World Scientific Series in Robotics and Automated Systems – Vol. 6

INTELLIGENT CONTROL

Aspects of Fuzzy Logic and Neural Nets

C. J. Harris, C. G. Moore & M. Brown

Advanced Systems Research Group
University of Southampton, UK

World Scientific
Singapore • New Jersey • London • Hong Kong

Published by

World Scientific Publishing Co. Pte. Ltd.
P O Box 128, Farrer Road, Singapore 9128
USA office: Suite 1B, 1060 Main Street, River Edge, NJ 07661
UK office: 73 Lynton Mead, Totteridge, London N20 8DH

INTELLIGENT CONTROL: ASPECTS OF FUZZY LOGIC AND NEURAL NETS

ISBN 981-02-1042-6

Printed in Singapore.

INTELLIGENT CONTROL

Aspects of Fuzzy Logic and Neural Nets

WORLD SCIENTIFIC SERIES IN ROBOTICS AND AUTOMATED SYSTEMS

Editor-in-Charge: Prof T M Husband
(*Vice Chancellor, University of Salford*)

Vol. 1: Genetic Algorithms and Robotics — A Heuristic Strategy for Optimization (*Y Davidor*)

Vol. 2: Parallel Computation Systems for Robotics: Algorithms and Architectures (*Eds. A Bejczy and A Fijany*)

Vol. 4: Computer Vision, Models and Inspection (*A D Marshall and R R Martin*)

Vol. 5: Advanced Tactile Sensing for Robotics (*Ed. H R Nicholls*)

Vol. 6: Intelligent Control: Aspects of Fuzzy Logic and Neural Nets (*C J Harris, C G Moore and M Brown*)

Vol. 8: Modelling and Simulation of Robot Manipulators: A Parallel Processing Approach (*A Y Zomaya*)

Forthcoming volumes:

Vol. 3: Intelligent Robotic Planning Systems (*P C-Y Sheu*)

Vol. 7: Visual Servoing (*Ed. K Hashimoto*)

Vol. 9: Advanced Guided Vehicles – Aspects of the Oxford AGV Project (*S Cameron and P Probert*)

Vol. 10: Mobile Robots (*Ed. Y F Zheng*)

To
Joy, Caroline, Ruth
and Philip

PREFACE

The increasing complexity of dynamical systems coupled with increasingly stringent performance criteria necessitates the utilisation of more complex and sophisticated controllers, that can accommodate temporal and spatial variations, are robust to minor faults and disturbances, and can cope with nonlinear relationships. Current developments in knowledge based, and associated learning systems, for real time control offer opportunities for radical innovation and significant improvements in product quality assurance and fault tolerance, as well as the opportunity of dealing with the optimal management of complex systems in an integrated manner by considering quantitative and qualitative aspects simultaneously. Intelligent controllers are enhanced adaptive or self-organising controllers that automatically adapt to plant and environmental changes *without* prior knowledge of the changes or even of physical models of the process, rather, utilising input/output data to formulate control strategies. Intelligent control is based upon ideas and techniques from the disciplines of neurophysiology, psychology, operational research, control theory and computer science. Central to any control theory is the construction of, or identification of plant models; rather than be based upon linear physio - mathematical models, intelligent control derives models of the plant input/output mapping from experiential evidence via an associative memory. The advantage of this approach is that it does not depend upon the linear time invariance properties of the plant, also its natural parallelism offers the potential of adaptive real time control of nonlinear stochastic processes. Of particular importance in intelligent control are direct learning schemas that implement piecewise continuous nonlinear mappings or models with continuous mapping. A central thesis of this book is the development and use of single layer associative memory networks which map fixed input signals to higher dimensional functional spaces, whose outputs are linearly additive through weights or beliefs that are adapted by first order learning laws. The advantages of this approach is that the approximation can be shown to be optimal in the mean squared error sense (i.e. is a *best* approximation), utilises *linear* optimisation in adaptation (even for nonlinear input/output mappings), offers known convergence properties, learns in real time new mappings, provides local generalisation, and is robust to disturbances. Two apparently different approaches to intelligent control are developed in this book - based respectively upon Neural Networks and Fuzzy Logic. It is shown that both can be considered as a class of single layer associative memory devices that allow learning through linear weight (belief) adaptation, from which, estimates of dynamical systems can be achieved without mathematical models of the input/output functional dependence, in which the system structure or relationship is encoded through a parallel distributed mechanism.

Many of the results of this book are entirely new, some integrate previously derived results in self-organising fuzzy logic and neural networks, and some well established theory in basic fuzzy logic and its application to control are included to both unify the theory and the approach of the book, but also to place into context the significance of the new research. The mathematical approach adopted in the book is to minimise the technical requirements to a level sufficient to justify derivations and results; where necessary, essential mathematical prerequisites are included in the Appendix. Readers requiring more formal proofs should consult the references quoted.

The basic philosophy behind learning systems, in the context of intelligent control, is developed in Chapter 1. Whilst the prime objectives of intelligent control in this volume is at the servo or direct control level, the general architectural issues of intelligent control at the executor, co-ordination and organisational levels within a hierarchical architecture are discussed; covering in particular the minimal architectural attributes or features of intelligent control. The three approaches to intelligent control are highlighted, and the general philosophy behind the classes fuzzy logic and neural networks utilised in this book, are established in Chapter 1.

As fuzzy logic forms the major part of the book, Chapter 2 is devoted to the fundamental theory of fuzzy logic covering fuzzy sets, fuzzy inference and compostion, fuzzy relations, and defuzzification. B-splines as a means of representing fuzzy sets is introduced early as a preliminary to identifying the relationship between fuzzy logic and neural nets.

