

Liuping Wang

Model Predictive Control System Design and Implementation Using MATLAB[®]



Springer

Contents

List of Symbols and Abbreviations	xxvii
1 Discrete-time MPC for Beginners	1
1.1 Introduction	1
1.1.1 Day-to-day Application Example of Predictive Control ..	1
1.1.2 Models Used in the Design	3
1.2 State-space Models with Embedded Integrator	4
1.2.1 Single-input and Single-output System	4
1.2.2 MATLAB Tutorial: Augmented Design Model.....	6
1.3 Predictive Control within One Optimization Window	7
1.3.1 Prediction of State and Output Variables	7
1.3.2 Optimization	9
1.3.3 MATLAB Tutorial: Computation of MPC Gains	13
1.4 Receding Horizon Control	15
1.4.1 Closed-loop Control System	16
1.4.2 MATLAB Tutorial: Implementation of Receding Horizon Control	20
1.5 Predictive Control of MIMO Systems	22
1.5.1 General Formulation of the Model	22
1.5.2 Solution of Predictive Control for MIMO Systems	26
1.6 State Estimation	27
1.6.1 Basic Ideas About an Observer.....	28
1.6.2 Basic Results About Observability.....	30
1.6.3 Kalman Filter	33
1.6.4 Tuning Observer Dynamics	34
1.7 State Estimate Predictive Control	34
1.8 Summary	37
Problems	39

2 Discrete-time MPC with Constraints	43
2.1 Introduction	43
2.2 Motivational Examples	43
2.3 Formulation of Constrained Control Problems	47
2.3.1 Frequently Used Operational Constraints	47
2.3.2 Constraints as Part of the Optimal Solution	50
2.4 Numerical Solutions Using Quadratic Programming	53
2.4.1 Quadratic Programming for Equality Constraints	53
2.4.2 Minimization with Inequality Constraints	58
2.4.3 Primal-Dual Method	62
2.4.4 Hildreth's Quadratic Programming Procedure	63
2.4.5 MATLAB Tutorial: Hildreth's Quadratic Programming	67
2.4.6 Closed-form Solution of λ^*	68
2.5 Predictive Control with Constraints on Input Variables	69
2.5.1 Constraints on Rate of Change	70
2.5.2 Constraints on Amplitude of the Control	73
2.5.3 Constraints on Amplitude and Rate of Change	77
2.5.4 Constraints on the Output Variable	78
2.6 Summary	81
Problems	83
3 Discrete-time MPC Using Laguerre Functions	85
3.1 Introduction	85
3.2 Laguerre Functions and DMPC	85
3.2.1 Discrete-time Laguerre Networks	86
3.2.2 Use of Laguerre Networks in System Description	90
3.2.3 MATLAB Tutorial: Use of Laguerre Functions in System Modelling	90
3.3 Use of Laguerre Functions in DMPC Design	92
3.3.1 Design Framework	93
3.3.2 Cost Functions	94
3.3.3 Minimization of the Objective Function	97
3.3.4 Convolution Sum	98
3.3.5 Receding Horizon Control	98
3.3.6 The Optimal Trajectory of Incremental Control	99
3.4 Extension to MIMO Systems	106
3.5 MATLAB Tutorial Notes	108
3.5.1 DMPC Computation	108
3.5.2 Predictive Control System Simulation	115
3.6 Constrained Control Using Laguerre Functions	118
3.6.1 Constraints on the Difference of the Control Variable	118
3.6.2 Constraints on the Amplitudes of the Control Signal	121
3.7 Stability Analysis	127
3.7.1 Stability with Terminal-State Constraints	127
3.7.2 Stability with Large Prediction Horizon	129

