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To Janet
E.F.C.

To Carlos and Marta
C.B.

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 evolved for the topic to be taught as a specialised tutorial workshop or as a course to undergraduate, graduate or industrial engineers. *Advanced Textbooks in Control and Signal Processing* are 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 and systematic presentation of some of the newer emerging control and signal processing technologies in the textbook series.

The books of E.F. Camacho and C. Bordons on model predictive control provide a valuable archive of the development of this particular control technology and theoretical paradigm. In 1995 Professors Camacho and Bordons published their monograph *Model Predictive Control in the Process Industries* (ISBN 3-540-19924-1) in the Springer-Verlag London *Advances in Industrial Control* series. As the title demonstrates, this monograph emphasized the widespread use of the model predictive control technique in the process industries. It was the use of simple models and the ability of the method easily to accommodate system constraints that gave the method its advantage over classical control. Another feature was the optimisation framework of the method where minimising energy and resource usage are widely used concepts in the process industries.

The *Advances in Industrial Control* monograph on model predictive control was a very successful book. Somehow the mix of introductions to Model Predictive Control theory and the empirical practical guidelines developed by the authors was readily absorbed by industrial engineers and academic researchers alike. So that

just three years later in 1998, the monograph was revised and reincarnated as a volume in the *Advanced Textbooks in Control and Signal Processing* series simply titled *Model Predictive Control* (ISBN 3-540-76241-8).

Now a further five years has passed and the subject of model predictive control continues to grow along with the stature and experience of the distinguished authors, Professors Camacho and Bordons. This second edition has three new chapters and an up-graded applications chapter. The mix of theory and empirical practical insight remains the same but the new chapters are on nonlinear model predictive control, applications to hybrid systems and on fast implementation methods. The new applications included are for an olive oil mill and a robot problem. Thus the second edition archives recent theoretical developments to nonlinear and hybrid systems whilst the robot application broadens the applications archive to areas other than the process industries.

We welcome this second edition of Professors Camacho and Bordons' *Model Predictive Control*. Engineers and control researchers new to the predictive control methods will find the early chapters of the book provide an excellent historical and tutorial introduction to the techniques. Seasoned researchers will be interested to add to their knowledge an assessment of the potential of predictive control methods for nonlinear and hybrid systems. In five years' time we may even be looking forward to a further update of this very successful control engineering method in a third edition of a fine *Advanced Textbooks in Control and Signal Processing* volume!

M.J. Grimble and M.A. Johnson
Industrial Control Centre
Glasgow, Scotland, U.K.
October 2003

Preface

Model Predictive Control (MPC) has developed considerably over the last two decades, both within the research control community and in industry. This success can be attributed to the fact that Model Predictive Control is, perhaps, the most general way of posing the process control problem in the time domain. Model Predictive Control formulation integrates optimal control, stochastic control, control of processes with dead time, multivariable control and future references when available. Another advantage of Model Predictive Control is that because of the finite control horizon used, constraints and, in general nonlinear processes which are frequently found in industry, can be handled. Although Model Predictive Control has been found to be quite a robust type of control in most reported applications, stability and robustness proofs have been difficult to obtain because of the finite horizon used. This has been a drawback for a wider dissemination of Model Predictive Control in the control research community. Some new and very promising results in this context allow one to think that this control technique will experience greater expansion within this community in the near future. On the other hand, although a number of applications have been reported in both industry and research institutions, Model Predictive Control has not yet reached in industry the popularity that its potential would suggest. One reason for this is that its implementation requires some mathematical complexities which are not a problem in general for the research control community, where mathematical packages are normally fully available, but which represent a drawback for the use of the technique by control engineers in practice.

One of the goals of this text is to contribute to filling the gap between the empirical way in which practitioners tend to use control algorithms and the powerful but sometimes abstractly formulated techniques developed by control researchers. The book focuses on implementation issues for Model Predictive Controllers and intends to present easy ways of implementing them in industry. The book also aims to serve as a guide to implement Model Pre-

dictive Control and as a motivation for doing so by showing that using such a powerful control technique does not require complex control algorithms.

