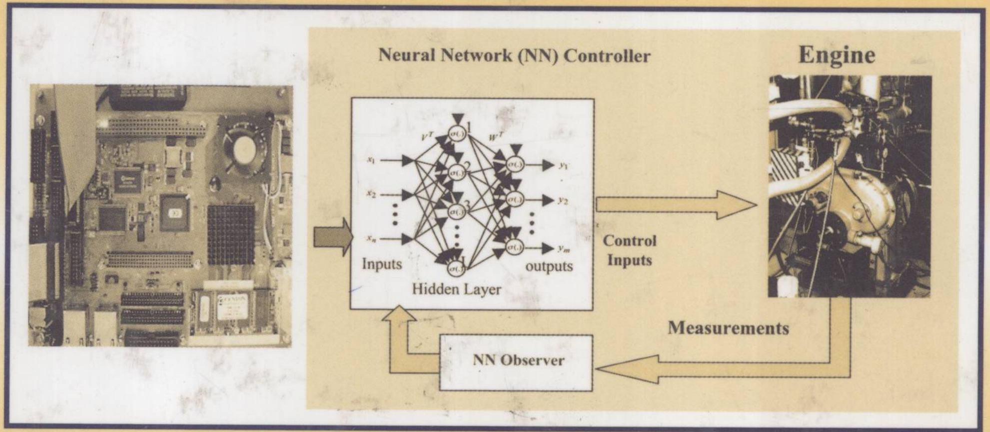
Control Engineering Series

Neural Network Control of Nonlinear Discrete-Time Systems



Jagannathan Sarangapani

CRC Taylor & Francis
Taylor & Francis Group

Neural Network Control of Nonlinear Discrete-Time Systems

Jagannathan Sarangapani
The University of Missouri
Rolla, Missouri

CRC Taylor & Francis
Taylor & Francis Group
Boca Raton London New York

CRC is an imprint of the Taylor & Francis Group,
an informa business

Published in 2006 by
CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8247-2677-4 (Hardcover)
International Standard Book Number-13: 978-0-8247-2677-5 (Hardcover)
Library of Congress Card Number 2005036368

Library of Congress Cataloging-in-Publication Data

Sarangapani, Jagannathan.
Neural network control of nonlinear discrete-time systems / Jagannathan Sarangapani.
p. cm. -- (Control engineering)
Includes bibliographical references and index.
ISBN 0-8247-2677-4 (978-0-8247-2677-5)
1. Automatic control. 2. Nonlinear control theory. 3. Neural networks (Computer science) 4. Discrete-time systems. I. Title. II. Series: Control engineering (Taylor & Francis)

TJ213.S117 2006
629.8'36--dc22

2005036368

informa
Taylor & Francis Group
is the Academic Division of Informa plc.

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Neural Network Control of Nonlinear Discrete-Time Systems

CONTROL ENGINEERING

A Series of Reference Books and Textbooks

1. Nonlinear Control of Electric Machinery, *Darren M. Dawson, Jun Hu, and Timothy C. Burg*
2. Computational Intelligence in Control Engineering, *Robert E. King*
3. Quantitative Feedback Theory: Fundamentals and Applications, *Constantine H. Houpis and Steven J. Rasmussen*
4. Self-Learning Control of Finite Markov Chains, *A. S. Poznyak, K. Najim, and E. Gómez-Ramírez*
5. Robust Control and Filtering for Time-Delay Systems, *Magdi S. Mahmoud*
6. Classical Feedback Control: With MATLAB®, *Boris J. Lurie and Paul J. Enright*
7. Optimal Control of Singularly Perturbed Linear Systems and Applications: High-Accuracy Techniques, *Zoran Gajif and Myo-Taeg Lim*
8. Engineering System Dynamics: A Unified Graph-Centered Approach, *Forbes T. Brown*
9. Advanced Process Identification and Control, *Enso Ikonen and Kaddour Najim*
10. Modern Control Engineering, *P. N. Paraskevopoulos*
11. Sliding Mode Control in Engineering, *edited by Wilfrid Perruquetti and Jean-Pierre Barbot*
12. Actuator Saturation Control, *edited by Vikram Kapila and Karolos M. Grigoriadis*
13. Nonlinear Control Systems, *Zoran Vukić, Ljubomir Kuljača, Dali Donlagič, and Sejid Tesnjak*
14. Linear Control System Analysis & Design: Fifth Edition, *John D'Azzo, Constantine H. Houpis and Stuart Sheldon*
15. Robot Manipulator Control: Theory & Practice, Second Edition, *Frank L. Lewis, Darren M. Dawson, and Chaouki Abdallah*
16. Robust Control System Design: Advanced State Space Techniques, Second Edition, *Chia-Chi Tsui*
17. Differentially Flat Systems, *Hebertt Sira-Ramirez and Sunil Kumar Agrawal*

18. Chaos in Automatic Control, *edited by Wilfrid Perruquetti and Jean-Pierre Barbot*
19. Fuzzy Controller Design: Theory and Applications, *Zdenko Kovacic and Stjepan Bogdan*
20. Quantitative Feedback Theory: Fundamentals and Applications, Second Edition, *Constantine H. Houpis, Steven J. Rasmussen, and Mario Garcia-Sanz*
21. Neural Network Control of Nonlinear Discrete-Time Systems, *Jagannathan Sarangapani*

Dedication

This book is dedicated to my parents, my uncle, and to my wife Sandhya, my daughter Sadhika, and my son Anish Seshadri.

