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Advanced Control of Industrial Processes

Structures and Algorithms

Springer

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British Library Cataloguing in Publication Data
Tatjewski, Piotr
Advanced control of industrial processes : structures and algorithms. - (Advances in industrial control)
1. Predictive control - Mathematics 2. Fuzzy algorithms
I. Title
629.8'015181
ISBN-13: 9781846286346
ISBN-10: 1846286344

Library of Congress Control Number: 2006936016

Advances in Industrial Control series ISSN 1430-9491
ISBN 978-1-84628-634-6 e-ISBN 1-84628-635-2 Printed on acid-free paper

9 8 7 6 5 4 3 2 1

Springer Science+Business Media
springer.com

Advances in Industrial Control

To the memory of my mother

Series Editors' Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline. New theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new philosophies..., new challenges. Much of this development work resides in industrial reports, feasibility study papers and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination. Industrial process control usually requires process unit control and global plant-wide control. The question is how to model and solve these often large-scale control problems. In practice, industrial and control engineers find a way to make these processes work and then refine and optimize the control structures. The involvement of the academic control community in the solution of these problems is often third-hand and usually *after* the process is up and running. Consequently, the amount of teaching and research devoted to industrial process supervisory control tends to be rather small when compared with activity in control loop design. This is a pity because these higher-level problems in process control are both important and challenging.

The two seminal textbooks in this field are *Theory of Hierarchical Multilevel Systems* by M.D. Mesarovic, D. Macko and Y. Takahara (Academic Press, New York, 1970) and *Control and Coordination in Hierarchical Systems* by W. Findeisen, F.N. Bailey, M. Brdys, K. Malinowski, P. Tatjewski and A. Wozniak (J. Wiley and Sons, Chichester, U.K., 1980). These books provided the mental models and the system vocabulary to bring a concrete framework to the engineering community tackling large-scale industrial process control. The key concept in this ordering was the *hierarchy* and the key tool was *optimisation.* Since these seminal texts emerged, the use of a hierarchical structure in industrial control is usually implicitly or explicitly present. Many global plant control schemes are designed around a hierarchical layered framework because this enables objectives, methods and operation to be clearly and unambiguously stated and implemented. The hierarchical structure often facilitates the easy transfer of knowledge of the plant control objectives and methods as new engineers join the operational team. Enhancing the effectiveness of global plant control becomes an easier task if the control is decomposed into layers that are usually time-frame decoupled, too.

Despite the passage of time, *optimisation* remains the key tool but what has changed are the optimisation methods. Optimisation in the 1970s usually meant static optimisation techniques whereas today constrained dynamic optimisation of complex nonlinear processes is routinely feasible. Model predictive control methods are versatile and commonly found in the higher reaches of the process control hierarchy, as well as providing the control designs in the lower control-loop and set-point-changeover levels.

Piotr Tatjewski was one of the original authorial team that produced the seminal text *Control and Coordination in Hierarchical Systems*. Consequently, it comes as no surprise to find that his *Advances in Industrial Control* monograph, *Advanced Control of Industrial Processes* has the sub-title *Structures and Algorithms*. For what the reader will find in this exemplary monograph is two chapters reviewing and extending the original concepts of the multi-layer hierarchical control structure and two chapters introducing in considerable scholarly depth the control algorithms of model fuzzy control and model predictive control. The two control algorithms can be considered for use at different levels and to achieve different objectives within the hierarchical control structure. Of course, the model predictive control tool facilitates optimisation whilst model fuzzy control can be viewed as a loop controller model devised to achieve good nonlinear process control performance in the direct control layer of the hierarchy.

The monograph has been written with considerable care given to the steps of review, exposition and demonstration. Industrially relevant examples have been chosen to demonstrate different aspects of the concepts under discussion. The careful presentation enables both the industrial engineer and the academic researcher to appreciate the context of the ideas being discussed before proceeding to the more challenging aspects of the exposition. Since sufficient information has been given about many of the various examples presented, enthusiastic readers may wish to repeat them for themselves.

