

SECOND EDITION

Model Predictive Control

E.F. Camacho and C. Bordons



Springer

ADVANCED TEXTBOOKS IN CONTROL AND SIGNAL PROCESSING

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