, Massachusetts

A. Turi (367), Research Group for Automation Control, Research and Design Institute for Silicate Industry, Budapest, Hungary

H. Unbehauen (509), Department of Electrical Engineering, Ruhr-University Bochum, Germany

I. Vajk (367), Department of Automation, Technical University of Budapest, Hungary

R. Van Allen (423), USAF, Kirtland Air Force Base, Albuquerque, New Mexico

R. Wan (379), Department of Chemical Engineering, University of Alberta, Edmonton, Alberta, Canada

[1]Present address: Control Systems Department, Scientific Research Laboratory, Ford Motor Company, Dearborn, Michigan

[2]Present address: Dynamics Technology, Inc., Torrance, California

Preface

The adaptive control of systems has been a dream of control system theorists and practitioners for at least a quarter of a century. It arose from a desire and need for improved performance of increasingly complex engineering systems with large uncertainties. This is especially important in systems with many unknown parameters that are changing with time. Roughly speaking, an adaptive system is one that continually monitors these changes and adjusts its control parameters automatically to maintain good performance. In mathematical terms, such a system is generally a nonlinear nonautonomous dynamic system. Hence, adaptive systems can be considered as a class of control systems that have been made deliberately nonlinear.

We have engaged in many hours of discussion throughout the past decade as to why the promise of adaptive control has been so slow in coming to fruition. From these discussions several key reasons emerged. First, early schemes for adaptive control, though ingeneous, did not guarantee global stability of the adaptive system. Those who tried to apply these schemes either had great difficulty in showing even local stability of the resulting control systems and, therefore, were reluctant to use them, or, worse, implemented them on systems with unfortunate, and perhaps even disastrous, results. Second, globally stable adaptive control algorithms have been developed only recently, and these are not yet known to most practitioners. Third, researchers in adaptive control, for the most part, are not well versed in the potential applications of the theory. Finally, the technology of the past decade was not adequate to the task.

With recent advances in microprocessor technology, it has become feasible to implement adaptive algorithms efficiently in real time at reasonable cost. This fact together with recent developments in theory and the keen interest shown by industry in adaptive control prompted us to organize the Workshop on Applications of Adaptive Control, which was held in August 1979 at Yale University. Of the one hundred participants at the workshop, approximately sixty percent were potential users of adaptive control from industry and forty percent were researchers from universities. The objectives of the workshop were to :

(i) make potential users aware of recent advances in control theory;
(ii) make theorists aware of the potential applications and especially aspects of applications which do not satisfy the assumptions being made by the theorists;
(iii) determine if the reasons for the concept of adaptive control falling into disfavor in the flight control community are still valid.

Workshop participants agree that the objectives were met reasonably well. This motivated us to share, via this book, the workshop experience with a broader audience. Papers included here represent a selection of those presented at the workshop and do illustrate that it is becoming increasingly realistic to consider using adaptive control in many practical problems.

The first two papers, "Self-tuning regulators—design principles and applications" by Åström and "Design of stable model reference adaptive controllers" by Narendra and Lin are tutorials that bring together important recent results in two of the most studied approaches to adaptive control—self-tuning regulators (STR) and model reference adaptive control (MRAC). In addition to presenting a clear exposition of the theory of STR and its relationship to MRAC, Åström also gives numerous examples of successful applications. The importance of error models in the stability analysis of MRAC is stressed in the paper by Narendra and Lin, and it is shown that the different independent proofs of stability given recently are equivalent. Although STR and MRAC were developed separately by different research groups, current research is beginning to reveal the similarities between these two approaches.

The section on signal processing has papers contributed by N. L. Owsley and E. H. Satorius and M. J. Shensa. Though not dealing with adaptive control per se, it was felt essential to include these papers because algorithms used for adaptive signal processing are very similar to those used in adaptive control. For this reason, control theorists and practitioners can benefit from an understanding of work in this area.

In the section on power systems, the paper by R. K. Mehra and J. S. Eterno presents a good description of the types of power systems problems that could benefit from application of adaptive control. Electricité du France has had a research and development effort in adaptive controls for several years now, and E. Irving describes how they are attempting to apply adaptive control algorithms for controlling large electric generators.

Adaptive control in aircraft systems is discussed in the papers by E. G. Rynaski, G. Kreisselmeier, G. Stein, and M. J. Balas and C. R. Johnson. G. Stein makes the point that many flight control problems are solvable by gain scheduling based on data from air sensors. However, he does point out some areas in flight control where an adaptive controller may be necessary. In his paper, Rynaski describes how adaptive control fell into disfavor in the flight control community, and points out that a residual negative bias still exists. He also describes the utility of the model following approach in flight control, where, in the examples he considers, the adaptive feature is not required. Kreisselmeier dicusses the desirability of eliminating the cost of air data sensors in less-sophisticated flight control systems. This may be made possible by use of adaptive control techniques. In the paper by Balas and Johnson, adaptive control of distributed parameter systems is considered. The problem they address, control of large structures in space, is one where adaptive control may be the only method to deal with ignorance of system structure, order, and parameters.