The book is aimed mainly at practitioners, although it can be followed by a wide range of readers, as only basic knowledge of control theory and sample data systems is required. A general survey of the field, and guidance in the choice of appropriate implementation techniques, as well as many illustrative examples, are given for practicing engineers and senior undergraduate and graduate students. The book covers most Model Predictive Control algorithms with a special emphasis on Generalized Predictive Control. This control method uses a transfer function model of the process in terms of gains, time constants and dead times which are well understood in industry. This method is middle of the road between industry and academy, where state space-based methods are more attractive because they allow easy analysis of stability and robustness.

We have not tried to give a full description of all MPC algorithms and their properties, although the main ones and their main properties are described. Neither do we claim this technique to be the best choice for the control of every process, although we feel that it has many advantages. Therefore we have not tried to make a comparative study of different Model Predictive Control algorithms amongst themselves and versus other control strategies.

The text gathers recent results and developments that have appeared in the active field of Model Predictive Control since the first edition was published in 1999. The text is composed of material collected from lectures given to senior undergraduate students and articles written by the authors, and is also based on a previous book (*Model Predictive Control in the Process Industry*, Springer, 1995), written by the authors.

This second edition is not just an updated version of the previous book; it also includes exercises and companion software. This MATLAB[®]-based software package can be freely downloaded from the book's companion web site (<http://www.esi.us.es/MPCBOOK>) and allows the examples that appear in the book to be reproduced.

E. F. Camacho and C. Bordons
Seville, March 2004

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Glossary

Notation

A(\cdot) boldface upper case letters denote polynomial matrices.

A(\cdot) italic and upper case letters denote polynomials.

M italic upper case letters denote real matrices.

b boldface lower letters indicate real vectors composed of elements at different time instants.

M boldface upper case letters denote real matrices composed of other matrices or vectors.

Symbols

s complex variable used in Laplace transform

z^{-1} backward shift operator

z forward shift operator and complex variable used in z – transform

$(M)_{ij}$ element ij of matrix M

$(v)_i$ i^{th} – element of vector v

$(\cdot)^T$ transpose of (\cdot)

$diag(x_1, \dots, x_n)$ diagonal matrix with diagonal elements equal to x_1, \dots, x_n

$|(\cdot)|$ absolute value of (\cdot)

$\|\mathbf{v}\|_Q^2$ $\mathbf{v}^T Q \mathbf{v}$

$\|\mathbf{v}\|_l$ l – norm of \mathbf{v}

$\|\mathbf{v}\|_\infty$ infinity norm of \mathbf{v}

- $I_{n \times n}$ ($n \times n$) identity matrix
- I identity matrix of appropriate dimensions
- $\mathbf{0}_{p \times q}$ ($p \times q$) matrix with all entries equal to zero
- $\mathbf{0}$ matrix of appropriate dimensions with all entries equal to zero
- $\mathbf{1}_n$ column vector of dimension n with all entries equal to one
- $\mathbf{1}$ column vector with all entries equal to one
- $\langle x, z \rangle$ dot product of vectors x and z
- $E[\cdot]$ expectation operator
- $\hat{\cdot}$ expected value
- $\hat{x}(t + j|t)$ expected value of $x(t + j)$ with available information at instant t
- $\delta(P(\cdot))$ degree of polynomial $P(\cdot)$
- Δ $1 - z^{-1}$. increment operator
- $\det(M)$ determinant of matrix M
- $\min_{x \in \mathbf{X}} J(x)$ the minimum value of $J(x)$ for all values of $x \in \mathbf{X}$

Model parameters and variables

- m number of input variables
- n number of output variables
- $u(t)$ input variables at instant t
- $y(t)$ output variables at instant t
- $x(t)$ state variables at instant t
- $e(t)$ discrete white noise with zero mean
- d dead time of the process expressed in sampling time units
- $\mathbf{A}(z^{-1})$ process left polynomial matrix for the LMFD
- $\mathbf{B}(z^{-1})$ process right polynomial matrix for the LMFD
- $\mathbf{C}(z^{-1})$ colouring polynomial matrix

Controller parameters and variables

- N_1 lower value of prediction horizon
- N_2 higher value of prediction horizon
- N number of points of prediction horizon ($N = N_2 - N_1$)
- N_3 control horizon (N_u)
- λ weighting factor for control increments
- δ weighting factor for predicted error

