M. Nørgaard, O. Ravn, N.K. Poulsen
and L.K. Hansen

Neural Networks for Modelling and Control of Dynamic Systems

A Practitioner's Handbook

With 84 Figures

Springer

M. Nørgaard, O. Ravn, N.K. Poulsen
and L.K. Hansen

Neural Networks for Modelling and Control of Dynamic Systems

A Practitioner's Handbook

With 84 Figures

Springer

M. Nørgaard, MSc, EE, PhD
Department of Automation, Technical University of Denmark, Building 326, DK-2800, Lyngby, Denmark

O. Ravn, MSc, EE, PhD
Department of Automation, Technical University of Denmark, Building 326, DK-2800, Lyngby, Denmark

N.K. Poulsen, MSc, EE, PhD
Department of Mathematical Modelling, Technical University of Denmark, Building 321, DK-2800, Lyngby, Denmark

L.K. Hansen, MSc, PhD
Department of Mathematical Modelling, Technical University of Denmark, Building 321, DK-2800, Lyngby, Denmark

ISBN 1-85233-227-1 Springer-Verlag London Berlin Heidelberg

British Library Cataloguing in Publication Data
Neural networks for modelling and control of dynamic
systems : a practitioner's handbook. - (Advanced textbooks
in control and signal processing)
1.Neural networks (Computer science) 2.Automatic control
I.Norgaard, M.
629.8'9
ISBN 1852332271

Library of Congress Cataloging-in-Publication Data
Neural networks for modelling and control of dynamic systems : a practitioner's
handbook / M. Nørgaard ... [et al.].
p. cm. -- (Advanced textbooks in control and signal processing)
Includes bibliographical references and index.
ISBN 1-85233-227-1 (alk. paper)
1. Neural networks (Computer science) 2. Computer simulation. 3. Automatic control.
4.Nonlinear theories. I. Nørgaard, Magnus. II. Series.
QA76.87 N4847 2000
006.3'2--dc21 99-049801

Printed in Great Britain
2nd printing 2001
3rd printing, with corrections 2003

Typesetting: Camera ready by authors
Printed and bound at the Athenæum Press Ltd., Gateshead, Tyne and Wear
69/3830-5432 Printed on acid-free paper SPIN 10911488

Series Editors' Foreword

The topics of control engineering and signal processing continue to flourish and develop. In common with general scientific investigation, new ideas, concepts and interpretations emerge quite spontaneously and these are then discussed, used, discarded or subsumed into the prevailing subject paradigm. Sometimes these innovative concepts coalesce into a new sub-discipline within the broad subject tapestry of control and signal processing. This preliminary battle between old and new usually takes place at conferences, through the Internet and in the journals of the discipline. After a little more maturity has been acquired by the new concepts then archival publication as a scientific or engineering monograph may occur.

A new concept in control and signal processing is known to have arrived when sufficient material has developed for the topic to be taught as a specialised tutorial workshop or as a course to undergraduates, graduates or industrial engineers. The *Advanced Textbooks in Control and Signal Processing* series is designed as a vehicle for the systematic presentation of course material for both popular and innovative topics in the discipline. It is hoped that prospective authors will welcome the opportunity to publish a structured presentation of either existing subject areas or some of the newer emerging control and signal processing technologies.

This is a fascinating and well-written book. According to the authors: *Neural Networks constitutes a very large research field, and it is difficult to obtain a clear overview of the entire field.* This book threads a careful way through that field to guide the reader to the items necessary to use neural networks in system identification and ultimately in control systems applications. So if you wanted to know *Why use Neural Networks?* then this is the book for you.

The book comes with plenty of added features. There is neural network software available at an associated website and an e-mail address to further the dialogue on the contents of the book itself. There is even a challenge, for early in the book the authors state their belief that it is possible to reduce development time and achieve better performance using neural networks as opposed to using auto-tuned PID for general purpose controllers. It might be interesting for some enterprising student to put that belief to the test and assess the advantages and disadvantages of both approaches on some benchmark problems.

In conclusion a very welcome addition to the *Advanced Textbooks in Control and Signal Processing* series and a nice complementary book to another in the series, that of Kim Man, and his colleague on *Genetic Algorithms* (ISBN 1-85233-072-4).