Preface

Modern feedback control systems have been responsible for major successes in the fields of aerospace engineering, automotive technology, defense, and industrial systems. The function of a feedback controller is to alter the behavior of the system in order to meet a desired level of performance. Modern control techniques, whether linear or nonlinear, were developed using state space or frequency domain theories. These techniques were responsible for effective flight control systems, engine and emission controllers, space shuttle controllers, and for industrial systems. The complexity of today's man-made systems has placed severe constraints on existing feedback design techniques. More stringent performance requirements in both speed and accuracy in the face of system uncertainties and unknown environments have challenged the limits of modern control. Operating a complex system in different regimes requires that the controller be intelligent with adaptive and learning capabilities in the presence of unknown disturbances, unmodeled dynamics, and unstructured uncertainties. Moreover, these controllers driven by the hydraulic, electrical, pneumatic, and bio-electrical actuators have severe multiple nonlinearities in terms of friction, deadzone, backlash, and time delays.

The intelligent control systems, which are modeled after biological systems and human cognitive capabilities, possess learning, adaptation, and classification capabilities. As a result, these so-called intelligent controllers provide the hope of improved performance for today's complex systems. These intelligent controllers were being developed using artificial neural networks (NN), fuzzy logic, genetic algorithms, or a combination thereof. In this book, we explore controller design using artificial NN since NN capture the parallel processing, adaptive, and learning capabilities of biological nervous systems.

The application of NN in closed-loop feedback control systems has only recently been rigorously studied. When placed in a feedback system, even a static NN becomes a dynamical system and takes on new and unexpected behaviors. Recently, NN controllers have been developed both in continuous- and discrete-time. Controllers designed in discrete-time have the important advantage that they can be directly implemented in digital form on modern-day embedded hardware. Unfortunately, discrete-time design is far more complex than the continuous-time design when Lyapunov stability analysis is used since the first difference in Lyapunov function is quadratic in the states not linear as in the case of continuous-time.

This book for the first time presents the neurocontroller design in discrete-time. Several powerful modern control techniques in discrete-time are used in the book for the design of intelligent controllers using NN. Thorough development, rigorous stability proofs, and simulation examples are presented in each case. Chapter 1 provides background on NN while Chapter 2 provides background information on dynamical systems, stability theory, and discrete-time adaptive controller also referred to as a self tuning regulator design. In fact, Chapter 3 lays the foundation of NN control used in the book by deriving NN controllers for a class of nonlinear systems and feedback linearizable, affine, nonlinear discrete-time systems. Both single- and multiple-layer NN controllers and NN passivity properties are covered. In Chapter 4, we introduce actuator nonlinearities and use artificial neural networks to design controllers for a class of nonlinear discrete-time systems with magnitude constraints on the input. This chapter also uses function inversion to provide NN controllers with reinforcement learning for systems with multiple nonlinearities such as dead zone and saturation. Chapter 5 confronts the additional complexity introduced by uncertainty in the control influence coefficient and presents discrete backstepping design for a class of strict feedback nonlinear discrete-time multi-input and multi-output systems. Mainly an output feedback controller is derived. Chapter 6 extends the state and output feedback controller design using NN backstepping to nonstrict feedback nonlinear systems with magnitude constraints. A practical industrial example of controlling a spark ignition engine is discussed. In Chapter 7, we discuss the system identification by developing suitable nonlinear identifier models for a broad class of nonlinear discrete-time systems using neural networks. In Chapter 8, model reference adaptive control of a class of nonlinear discrete-time systems is treated. Chapter 9 presents a novel optimal neuro controller design of a class of nonlinear discrete-time systems using Hamilton–Jacobi–Bellman formulation.

An important aspect of any control system is its implementation on an actual industrial system. Therefore, in Chapter 10 we develop the framework needed to implement intelligent control systems on actual industrial systems using embedded computer hardware. Output feedback controllers using NN were designed for lean engine operation with and without high exhaust gas recirculation (EGR) levels. Experimental results for the lean engine operation are included and EGR controller development was also included using an experimentally validated model. The appendices at the end of each chapter include analytical proofs for the controllers and computer code needed to build intelligent controllers for the above class of nonlinear systems and for real-time control applications.

This book has been written for senior undergraduate and graduate students in a college curriculum, for practicing engineers in industry, and for university researchers. Detailed derivations, stability analysis, and computer simulations show how to understand NN controllers as well as how to build them.

Acknowledgments and grateful thanks are due to my teacher, Dr. F.L. Lewis, who gave me inspiration, passion, and taught me persistence and attention to details; Dr. Paul Werbos for introducing me to the topic of adaptive critics and guiding me along; Dr. S.N. Balakrishnan, who gave me inspiration and humor behind the control theory; Dr. J. Drallmeier who introduced me to the engine control problem. Also special thanks to all my students, in particular Pingan He, Atmika Singh, Anil Ramachandran, and Jonathan Vance who forced me to take the work seriously and become a part of it. Without monumental efforts at typing and meeting deadlines by Atmika Singh and Anil Ramachandran, this book would not be a reality.

This research work is supported by the National Science Foundation under grants ECS-9985739, ECS-0296191, and ECS-0328777.

Jagannathan Sarangapani
Rolla, Missouri

Contents