The fundamental fuzzy logic controller subsystems of quantisation, fuzzification, database, control rule base (inferencing mechanism) and defuzzification, are introduced in Chapter 3. Additionally the dynamic and static design requirements for a fuzzy logic controller are considered. For static design, the issues of control rule base completeness consistency and interaction are formally defined, similarly for dynamic design, controller performance issues such as reachability and controllability are established. These design criteria are exemplified by the derivation of a new fuzzy analysis tool - the fuzzy phase plane in section 3.4, which is used to evaluate various control rule bases later in the text.

Whilst the emphasis of this book is upon learning systems in control, the majority of theoretical and practical implementations of fuzzy logic control has been for static of fixed control rule bases, established from *a priori* process knowledge. Therefore for completeness, and to underpin the self-organising fuzzy logic controller, Chapter 4 contains a review of the basic methods of static fuzzy logic control, including the fuzzy PID controller, and the linguistic rule inversion which may be readily evaluated via the fuzzy phase plane method. This Chapter introduces a topical problem that is difficult to control via conventional techniques, that of the control and guidance of an autonomous guided land vehicle subject to unpredictable environmental and plant variations, this problem is developed throughout the book as a theme for intelligent control.

The second half of the book, Chapters 5 to 9, addresses the books' main objectives, that of learning, intelligent adaptive or self organising control for dynamical systems. In model reference adaptive control there are two approaches, *direct* control and *indirect* control. In direct control, the controller parameters are directly synthesised from the error between the desired and actual response of the plant via some performance measure. Currently there are no analytical methods for direct adaptive control of nonlinear systems, however the self-organising fuzzy logic controllers (SOFLIC's) of Chapter 5 address this problem in which the reference model is encapsulated in a performance index that directs the rule updating process. The SOFLIC is an experientially determined multivariable processor which has to perform two simultaneous tasks (i) observe the process and its environment whilst generating control actions (ii) using the results of these control actions in the static performance measure, adjust the control rule base to further improve controller behaviour or to track changes in the plants' parameters. SOFLIC's can cope with minimal *a priori* process knowledge, plant nonlinearities, temporal and spatial variation in parameters, and random internal/external disturbances. Chapter 5 addresses the practical issue of implementing the direct SOFLIC through a series of case studies that include a ships yaw control, and laboratory control experiments.

The indirect adaptive fuzzy logic controller or SOFLIC introduced in Chapter 6, has certain advantages over the direct approach (i) the generation of a fuzzy rule based plant model enables sudden parametric changes to be detected, as well as the tracing of temporal characteristics - this is invaluable for intelligent fault monitoring diagnosis and fault isolation (ii) separating the model adaptation from controller design enables model or parametric convergence to be analysed separately from controller performance and system stability (iii) the controller specification can be altered to accommodate new goals or tasks without effecting the model rule base. The self-organisation is achieved via a forgetting factor in the rule base of the plant relational matrix that causes old rules to slowly decay as new rules based upon new observations are added. The controller design is achieved by the composition of the inverse linguistic model of the plant and a fixed next desired state performance fuzzy matrix. It is noted in Chapter 6 that the discretisation associated with fuzzification can lead to bounded oscillatory behaviour around operating points, however by introducing a nested or hybrid controller that utilises the SOFLIC for global response and a parameterised fuzzy PID controller for local response, overcomes this problem. The indirect adaptive fuzzy controller is applied in Chapter 7 to a variety of case studies, starting with some IFAC bench mark comparative case studies and finishing with the guidance and control of an autonomous land vehicle. These examples readily demonstrate the learning capability and robustness of the indirect SOFLIC.

The final Chapters, 8 and 9, are concerned with the use of neural networks for control and modelling of nonlinear processes and their relationship to self organising fuzzy logic. Chapter 8 is primarily concerned with the approximation properties of neural networks, dividing them into two classes (i) those, such as the multi-layer perceptron, which form weighted linear combinations of the inputs followed by nonlinear transformations and (ii) those, such as the B-spline, CMAC, RBF, which form fixed nonlinear transformations of the inputs into a higher dimensional space which is linearly weighted to form an output. This latter class is shown to be a best approximation class, with local generalisation properties, fast and guaranteed convergence properties, making them ideal for neurocontrol. Comparative examples are used to illustrate the learning properties of the various candidate neural networks.

The B-spline neural network (BSNN) of Chapter 9, is a new associative memory single layer neural network, devised for on-line adaptive modelling and control, as well as for static off-line design such as trajectory planning subject to dynamic constraints. A variety of first order learning rules are introduced that ensure mean squared convergence in learning to a global minimum in the cost functional weight space. Of particular significance is the many to one relationship between the self-organising fuzzy logic and BSNN , if the defining fuzzy sets are normalised B-splines and the product operator is used for logical implication. This ensures that all the convergence and stability proofs of the BSNN translate over a class of self-organising fuzzy logic, formalising fuzzy logic as an associative memory device.

ACKNOWLEDGEMENT

Much of this book is the result of theoretical work in intelligent control carried out by researchers in the Advanced Systems Research Group at Southampton University, in the support of multi-institutional/industry collaborative research projects in Intelligent Autonomous Vehicles. In particular, I would like to thank group researchers who have contributed to the book in a variety of ways - Adrian Alford, Edgar An, Simon Corfield, Robert Fraser and Alan Lawrence. Special thanks go to Martin Brown and Chris Moore whose doctoral work formed the basis of Chapters Six to Nine. Lucas Aerospace, British Aerospace, the EEC, SERC and the UK Ministry of Defence have all provided generous financial support and sponsorship for this research and this is gratefully acknowledged. Finally, I would like to thank Amanda Goodacre for turning an untidy and complex manuscript into this final version, and to my wife Joy for her efforts in proof reading and corrections, but most of all for her patience.

Chris Harris
June 1992

CONTENTS