Readers of all levels of attainment in industrial process control will find something of interest in this fine monograph. It is a very welcome new title in the *Advances in Industrial Control* series.

M.J. Grimble and M.A. Johnson
Glasgow, Scotland, U.K.

Preface

The subject of this book is *advanced control* of industrial processes. Therefore, algorithms of advanced feedback control are mainly presented, but also on-line set-point optimization is discussed, in appropriate structures. A starting point for the topic defined in this way is a *multilayer control structure* of industrial processes. This structure enables reasonable and safe control and management through a decomposition and distribution of tasks and responsibilities into a few well-defined and simpler sub-tasks of a more homogeneous character, mutually interconnected. The basic layers of the multilayer structure are two feedback control layers (regulatory control layers) and the optimization layer.

Feedback control is now often carried out at two layers, especially for more complex, multivariable processes. The first and lowest one is the *direct control layer*, also called the basic control layer. Its main task is to maintain the process within desirable limits defined by the set-point values for its controllers (direct controllers). It is usually also equipped with certain control logic responsible for overriding the control designed for normal operating conditions, if a danger of violating constraints leading to an emergency state is encountered. Set-points of certain direct controllers of complex processes are now more and more often under supervisory control of advanced controllers, which can therefore be called the set-point controllers. They constitute a (higher) *set-point control layer*, which is even more commonly called a *constraint control layer*, as its controllers are usually responsible for controlling certain technological constraints influencing product quality.

As a result of the development of electronics and computer technology, the powerful DCS (Distributed Control System) and SCADA (Supervisory Control and Data Acquisition) systems are now a standard, enabling advanced realization of feedback control tasks. Thus, it is possible to apply, in real time, the advanced control techniques. They are usually understood as algorithms more complex than those based on the classic PID control law. These techniques are now applied mainly at the constraint control layer, where process nonlinearity, its multivariable nature and constraints play an important role. However, they can also be addressed to direct control loops which are difficult for classic PID control, *e.g.*, due to large delays, signal constraints or nonlinearities.

The task of the *optimization layer* is to economically evaluate best set-point values for the feedback controllers. Due to an increased computing power it is now realistic to apply on-line optimization, that is optimal and automatic adjustment of the set-points to the varying external influences. However, frequent changes of the set-points calculated at the optimization layer require that the feedback controllers operate not only in the vicinity of one equilibrium point, but can cope with a wider range of variability of input and output process values as well. Real processes are generally nonlinear, therefore there is a need for nonlinear control systems. Moreover, the more precise the optimizer's model of the process and the more precise the stabilization of the optimal values by the feedback controllers, the higher the profits from the optimization. Therefore, the optimization usually sets new requirements for feedback control systems, creating a need for application of advanced control algorithms (in the sense defined earlier).

The subject of the book is situated within the scope of the discussed problems. In the first chapter general issues related to the control in the multilayer structure are discussed. Starting from basic control objectives, the question of a decomposition which leads to the structure is considered. Then the tasks, realization aspects and features of the direct control layer, the constraint control layer and the optimization layer are presented and discussed. Presentation of the multilayer control structure is supported by a carefully chosen worked example of a nonlinear chemical reactor, showing many aspects of the discussed topic, from a decomposition of the process dynamics to the set-point optimization.

The second chapter is devoted to nonlinear control algorithms using fuzzy structures of the Takagi-Sugeno (TS) type. After a short introduction to fuzzy logic and fuzzy nonlinear modeling, design procedures for discrete-time and continuous-time nonlinear TS fuzzy control algorithms are described, both for state-space and input-output process models. The questions of stability analysis of resulting nonlinear control systems are thoroughly addressed. It is not only the author's opinion that the TS fuzzy control is an efficient technique, relatively easy to design and convincing, since it can be treated as a natural nonlinear generalization of the classical linear control algorithms. In particular, it is shown to be a generalization of the well-established PID technique to the form of a nonlinear TS fuzzy PID controller. Constituting a systematic design alternative, the nonlinear fuzzy TS controllers are also a good solution in places where it is necessary to move from linear to nonlinear algorithms, without loosing the experience gathered.