M.J. Grimble and M.A. Johnson
Industrial Control Centre
Glasgow, Scotland, U.K.
November 1999

Preface

Aim of the book. The main goal of this book is to describe approaches to neural-network-based control that are found to be practically applicable to a reasonably wide class of unknown nonlinear systems. System identification is an integral part of such a control system design and consequently it calls for considerable attention as well. The system identification is necessary to establish a model based on which the controller can be designed, and it is useful for tuning and simulation before applying the controller to the real system. However, system identification is relevant in many other applications, e.g., simulation, prediction, and fault detection. For this reason the theoretical explorations in the book have been split into two main sections that are weighted approximately equally: a section about system identification and a section about design of control systems. Although the treatment of system identification has a certain bias towards the application to control, it has been written so that expert knowledge about control theory is not necessary.

In writing the book an attempt has been made to outline a feasible path through the "jungle" of neural network solutions. The emphasis is on guidelines for working solutions and on practical advice on implementation issues. A completely automatic procedure for system identification and control system design is not realistic. Thus, an attempt has been made to provide techniques that minimize the effort required by the user and leave it up to him/her to answer only a few reasonably well-defined assessment questions. Algorithms are detailed to be fast and numerically sound, but the book does not go as far as to describe the actual programming. The necessary theoretical background is given for the methods presented, but the reader will not find rigorous mathematical proofs for the statements.

Approach. The philosophy underlying the selection of topics for the book is that a pragmatic approach is the road to success. It is believed that one of the most important lessons to be learned from the numerous automatic control applications developed over the past half century is that simple solutions actually solve most problems quite well. Regardless of the fact that all systems to some extent exhibit a nonlinear behavior, it turns out that they can often be controlled satisfactorily with simple linear controllers. When neural networks are introduced as a tool for improving the performance of control systems for a general class of unknown nonlinear systems, it should be done in the same spirit. Thus, most of the theory is derived in a somewhat heuristic fashion. It has been important to pursue methods that yield good performance in practice and thus there is generally little concern with the possibility for proving stability. In writing the book we have avoided becoming too deeply absorbed in the mathematical and statistical foundation for the neural-network-based methods. The reader will find many mathematical derivations, but we have tried not to bring in more theory than is needed to provide the reader with the insight to understand the principles behind the methods and the detail enabling an implementation.

A consequence of this philosophy is that the focus is placed on two-layer perceptron neural networks with hyperbolic tangent hidden units and linear output units. This is probably the most commonly used network architecture as it works quite well in many practical applications. While the implementation details are adapted to these networks, most theoretical explorations apply directly to neural networks in general. However, the reader is referred to more fundamental textbooks on neural networks for a treatment of other types of neural networks.

Supporting software. The book provides the theoretical foundation for two sets of tools for the mathematical software package MATLAB®:

- The NNSYSID Toolbox, which contains a collection of MATLAB® functions for system identification with neural networks.
- The NNCTRL Toolkit, which contains a set of tools for design and simulation of neural-network-based controllers.

Detailed description of the contents and use of the two packages can be found in the manuals Nørgaard (1997) and Nørgaard (1996a). Software and manuals can be downloaded from the internet at:
`http://www.iau.dtu.dk/nnspringer.html`

On this Web page there is additional supporting material for the book as well. For example, assignments, simulation models, list of errors, etc. The authors would like to encourage the readers to provide additional material for the web page or to give feedback on the book by using the e-mail address:
`nnspringer@iau.dtu.dk`

Prerequisites. Primarily, this book addresses engineering students at the graduate level. It is appropriate as a textbook in a course that mixes theory with practical laboratory sessions. It is also useful as a handbook in practical projects and courses. Engineering professionals should find the book relevant as well; either for self-study or as a handbook for implementation.

An introductory course in adaptive control is considered the most appropriate prerequisite for the book. As a minimum the reader should know about matrix calculus, basic statistics, system identification/time series analysis, and digital control (Chapter 3). It is an advantage if the reader is acquainted with the neural network field, but it is not a vital prerequisite for understanding the material.

Outline of the book. The book has four chapters:

Chapter 1 introduces the multilayer perceptron neural network and discusses why and when it is relevant to use it in system identification and control system design.

Chapter 2 outlines a procedure for system identification with neural networks and proceeds with a thorough treatment of each stage in the procedure. The covered issues encompass:

- Experiment design. How to conduct an experiment to collect a set of data for neural network modelling.
- Model structure selection. Conventional linear model structures are extended to nonlinear systems by incorporation of neural networks. Automatic methods for selection of neural network architectures, so-called pruning algorithms, are also described.
- Neural network training. It is described how to train networks as models of dynamic system with a prediction error method. Optimization methods relevant for neural network training are described. Regularization by weight decay is introduced as an extension of the basic prediction error method.
- Validation. Techniques for assessing neural network models are treated and concepts like generalization error and average generalization error are introduced
- The chapter is concluded by outlining a set of rules of thumb for system identification with neural networks.