3.8	Closed-form Solution of Constrained Control for SISO Systems	131
3.8.1	MATLAB Tutorial: Constrained Control of DC Motor	135
3.9	Summary	143
	Problems	144
4	Discrete-time MPC with Prescribed Degree of Stability	149
4.1	Introduction	149
4.2	Finite Prediction Horizon: Re-visited	149
4.2.1	Motivational Example	150
4.2.2	Origin of the Numerical Conditioning Problem	150
4.3	Use of Exponential Data Weighting	152
4.3.1	The Cost Function	152
4.3.2	Optimization of Exponentially Weighted Cost Function	153
4.3.3	Interpretation of Results from Exponential Weighting	156
4.4	Asymptotic Closed-loop Stability with Exponential Weighting	158
4.4.1	Modification of Q and R Matrices	158
4.4.2	Interpretation of the Results	160
4.5	Discrete-time MPC with Prescribed Degree of Stability	165
4.6	Tuning Parameters for Closed-loop Performance	170
4.6.1	The Relationship Between P_∞ and J_{min}	171
4.6.2	Tuning Procedure Once More	176
4.7	Exponentially Weighted Constrained Control	179
4.8	Additional Benefit	182
4.9	Summary	186
	Problems	188
5	Continuous-time Orthonormal Basis Functions	193
5.1	Introduction	193
5.2	Orthonormal Expansion	193
5.3	Laguerre Functions	194
5.4	Approximating Impulse Responses	197
5.5	Kautz Functions	202
5.5.1	Kautz Functions in the Time Domain	204
5.5.2	Modelling the System Impulse Response	205
5.6	Summary	206
	Problems	207
6	Continuous-time MPC	209
6.1	Introduction	209
6.2	Model Structures for CMPC Design	209
6.2.1	Model Structure	211
6.2.2	Controllability and Observability of the Model	215
6.3	Model Predictive Control Using Finite Prediction Horizon	216
6.3.1	Modelling the Control Trajectory	217
6.3.2	Predicted Plant Response	218

6.3.3	Analytical Solution of the Predicted Response	219
6.3.4	The Recursive Solution	221
6.4	Optimal Control Strategy	224
6.5	Receding Horizon Control	227
6.6	Implementation of the Control Law in Digital Environment	234
6.6.1	Estimation of the States	234
6.6.2	MATLAB Tutorial: Closed-loop Simulation	237
6.7	Model Predictive Control Using Kautz Functions	240
6.8	Summary	244
	Problems	245
7	Continuous-time MPC with Constraints	249
7.1	Introduction	249
7.2	Formulation of the Constraints	249
7.2.1	Frequently Used Constraints	249
7.2.2	Constraints as Part of the Optimal Solution	251
7.3	Numerical Solutions for the Constrained Control Problem	257
7.4	Real-time Implementation of Continuous-time MPC	262
7.5	Summary	266
	Problems	267
8	Continuous-time MPC with Prescribed Degree of Stability	271
8.1	Introduction	271
8.2	Motivating Example	271
8.3	CMPC Design Using Exponential Data Weighting	274
8.4	CMPC with Asymptotic Stability	277
8.5	Continuous-time MPC with Prescribed Degree of Stability	283
8.5.1	The Original Anderson and Moore's Results	283
8.5.2	CMPC with a Prescribed Degree of Stability	284
8.5.3	Tuning Parameters and Design Procedure	286
8.6	Constrained Control with Exponential Data Weighting	288
8.7	Summary	291
	Problems	293
9	Classical MPC Systems in State-space Formulation	297
9.1	Introduction	297
9.2	Generalized Predictive Control in State-space Formulation	298
9.2.1	Special Class of Discrete-time State-space Structures	298
9.2.2	General NMSS Structure for GPC Design	301
9.2.3	Generalized Predictive Control in State-space Formulation	302
9.3	Alternative Formulation to GPC	305
9.3.1	Alternative Formulation for SISO Systems	305
9.3.2	Closed-loop Poles of the Predictive Control System	307
9.3.3	Transfer Function Interpretation	310

9.4	Extension to MIMO Systems.....	313
9.4.1	MNSS Model for MIMO Systems	314
9.4.2	Case Study of NMSS Predictive Control System	315
9.5	Continuous-time NMSS model	320
9.6	Case Studies for Continuous-time MPC	323
9.7	Predictive Control Using Impulse Response Models	326
9.8	Summary.....	329
	Problems	330
10	Implementation of Predictive Control Systems.....	333
10.1	Introduction	333
10.2	Predictive Control of DC Motor Using a Micro-controller	333
10.2.1	Hardware Configuration	334
10.2.2	Model Development	336
10.2.3	DMPC Tuning	337
10.2.4	DMPC Implementation	338
10.2.5	Experimental Results	339
10.3	Implementation of Predictive Control Using xPC Target	340
10.3.1	Overview	340
10.3.2	Creating a SIMULINK Embedded Function.....	342
10.3.3	Constrained Control of DC Motor Using xPC Target ..	347
10.4	Control of Magnetic Bearing Systems	349
10.4.1	System Identification	351
10.4.2	Experimental Results	352
10.5	Continuous-time Predictive Control of Food Extruder	353
10.5.1	Experimental Setup	355
10.5.2	Mathematical Models	357
10.5.3	Operation of the Model Predictive Controller	358
10.5.4	Controller Tuning Parameters.....	359
10.5.5	On-line Control Experiments.....	360
10.6	Summary.....	365
References	367	
Index	373	