Chapter 3 is devoted to predictive control algorithms, defined by a now commonly used acronym MPC (Model Predictive Control). The MPC is one of the advanced techniques which has achieved great, unquestionable success in practical applications, and has recently had a dominant impact on the direction of development of industrial control systems as well as scientific research within the area of feedback control. There are several reasons for this. The MPC algorithms are indeed the first technique which directly takes into account constraints on both process inputs and outputs. It generates manipulated inputs while also considering internal interactions in the process, due to the direct use of the process model. Therefore, it is efficacious in application to multivariable processes, including those with a different number of manipulated inputs and controlled outputs. Moreover, the principles of operation and tuning of MPC algorithms are comprehensible, relatively easy to explain to engineering and operator staff – an important aspect when introducing new techniques to industrial practice. Needing more calculations at each sampling instant, initially the MPC algorithms were used mainly at the set-point control layer, where longer sampling periods are typical and the key questions are those of constraints and interactions. With increase in computing power and reliability and decrease in prices of processors it has become possible to apply the predictive algorithms also in direct control loops.

In Chapter 3 first linear predictive control algorithms are presented, concentrating on most important formulations: the DMC (Dynamic Matrix Control) algorithm, undoubtedly most popular in industrial process control practice and the GPC (Generalized Predictive Control) algorithm. Explicit versions (constraint free, leading to control laws) are discussed, as well as numerical ones, when at every sampling instant a numerical task of quadratic programming is solved on-line. Starting from linear formulations, the structures of basic nonlinear MPC algorithms are presented, paying particular attention to versions with linearizations, which are essential for effective applications. It is shown that these versions can be particularly easy to implement for nonlinear fuzzy models of the TS type. Problems of stability of MPC algorithms are also discussed, as well as questions of interpretation and adjustment of tuning knobs.

The fourth and last chapter is devoted to algorithms for set-point optimization. After a more general discussion about steady-state optimization in a multilayer control structure, steady-state optimization for control structures with MPC controllers is the subject of presentation. First, attention is devoted to a case when dynamics of disturbances can be comparable with the dynamics of the controlled process. In this case, the classical multilayer approach, with significantly different frequencies of intervention of different layers (the higher the layer, the slower the frequency) usually fails to result in a globally optimal control structure. However, applying an additional simplified steady-state optimization coordinated with the MPC dynamic optimization allows to improve the results. An interesting subject here is an algorithm integrating set-point and MPC dynamic optimizations. In the second part of the chapter, algorithms for on-line measurement-based iterative optimization (iterative improvement) of a steady-state operating point, under significant uncertainty caused by an imprecise model of the controlled process and/or errors in disturbance estimations, are presented. These algorithms are based mainly on the technique of integrated system optimization and parameter estimation.

In the book several important and well-established control structures and algorithms are presented. Starting from basic and known formulations (though supplemented with original views of the author, such as a new, alternative formulation of the GPC control law), the book also includes a series of research results obtained by the author, including those with his PhD students, concerning the nonlinear fuzzy control, the MPC algorithms and the set-point optimization techniques. Therefore, the book is addressed both to research staff and postgraduate students as well as to readers interested in the basic mechanisms of the presented techniques of advanced control, including engineers and practitioners. An appealing feature of the book is illustration of the presented concepts and algorithms by many worked examples in the text, as well as by results of many simulations based on industrial process models, stemming primarily from petrochemical and chemical industries.

This new book is based on a text published originally by the author in Polish in 2002, but several parts of this text have been improved or substantially changed when preparing this edition. In particular, certain topics have been deleted and new topics and research results have been included.