Chapter 3 provides an overview of a wide range of approaches to neural-network-based control system design. The features of each particular design are explored and the implementation issues treated. Some designs are characterized by being restricted to a relatively limited class of systems but simple to implement. Others are characterized by being applicable to a wider class of systems, but more difficult to implement. The designs have been divided into two categories:

- Direct design. The controller is in itself a neural network. Examples of designs in this category are direct inverse control, internal model control, feedback linearization, feedforward, and optimal control.

- Indirect design. Designs based on a neural network model of the system to be controlled. The controller is in this case either a time-varying linear controller or an optimization algorithm. Two approaches to indirect design are described. One is to use a conventional design based on models obtained by linearization of the neural network model. The second is a nonlinear predictive control design based on on-line optimization.

A benchmark system is used for illustrating the properties of the designs. The chapter is concluded by providing some guidelines for selecting the most appropriate controller for a particular application.

Chapter 4 describes four case studies in the use of neural networks for system identification and control. Each case illustrates several topics covered in the book.

Background of the work. The main portion of the material used in this book comes from the Ph.D. thesis written by the first author (Nørgaard, 1996b). The work was carried out at the Department of Automation, Technical University of Denmark with the other three authors as supervisors. In the Ph.D.-study the previously mentioned software tools were developed to demonstrate that practical use of the described methods was in fact possible. The tools were made available on the internet in 1994 and 1995, respectively, and since then thousands have downloaded and used the software. Many users have been eager to understand the underlying theory and have requested the thesis. The overwhelming interest in the work made the authors approach Springer-Verlag, London in order to make the material available to an even wider audience. Compared with the Ph.D. thesis, the text has been revised, some issues are no longer covered, and a few new sections have been added.

Acknowledgments. The authors would like to thank several people who have helped in the creation of the book: Kevin Wheeler for proofreading the manuscript, Paul Haase Sørensen for providing the material for the pneumatic servomechanism in Section 4.3, Svante Gunnarsson for providing material and data for the hydraulic crane example in Section 4.2, and Egill Rostrup for providing the fMRI data presented in Chapter 1.

Lyngby

November 1999

Magnus Nørgaard

Ole Ravn

Niels Kjølstad Poulsen

Lars Kai Hansen

Contents

1. Introduction

Many of the abilities one possesses as a human have been learned from examples. Thus, it is only natural to try to carry this "didactic principle" over to a computer program to make it learn how to output the desired answer for a given input. In a sense the artificial neural network is one such computer program; it is a mathematical formula with several adjustable parameters, which are tuned from a set of examples. These examples represent what the network should output when it is shown a particular input.

The book deals with two specific neural network applications: modelling of dynamic systems and control. Despite the fact that "learning from examples" sounds easy, many have been surprised to experience that often it is in fact extremely difficult to obtain working neural network solutions. It is hoped that the methods and recommendations given in this book will guide the reader to many successful neural network implementations.

1.1 Background

Today automatic control systems have become an integrated part of our everyday life. They appear in everything from simple electronic household products to airplanes and spacecrafts (see Figure 1.1). Automatic control systems can take highly different shapes but common to them all is their function to manipulate a system so that it behaves in a desired fashion. When designing a controller for a particular system, it is obvious that a vital intermediate step is to acquire some knowledge about how the system will respond when it is manipulated in various ways. Not until such knowledge is available, can one plan how the system should be controlled to exhibit a certain behavior.

1.1.1 Inferring Models and Controllers from Data

A common and practically oriented approach to control system design is to use physical insights about the system supplemented with a series of practical closed-loop tests. In the tests different design parameters are tried until a working controller is obtained. Another often-used approach is based on conducting a simple experiment with the system to provoke a particular response. Based on the knowledge of how this particular response is obtained, simple rules of thumb subsequently explain how the automatic control system should be designed (Ziegler and Nichols, 1942). Such procedures have even been automated in commercially available devices known as *auto-tuners*. Sometimes,

Figure 1.1. The NF-15B research aircraft. Boeing and the NeuroEngineering Group at NASA Ames Research Center have developed an adaptive neural-network-based flight control system capable of recovering from damages due to failures or serious accidents. The control system has been tested on the NF-15B at NASA Dryden Flight Research Center. The F-15 has been modified so that damages can be simulated by activating the canards (the small front wings), thereby changing the airflow over the main wings. (NASA Photo by Tony Landis, Dryden Flight Research Center.)

simple design approaches such as those just cited, are not adequate, either because they simply fail to work or because demands in performance are too strong to be satisfied by means of simple rules of thumb. In such cases more advanced design methods must be considered. These designs will in general require that knowledge about the system to be controlled is more structured in that it should be specified in terms of differential or difference equations. A mathematical description of this kind is called *a model* of the system. Basically, there are two ways in which a model can be established: it can be derived in a deductive manner using laws of nature, or it can be inferred from a set of data collected during a practical experiment with the system.