- \mathbf{u} vector of future control increments for the control horizon
- \mathbf{y} vector of predicted outputs for prediction horizon
- \mathbf{f} vector of predicted free response
- \mathbf{w} vector of future references
- $\bar{\mathbf{U}}$ vector of maximum allowed values of manipulated variables
- $\underline{\mathbf{U}}$ vector of minimum allowed values of manipulated variables
- \bar{u} vector of maximum allowed values of manipulated variable
slew rates
- \underline{u} vector of minimum allowed values of manipulated variable
slew rates
- \bar{y} vector of maximum allowed values of output variables
- \underline{y} vector of minimum allowed values of output variables
- $\tilde{\mathbf{A}}(z^{-1})$ polynomial $\mathbf{A}(z^{-1})$ multiplied by Δ

Acronyms

- ANN Artificial Neural Network
- CARIMA Controlled Autoregressive Integrated Moving Average
- CARMA Controlled Autoregressive Moving Average
- CRHPC Constrained Receding Horizon Predictive Control
- DMC Dynamic Matrix Control
- EHAC Extended Horizon Adaptive Control
- EPSAC Extended Prediction Self-Adaptive Control
- FIR Finite Impulse Response
- FLOP Floating Point Operation
- GMV Generalized Minimum Variance
- GPC Generalized Predictive Control
- HIECON Hierarchical Constraint Control
- IDCOM Identification and Command
- KKT Karush-Kuhn-Tucker
- LCP Linear Complementary Problem
- LMFD Left Matrix Fraction Description
- LMI Linear Matrix Inequalities
- LP Linear Programming
- LQ Linear Quadratic
- LQG Linear Quadratic Gaussian
- LRPC Long Range Predictive Control
- LTR Loop Transfer Recovery
- MAC Model Algorithmic Control
- MILP Mixed Integer Linear Programming
- MIMO Multi-Input Multi-Output
- MIP Mixed Integer Programming
- MIQP Mixed Integer Quadratic Programming
- MLD Mixed Logical Dynamical

- MPC Model Predictive Control
- MPHC Model Predictive Heuristic Control
- MUSMAR Multi-Step Multivariable Adaptive Control
- MURHAC Multipredictor Receding Horizon Adaptive Control
 - NLP Nonlinear Programming
 - OPC Optimum Predictive Control
 - ODD Outside Unit Disk
 - PCT Predictive Control Technology
 - PFC Predictive Functional Control
 - PID Proportional Integral Derivative
 - PWA Piecewise Affine
 - QP Quadratic Programming
- RMPCT Robust Model Predictive Control Technology
- SCADA Supervisory Control and Data Acquisition
- SCAP Adaptive Predictive Control System
- SGPC Stable Generalized Predictive Control
- SISO Single-Input Single-Output
- SMCA Setpoint Multivariable Control Architecture
 - SQP Sequential Quadratic Programming
 - UPC Unified Predictive Control

Contents

1	Introduction to Model Predictive Control	1
1.1	MPC Strategy	2
1.2	Historical Perspective	5
1.3	Industrial Technology	8
1.4	Outline of the Chapters	10
2	Model Predictive Controllers	13
2.1	MPC Elements	13
2.1.1	Prediction Model	13
2.1.2	Objective Function	18
2.1.3	Obtaining the Control Law	21
2.2	Review of Some MPC Algorithms	22
2.3	State Space Formulation	27
3	Commercial Model Predictive Control Schemes	31
3.1	Dynamic Matrix Control	31
3.1.1	Prediction	32
3.1.2	Measurable Disturbances	34
3.1.3	Control Algorithm	34
3.2	Model Algorithmic Control	36
3.2.1	Process Model and Prediction	36
3.2.2	Control Law	38
3.3	Predictive Functional Control	39
3.3.1	Formulation	39
3.4	Case Study: A Water Heater	42
3.5	Exercises	45
4	Generalized Predictive Control	47
4.1	Introduction	47
4.2	Formulation of Generalized Predictive Control	48
4.3	The Coloured Noise Case	53