The author of this book is grateful to the colleagues and students from the Institute of Control and Computation Engineering, Warsaw University of Technology, for fruitful discussions, help and encouragement to write this book. In particular, the author is much indebted to Professor Władysław Findeisen, his esteemed teacher and to Professor Krzysztof Malinowski, longtime head of the University Priority Research Program in Control, Information Technology and Automation, supporting the author's research activities. The author is also very grateful to Professors P. D. Roberts from City University, London, and M. A. Brdyś from Birmingham University, for invitations to spend considerable time at these universities and for direct cooperation in research on steady-state optimizing control. The author is also thankful to his former PhD students and actual co-workers, in particular to Dr. Maciej Ławryńczuk and Dr. Piotr Marusak for cooperation in research on predictive control and for help in calculation of some examples and proofreading of the manuscript.

Acknowledgments are also due to the Polish Committee of Scientific Research and then the Polish Ministry of Scientific Research and Information Technology, for supporting the author's research from Polish budget funds in the form of research projects, in particular the one in the last two years, which contributed to this book.

Finally, the author is much indebted to his niece, Anna Basiukiewicz, a specialist in English language, who agreed to read and correct the final text of the book. Last but not least, the author owes a debt of gratitude to his wife Magda for her patience, understanding and support during the course of the book's preparation.

Warsaw, Poland, *Piotr Tatjewski*
August 2006

Contents

Notation

General

$x,\ y, ...$	variables or constants, scalar or vector-valued
n_x	dimensionality of vector x, $n_x = \dim x$
$\mathbf{A}, \mathbf{B}, ...$	real matrices
$x^T,\ \mathbf{A}^T$	transpose of vector x, of matrix $\mathbf{A}$
$\lVert x \rVert^2_{\mathbf{R}}$	$x^T \mathbf{R} x$
$\mathrm{diag}\{a_1, ..., a_n\}$	diagonal matrix with $a_1, ..., a_n$ on the diagonal
(x, y)	ordered pair of elements x and y, also vector $[x^T\ y^T]^T$
$A(z^{-1})$	algebraic polynomial in unit delay operator z^{-1}
$E\{\cdot\}$	expected value operator
$g(\cdot),\ f(\cdot), ...$	scalar or vector functions
$g^{'}(x)$	derivative of function g at point x
	for $g : \mathbb{R}^n \to \mathbb{R},\ \ g^{'}(x) = [\frac{\partial g(x)}{\partial x_1}\ \cdots\ \frac{\partial g(x)}{\partial x_n}]$,
	for $g : \mathbb{R}^n \to \mathbb{R}^m,\ \ g^{'}(x) = \{\frac{\partial g_i(x)}{\partial x_j}\} = \begin{bmatrix} \frac{\partial g_1(x)}{\partial x_1} & \cdots & \frac{\partial g_1(x)}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial g_m(x)}{\partial x_1} & \cdots & \frac{\partial g_m(x)}{\partial x_n} \end{bmatrix}$
$\nabla g(x)$	gradient, $\nabla g(x) = (g^{'}(x))^T$
$g^{'}_x(x, y)$	partial derivative of function g with respect to x, at (x, y)

Specific

$\mu_C(\cdot)$	membership function of the fuzzy set C
$w^i(k)$	activation level of i-th fuzzy inference rule at sample k
$u(k)$	manipulated variable (process control input) at sample k
$y(k)$	controlled variable (process controlled output) at sample k
$x(k)$	state of dynamic system at sample k