The set of papers on process control includes applications not only to chemical processes, but to electromechanical systems as well. P. Bélanger, in his paper "Adaptive control in the process industries" offers a number of interesting reasons as to why adaptive control, so far, seems to have found wider applicability in the area of chemical process control than in electromechanical systems. One of these, which strikes us as particularly important, is the fact that in process control the dynamics are almost always well damped, whereas electromechanical systems often have several highly underdamped modes usually related to bending or vibration. Also, parameters of electromechanical systems can change rapidly, whereas changes in many chemical processes take place slowly enough to allow time for parameter identification to take place. Haber *et al.*, in their paper on "Adaptive level control in a glass furnace" show experimental results which clearly demonstrate the improvement possible with adaptive control. Their self-tuning regulator ensures a much smaller variance of the output around the reference value than does the traditional controller. Johnstone *et al.* show that model reference adaptive control applied to liquid level control is robust and has superior tracking and regulation properties as compared to the classical PI control. It is important to note that their results were achieved in spite of the fact that their pilot plant had nonlinearities and rapid changes of parameters which were not covered by the theory. Haque and Monopoli, in "Discrete adaptive control of a radio telescope," show the effectiveness of the discrete model reference control algorithms in removing the undesirable effects of unknown Coloumb friction level and unknown system inertia. Three adaptive gains in the telescope control system resulted in a decrease of tracking error by a factor of two. Gutmann, Monopoli, and Van Allen show the potential for using model reference adaptive control to improve the pointing accuracy of a high power laser pointing and tracking system. In their paper, "Adaptive control of a laser pointing and tracking system: A feasibility study," it is pointed out that good results are obtainable even though the design is based on a dominant second order model of a sixth order plant. In "Classical control interpretation and design of microcomputer adaptive controllers," Neuman and Morris compare three classes of model reference adaptive controllers in a common framework from the viewpoint of microcomputer implementation. This is a particularly important contribution because of the blending of the latest technology and theory. Hopkins and Borcherts, in "Discrete time modelling of the torque response of a spark-ignited fuel-injected engine," give experimental results of a model reference identification technique on which to base control strategies generated by linear quadratic theory. In the paper "Application of adaptive systems in process control" by Unbehauen an excellent survey of successful applications of adaptive control in various process control industries is given. Also, Unbehauen makes the important point that further successful applications of adaptive control will depend on a close and continuous collaboration between control design engineers and researchers in adaptive control theory.

Sound theory provides the basis for good practice, even though in real world problems the assumptions made for theoretical analysis are almost never strictly satisfied. The applications given in this volume are no exceptions since, in one way or another, they fail to satisfy the assumptions that have to be made to prove theoretically global stability. However, they appear to be robust, and to achieve the desired objective of improved performance over nonadaptive systems. These successful applications provide motivation for researchers to re-examine current theories and develop new ones to explain their behavior. This continuing interaction between theory and practice should lead to systematic design procedures for adaptive control systems.

此为试读，需要完整PDF请访问：www.ertongbook.com

Acknowledgments

We wish to express out appreciation to all participants in the Workshop on Applications of Adaptive Control held in August 23- 25, 1979 at Yale University. Our special thanks go to Ben Peterson who attended to many of the details of organizing the workshop and to Ian Gemmell for his help in running it.

Papers appearing in this book were presented at the workshop, and we are grateful to the authors for their continued cooperation. Carol Phelps's assistance in making the final drawings is also very much appreciated.

It is a great pleasure to acknowledge the invaluable assistance provided by Jean Gemmell at every stage in the preparation of this book: in organizing the workshop, in the arrangement and typing of the final manuscript, and by her attention to many other details with her usual thoroughness. The publication of the book on schedule is due in large measure to her efforts.

8264517

Contents

Contributors vii
Preface ix
Acknowledgments xiii

TUTORIAL

Self-Tuning Regulators—Design Principles and Applications 1
K. J. Aström

Design of Stable Model Reference Adaptive Controllers 69
Kumpati S. Narendra and Yuan-Hao Lin

SIGNAL PROCESSING

An Overview of Optimum-Adaptive Control in Sonar Array Processing 131
N. L. Owsley

On the Application of Recursive Least Squares Methods to Adaptive Processing 165
E. H. Satorius and M. J. Shensa

POWER SYSTEMS

Adaptive Power Plant Control: Problems and Prospects 193
Raman K. Mehra, John S. Eterno, and Sadashiva S. Godbole

New Developments in Improving Power Network Stability with Adaptive Generator Control 221
E. Irving

AIRCRAFT SYSTEMS

Adaptive Control Application to Aircraft 245
E. G. Rynaski

Perspectives on the Application of Adaptive Control to Aircraft Systems 269
Gerhard Kreisselmeier

8264517

Adaptive Flight Control: A Pragmatic View 291
Gunter Stein
Toward Adaptive Control of Large Structures in Space 313
Mark J. Balas and C. Richard Johnson, Jr.