4.4	An Example	54
4.5	Closed-Loop Relationships	57
4.6	The Role of the T Polynomial	61
4.6.1	Selection of the T Polynomial	61
4.6.2	Relationships with Other Formulations	62
4.7	The P Polynomial	62
4.8	Consideration of Measurable Disturbances	63
4.9	Use of a Different Predictor in GPC	66
4.9.1	Equivalent Structure	66
4.9.2	A Comparative Example	70
4.10	Constrained Receding Horizon Predictive Control	71
4.10.1	Computation of the Control Law	72
4.10.2	Properties	75
4.11	Stable GPC	76
4.11.1	Formulation of the Control Law	77
4.12	Exercises	78
5	Simple Implementation of GPC for Industrial Processes	81
5.1	Plant Model	82
5.1.1	Plant Identification: The Reaction Curve Method	82
5.2	The Dead Time Multiple of the Sampling Time Case	84
5.2.1	Discrete Plant Model	84
5.2.2	Problem Formulation	85
5.2.3	Computation of the Controller Parameters	87
5.2.4	Role of the Control-weighting Factor	89
5.2.5	Implementation Algorithm	90
5.2.6	An Implementation Example	90
5.3	The Dead Time Nonmultiple of the Sampling Time Case	93
5.3.1	Discrete Model of the Plant	93
5.3.2	Controller Parameters	95
5.3.3	Example	98
5.4	Integrating Processes	99
5.4.1	Derivation of the Control Law	100
5.4.2	Controller Parameters	102
5.4.3	Example	104
5.5	Consideration of Ramp Setpoints	105
5.5.1	Example	108
5.6	Comparison with Standard GPC	108
5.7	Stability Robustness Analysis	111
5.7.1	Structured Uncertainties	112
5.7.2	Unstructured Uncertainties	113
5.7.3	General Comments	116
5.8	Composition Control in an Evaporator	117
5.8.1	Description of the Process	117
5.8.2	Obtaining the Linear Model	119

5.8.3	Controller Design	121
5.8.4	Results	122
5.9	Exercises	125
6	Multivariable Model Predictive Control	127
6.1	Derivation of Multivariable GPC	127
6.1.1	White Noise Case	128
6.1.2	Coloured Noise Case	132
6.1.3	Measurable Disturbances	135
6.2	Obtaining a Matrix Fraction Description	138
6.2.1	Transfer Matrix Representation	138
6.2.2	Parametric Identification	141
6.3	State Space Formulation	143
6.3.1	Matrix Fraction and State Space Equivalences	144
6.4	Case Study: Flight Control	147
6.5	Convolution Models Formulation	149
6.6	Case Study: Chemical Reactor	152
6.6.1	Plant Description	152
6.6.2	Obtaining the Plant Model	154
6.6.3	Control Law	156
6.6.4	Simulation Results	157
6.7	Dead Time Problems	157
6.8	Case Study: Distillation Column	163
6.9	Multivariable MPC and Transmission Zeros	166
6.9.1	Simulation Example	170
6.9.2	Tuning MPC for Processes with OUD Zeros	173
6.10	Exercises	175
7	Constrained Model Predictive Control	177
7.1	Constraints and MPC	177
7.1.1	Constraint General Form	183
7.1.2	Illustrative Examples	183
7.2	Constraints and Optimization	187
7.3	Revision of Main Quadratic Programming Algorithms	188
7.3.1	The Active Set Methods	189
7.3.2	Feasible Direction Methods	191
7.3.3	Initial Feasible Point	192
7.3.4	Pivoting Methods	193
7.4	Constraints Handling	196
7.4.1	Slew Rate Constraints	196
7.4.2	Amplitude Constraints	198
7.4.3	Output Constraints	199
7.4.4	Constraint Reduction	199
7.5	1-norm	201
7.6	Case Study: A Compressor	203

7.7	Constraint Management	206
7.7.1	Feasibility	206
7.7.2	Techniques for Improving Feasibility	207
7.8	Constrained MPC and Stability	209
7.9	Multiobjective MPC	212
7.9.1	Priorization of Objectives	214
7.10	Exercises	216
8	Robust Model Predictive Control	217
8.1	Process Models and Uncertainties	218
8.1.1	Truncated Impulse Response Uncertainties	219
8.1.2	Matrix Fraction Description Uncertainties	220
8.1.3	Global Uncertainties	221
8.2	Objective Functions	224
8.2.1	Quadratic Cost Function	225
8.2.2	∞ - ∞ norm	226
8.2.3	1-norm	228
8.3	Robustness by Imposing Constraints	230
8.4	Constraint Handling	231
8.5	Illustrative Examples	232
8.5.1	Bounds on the Output	232
8.5.2	Uncertainties in the Gain	232
8.6	Robust MPC and Linear Matrix Inequalities	234
8.7	Closed-Loop Predictions	237
8.7.1	An Illustrative Example	238
8.7.2	Increasing the Number of Decision Variables	239
8.7.3	Dynamic Programming Approach	241
8.7.4	Linear Feedback	243
8.7.5	An Illustrative Example	245
8.8	Exercises	247
9	Nonlinear Model Predictive Control	249
9.1	Nonlinear MPC Versus Linear MPC	250
9.2	Nonlinear Models	251
9.2.1	Empirical Models	252
9.2.2	Fundamental Models	261
9.2.3	Grey-box Models	262
9.2.4	Modelling Example	262
9.3	Solution of the NMPC Problem	266
9.3.1	Problem Formulation	267
9.3.2	Solution	267
9.4	Techniques for Nonlinear Predictive Control	269
9.4.1	Extended Linear MPC	269
9.4.2	Local Models	270
9.4.3	Suboptimal NPMC	271