The first method can be simple, but in most cases it is excessively time-consuming. This is possibly the most time-consuming stage in the controller design. Not infrequently it may even be considered unrealistic or impossible to obtain a sufficiently accurate model in this way. The second method, which is commonly referred to as *system identification*, in these situations can be a useful short cut for deriving mathematical models. Although system identification not always results in equally accurate models, a satisfactory model can often be obtained with a reasonable effort. The main drawback is the requirement to conduct a practical experiment that brings the system through its entire range of operation. Also, a certain knowledge about the system is still required.

System identification techniques are widely used in relation to control system design and many successful applications have been made over the years. Sometimes system identification is even implemented as an integral part of the controller. This is known as an *adaptive controller* and it is typically designed to control systems whose dynamical characteristics vary with time. In the typical adaptive controller a model that is valid under the current operating conditions is identified on-the-fly, and the controller is then redesigned in agreement with the current model.

Much literature is available on system identification, adaptive control, and control system design in general, but traditionally most of it has focused on dealing with models and controllers described by linear differential or difference equations. However, motivated by the fact that all systems exhibit some kind of nonlinear behavior, there has recently been much focus on different approaches to nonlinear system identification and controller design. One of the key players in this endeavor is the *artificial neural network.* Artificial neural networks represent a discipline that originates from a desire to imitate the functions of a biological neural network, namely the brain. Artificial neural networks, or just *neural networks*, as they are most often abbreviated, have been one of the major buzz words in the recent years. Apart from system identification and control they have been applied in such diverse fields as insurance, medicine, banking, speech recognition, and image processing to mention just a very few examples. They are typically implemented in software, but dedicated neural network hardware is also available for increased execution speed.

Neural networks constitute a very large research field, and it is difficult to obtain a clear overview of the entire field. Several motives originally lead researchers to study neural networks. One of the primary motives was to create a computer program that was able to learn from experience. The hope was to create an alternative to conventional programming techniques, where rules were coded directly into the computer. When the experience mentioned is interpreted as knowledge about how certain inputs affect a system, it is obvious that neural networks must have something in common with the techniques applied in system identification and adaptive control.

As the research on neural networks has evolved, more and more types of networks have been introduced while still less emphasis is placed on the connection to the biological neural network. In fact, the neural networks that are most popular today have very little resemblance to the brain, and one might argue that it would be fairer to regard them simply as a discipline under statistics. These neural networks are vehicles that in a generic sense can learn nonlinear mappings from a set of observations. Neural networks are not the only technique available for approximating such generic nonlinear mappings; the list over similar techniques is in fact quite long. See Sjöberg et al. (1995) for some examples that are relevant to system identification.

1.1.2 Why Use Neural Networks?

Why have neural networks attracted particular attention compared with alternative techniques? For a given application it is of course difficult to say that one identification technique will outperform another before they have both been evaluated. Nevertheless, it is desirable to consider only one technique for all applications rather than having to evaluate several candidates on each new application. Partly because it simplifies the modelling process itself, and also because it will enable implementation of generic tools for control system design. When searching for a single technique that in most cases of practical interest performs reasonably well, certain types of neural network appear to be an excellent choice. In particular the multilayer perceptron network has gained an immense popularity. From numerous practical applications published over the past decade there seems to be substantial evidence that multilayer perceptrons indeed possess an impressive ability. Lately, there have also been some theoretical results that attempt to explain the reasons for this success. For supplementary information one may consult Barron (1993) and Juditsky et al. (1995).

How are neural networks useful for control system design? It is practical to distinguish between the following two categories of controllers:

Highly specialized controllers that are relevant when the system to be controlled is in some sense difficult to stabilize or when the performance is extremely important.

General purpose controllers where the same controller structure can be used on a wide class of practical systems. The controllers are characterized by being simple to tune so that a satisfactory performance can be achieved with a modest effort.