SECOND EDITION

Model Predictive Control

E.F. Camacho and C. Bordons

Springer

ADVANCED TEXTBOOKS IN CONTROL AND SIGNAL PROCESSING

E.F Camacho and C. Bordons

Model Predictive Control

Second Edition

With 139 Figures

Springer

E.F. Camacho Dr. Eng.
C. Bordons Dr. Eng.
Escuela Superior de Ingenieros, Universidad de Sevilla,
Camino de los Descubrimientos S/N, 41092 Sevilla, Spain

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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 four years later in 1999, 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 Predictive 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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Finally, both authors thank their families for their support, patience and understanding of family time lost during the writing of the book.

Glossary

Notation

$\mathbf{A}(\cdot)$ boldface upper case letters denote polynomial matrices.
$A(\cdot)$ italic and upper case letters denote polynomials.
M italic upper case letters denote real matrices.
$\mathbf{b}$ boldface lower letters indicate real vectors composed of elements at different time instants.
$\mathbf{M}$ 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 $(\cdot)$
$diag(x_1, \cdots, x_n)$	diagonal matrix with diagonal elements equal to $x_1, \cdots, x_n$
$\lvert(\cdot)\rvert$	absolute value of $(\cdot)$
$\lVert\mathbf{v}\rVert_Q^2$	$\mathbf{v}^T Q \mathbf{v}$
$\lVert\mathbf{v}\rVert_l$	$l -$ norm of $\mathbf{v}$
$\lVert\mathbf{v}\rVert_\infty$	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
$< x, z >$	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 $P(\cdot)$
$\triangle$	$1 - z^{-1}$. 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
$\overline{U}$ vector of maximum allowed values of manipulated variables
$\underline{U}$ vector of minimum allowed values of manipulated variables
$\overline{u}$ vector of maximum allowed values of manipulated variable slew rates
$\underline{u}$ vector of minimum allowed values of manipulated variable slew rates
$\overline{y}$ 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 $\triangle$

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
OUD 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

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