9.4.4	Use of Short Horizons	271
9.4.5	Decomposition of the Control Sequence	272
9.4.6	Feedback Linearization	274
9.4.7	MPC Based on Volterra Models	274
9.4.8	Neural Networks	277
9.4.9	Commercial Products	277
9.5	Stability and Nonlinear MPC	279
9.6	Case Study: pH Neutralization Process	282
9.6.1	Process Model	284
9.6.2	Results	285
9.7	Exercises	287
10	Model Predictive Control and Hybrid Systems	289
10.1	Hybrid System Modelling	289
10.2	Example: A Jacket Cooled Batch Reactor	292
10.2.1	Mixed Logical Dynamical Systems	293
10.2.2	Example	296
10.3	Model Predictive Control of MLD Systems	298
10.3.1	Branch and Bound Mixed Integer Programming	299
10.3.2	An Illustrative Example	302
10.4	Piecewise Affine Systems	303
10.4.1	Example: Tank with Different Area Sections	307
10.4.2	Reach Set, Controllable Set, and STG Algorithm	308
10.5	Exercises	309
11	Fast Methods for Implementing Model Predictive Control	311
11.1	Piecewise Affinity of MPC	311
11.2	MPC and Multiparametric Programming	314
11.3	Piecewise Implementation of MPC	316
11.3.1	Illustrative Example: The Double Integrator	317
11.3.2	Nonconstant References and Measurable Disturbances	320
11.3.3	Example	321
11.3.4	The 1-norm and ∞ -norm Cases	322
11.4	Fast Implementation of MPC for Uncertain Systems	326
11.4.1	Example	329
11.4.2	The Closed-Loop Min-max MPC	330
11.5	Approximated Implementation for MPC	333
11.6	Fast Implementation of MPC and Dead Time Considerations	334
11.7	Exercises	335
12	Applications	337
12.1	Solar Power Plant	337
12.1.1	Self-tuning GPC Control Strategy	339
12.1.2	Gain Scheduling Generalized Predictive Control	342

- 12.2 Pilot Plant 352
 - 12.2.1 Plant Description 352
 - 12.2.2 Plant Control 353
 - 12.2.3 Flow Control 354
 - 12.2.4 Temperature Control at the Exchanger Output 355
 - 12.2.5 Temperature Control in the Tank 357
 - 12.2.6 Level Control 358
 - 12.2.7 Remarks 358
- 12.3 Model Predictive Control in a Sugar Refinery 359
- 12.4 Olive Oil Mill 362
 - 12.4.1 Plant Description 364
 - 12.4.2 Process Modelling and Validation 365
 - 12.4.3 Controller Synthesis 366
 - 12.4.4 Experimental Results 368
- 12.5 Mobile Robot 371
 - 12.5.1 Problem Definition 371
 - 12.5.2 Prediction Model 372
 - 12.5.3 Parametrization of the Desired Path 374
 - 12.5.4 Potential Function for Considering Fixed Obstacles 374
 - 12.5.5 The Neural Network Approach 376
 - 12.5.6 Training Phase 378
 - 12.5.7 Results 379

- A Revision of the Simplex Method 381**
 - A.1 Equality Constraints 381
 - A.2 Finding an Initial Solution 382
 - A.3 Inequality Constraints 383

- B Dynamic Programming and Linear Quadratic Optimal Control 385**
 - B.1 Linear Quadratic Problem 385
 - B.2 Infinite Horizon 387

- References 389**

- Index 401**