$z(k)$	measured disturbance at sample k
$d(k)$	unmeasured disturbance at process output at sample k
$e(k)$	control error at sample k, $e(k) = y^{sp}(k) - y(k)$
$y^{sp}(k)$	set-point for the controlled variable $y(k)$ at sample k
c	decision variable of the optimization layer, simultaneously: set-point for controllers of lower layers (Chapters 1 and 4)
$y(k+p\|k)$	value of y predicted for sample $k+p$ at current sample k
$y^0(k+p\|k)$	free component of $y(k+p\|k)$
$\triangle y(k+p\|k)$	forced component of $y(k+p\|k)$
s_j	j-th element of discrete unit step response
D	dynamics horizon, *i.e.*, $s_j =$ const. for $j \geq D$
T_p	sampling period in a discrete dynamic system
τ	process time delay (defined as a number of sampling periods), excluding a unit discretization delay ($\tau \geq 0$)
$\bar{\tau}$	overall time delay in a discrete-time model (defined as a number of sampling periods), including the discretization delay, $\bar{\tau} = \tau + 1$
$F(\cdot)$	model of steady-state input-output process mapping
$F_*(\cdot)$	real (unknown) steady-state input-output process mapping

Parameters of model predictive controllers:

N	prediction horizon (defined as a number of sampling periods)
N_u	control horizon (defined as a number of sampling periods)
N_1	initial time for summing control errors in the predictive controller cost function ($1 \leq N_1$, usually $N_1 = \tau + 1$)
N_{cw1}, N_{cw}	lower and upper bound of the constraint window (defined as numbers of sampling periods), $N_1 \leq N_{cw1} < N_{cw} \leq N$
$\boldsymbol{\Psi}(p)$	weighting matrix for control errors predicted for sample $k+p$
$\underline{\boldsymbol{\Psi}}$	$\underline{\boldsymbol{\Psi}} = \mathrm{diag}\{\boldsymbol{\Psi}(N_1), ..., \boldsymbol{\Psi}(N)\}$
$\boldsymbol{\Lambda}(p)$	weighting matrix for control input moves for sample $k+p$
$\underline{\boldsymbol{\Lambda}}$	$\underline{\boldsymbol{\Lambda}} = \mathrm{diag}\{\boldsymbol{\Lambda}(0), ..., \boldsymbol{\Lambda}(N_u - 1)\}$
λ	scalar weighting coefficient in the case when $\boldsymbol{\Lambda}(p) = \lambda \mathbf{I}$
γ	coefficient of first-order linear filter defining reference trajectory for controlled variables

Acronyms

ANFIS	Adaptive Neuro-Fuzzy Inference System
ARMAX	Auto-Regressive Moving Average with eXogenous input
ARX	Auto-Regressive with eXogenous input
DCS	Distributed Control System

ISOPE	Integrated System Optimization and Parameter Estimation
LMI	Linear Matrix Inequalities
LP	Linear Programming
MIMO	Multi-Input Multi-Output
PDC	Parallel Distributed Compensation
QP	Quadratic Programming
SCADA	Supervisory Control and Data Acquisition
SISO	Single-Input Single-Output
SQP	Sequential Quadratic Programming

Model predictive control algorithms:

CRHPC	Constrained Receding Horizon Predictive Control
DMC	Dynamic Matrix Control
FDMC	Fuzzy DMC
FGPC	Fuzzy GPC
FMPC	Fuzzy MPC
FMPCS	Fuzzy MPCS
GPC	Generalized Predictive Control
IDCOM	IDentification and COMmand
LSSO	Local Steady-State Optimization
MAC	Model Algorithmic Control
MPHC	Model Predictive Heuristic Control
MPC	Model Predictive Control (Model-based Predictive Control)
MPC-NO	MPC with Nonlinear Optimization
MPC-NPL	MPC with Nonlinear Prediction and Linearization
MPC-NPL+	MPC-NPL algorithm with additional inner iteration loop
MPC-NSL	MPC Nonlinear with Successive Linearization
MPCS	MPC with State-space model
PFC	Predictive Functional Control
QDMC	Quadratic Dynamic Matrix Control
SMOC	Shell Multivariable Optimizing Controller
SSTO	Steady-State Target Optimization