PROCESS CONTROL

Adaptive Control in the Process Industries 345
Pierre R. Bélanger
Adaptive Level Control in a Glass Furnace 367
R. Haber, J. Hetthéssy, L. Keviczky, I. Vajk, A. Kovács, Z. Csaszar, N. Czeiner, A. Feher, and A. Turi
Experimental Evaluation of Hyperstable Model Reference Adaptive Control 379
R. M. Johnstone, S. L. Shah, D. G. Fisher, and R. Wan
Discrete Adaptive Control of a Radio Telescope 397
S. I. Haque and R. V. Monopoli
Adaptive Control of a Laser Pointing and Tracking System: A Feasibility Study 423
R. L. Gutmann, R. V. Monopoli, and R. Van Allen
Classical Control Interpretation and Design of Microcomputer Adaptive Controllers 453
C. P. Neuman and R. L. Morris
Discrete Time Modelling of the Torque Response of a Spark-Ignited Fuel-Injected Engine 491
H. G. Hopkins and R. H. Borcherts
Application of Adaptive Systems in Process Control 509
H. Unbehauen and Chr. Schmid

SELF-TUNING REGULATORS - DESIGN PRINCIPLES AND APPLICATIONS[1]

K. J. Åström

Department of Automatic Control
Lund Institute of Technology
Lund, Sweden

The basic principles of self-tuning regulators are discussed. The regulators are motivated from the viewpoint of nonlinear stochastic control theory. Self-tuning regulators based on pole-zero placement, minimum variance control and linear quadratic gaussian control are described in a common framework. Relations between self-tuning regulators and model reference adaptive control are discussed. Applications to different industrial process control problems are described. Practical and theoretical issues of relevance to design of self-tuning regulators are also treated.

[1]This research was supported by the Swedish Board of Technical Development (STU).

Copyright © 1980 by Academic Press, Inc.
All rights of reproduction in any form reserved.
ISBN 0-12-514060-6

1. INTRODUCTION

The tuning problem is one reason for using adaptive control. It is a well-known fact that many processes can be regulated satisfactorily with PI or PID regulators. It is fairly easy to tune a PI regulator which only has two parameters to adjust. However, for an installation which has several hundred regulators it is a substantial task to keep all the regulators well tuned. A PID regulator which has three or four parameters is not always easy to tune, particularly if the process dynamics is slow. The derivative action is, therefore, frequently switched off in industrial controllers.

Since many control loops are not critical three term controllers will undoubtedly be used extensively in the future too. With an increasing demand for efficiency in the use of energy and raw material there are, however, an increasing number of control problems where it is reasonable to use regulators which are more complicated than PID regulators. Such regulators, which may include feedforward, state feedback, and observers, can often have more than 10 adjustable parameters. It is not possible to adjust so many parameters without a systematic procedure. The lack of a suitable tuning procedure is one reason why modern control theory has not been used more extensively.

One possibility to tune a regulator is to develop a mathematical model for the process, and its disturbances, and to derive the regulator parameters from some control design procedure. The appropriate mathematical models can be obtained from physical modeling or from system identification. The drawback with such a procedure is that it may be fairly time consuming, and that it requires personnel with skills in modeling, system identification, and control design. The self-tuning regulator can be regarded as a convenient way to combine system identification and control design. Its name does, in fact, derive from such applications.

One reason for using adaptive control is thus to avoid the tuning problem. Another motivation for using adaptive control is that the characteristics of the process and its disturbances may change with time. If the changes are not too rapid a properly designed self-tuning regulator may be used for continuous tuning to obtain close to optimal performance.

Adaptive control has been a challenge to control engineers for a long time [1]. Many different schemes have been proposed [2-4]. In spite of this, progress in the field has been comparatively slow. One reason for this is that adaptive systems are difficult to understand because they are inherently nonlinear. The field is also fairly immature as a scientific discipline. Many ideas that are basically the same are derived and presented using very different approaches. There is a wide divergence in notations. A fundamental conceptual framework is also lacking. Recently there has been an increased interest in adaptive control. One reason for this is the availability of microprocessors which make it possible to implement adaptive controllers conveniently and cheaply [5-7]. Another reason is the success of adaptive control in pilot installations in industry [8-16]. A third reason is that some progress has recently been made in the theory of adaptive control [17-23].

The purpose of this paper is to give an overview of self-tuning regulators, which is <u>one</u> approach to adaptive control. The focus will be on concepts, theory, and applications. The paper is organized as follows.

A brief review of nonlinear stochastic control theory is given in Section 2. This theory gives a conceptual framework and a general structure of an adaptive regulator with many interesting features. The regulator obtained from nonlinear stochastic control theory is, however, so complicated that it can only be computed numerically in almost trivial cases. To obtain something useful it is thus necessary to make approximations. Self-tuning

此为试读，需要完整PDF请访问： www.ertongbook.com