SHAOYUAN LI • YI ZHENG

DISTRIBUTED MODEL PREDICTIVE CONTROL FOR PLANT-WIDE SYSTEMS

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Shaoyuan Li and Yi Zheng

Shanghai Jiao Tong University, China

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Contents

Preface **xi**

About the Authors **xv**

Acknowledgement **xvii**

List of Figures **xix**

List of Tables **xxiii**

1 Introduction **1**
1.1 Plant-Wide System 1
1.2 Control System Structure of the Plant-Wide System 3
  1.2.1 Centralized Control 4
  1.2.2 Decentralized Control and Hierarchical Coordinated Decentralized Control 5
  1.2.3 Distributed Control 6
1.3 Predictive Control 8
  1.3.1 What is Predictive Control 8
  1.3.2 Advantage of Predictive Control 9
1.4 Distributed Predictive Control 9
  1.4.1 Why Distributed Predictive Control 9
  1.4.2 What is Distributed Predictive Control 10
  1.4.3 Advantage of Distributed Predictive Control 10
  1.4.4 Classification of DMPC 11
1.5 About this Book 13

Part I FOUNDATION

2 Model Predictive Control **19**
2.1 Introduction 19
2.2 Dynamic Matrix Control 20
  2.2.1 Step Response Model 20
  2.2.2 Prediction 21

2.2.3 Optimization 22
2.2.4 Feedback Correction 23
2.2.5 DMC with Constraint 24
2.3 Predictive Control with the State Space Model 26
2.3.1 System Model 27
2.3.2 Performance Index 28
2.3.3 Prediction 28
2.3.4 Closed-Loop Solution 30
2.3.5 State Space MPC with Constraint 31
2.4 Dual Mode Predictive Control 33
2.4.1 Invariant Region 33
2.4.2 MPC Formulation 34
2.4.3 Algorithms 35
2.4.4 Feasibility and Stability 36
2.5 Conclusion 37

3 Control Structure of Distributed MPC 39
3.1 Introduction 39
3.2 Centralized MPC 40
3.3 Single-Layer Distributed MPC 41
3.4 Hierarchical Distributed MPC 42
3.5 Example of the Hierarchical DMPC Structure 43
3.6 Conclusion 45

4 Structure Model and System Decomposition 47
4.1 Introduction 47
4.2 System Mathematic Model 48
4.3 Structure Model and Structure Controllability 50
4.3.1 Structure Model 50
4.3.2 Function of the Structure Model in System Decomposition 51
4.3.3 Input–Output Accessibility 53
4.3.4 General Rank of the Structure Matrix 56
4.3.5 Structure Controllability 56
4.4 Related Gain Array Decomposition 58
4.4.1 RGA Definition 59
4.4.2 RGA Interpretation 60
4.4.3 Pairing Rules 61
4.5 Conclusion 63

Part II UNCONSTRAINED DISTRIBUTED PREDICTIVE CONTROL

5 Local Cost Optimization-based Distributed Model Predictive Control 67
5.1 Introduction 67
5.2 Local Cost Optimization-based Distributed Predictive Control 68
5.2.1 Problem Description 68
5.2.2 DMPC Formulation 69

- *5.2.3 Closed-loop Solution* 72
- *5.2.4 Stability Analysis* 79
- *5.2.5 Simulation Results* 79
- 5.3 Distributed MPC Strategy Based on Nash Optimality 82
  - *5.3.1 Formulation* 83
  - *5.3.2 Algorithm* 86
  - *5.3.3 Computational Convergence for Linear Systems* 86
  - *5.3.4 Nominal Stability of Distributed Model Predictive Control System* 88
  - *5.3.5 Performance Analysis with Single-step Horizon Control Under Communication Failure* 89
  - *5.3.6 Simulation Results* 94
- 5.4 Conclusion 99
- Appendix 99
- Appendix A. QP problem transformation 99
- Appendix B. Proof of Theorem 5.1 100

6 Cooperative Distributed Predictive Control 103

- 6.1 Introduction 103
- 6.2 Noniterative Cooperative DMPC 104
  - *6.2.1 System Description* 104
  - *6.2.2 Formulation* 104
  - *6.2.3 Closed-Form Solution* 107
  - *6.2.4 Stability and Performance Analysis* 109
  - *6.2.5 Example* 113
- 6.3 Distributed Predictive Control based on Pareto Optimality 114
  - *6.3.1 Formulation* 118
  - *6.3.2 Algorithm* 119
  - *6.3.3 The DMPC Algorithm Based on Plant-Wide Optimality* 119
  - *6.3.4 The Convergence Analysis of the Algorithm* 121
- 6.4 Simulation 121
- 6.5 Conclusions 123

7 Networked Distributed Predictive Control with Information Structure Constraints 125

- 7.1 Introduction 125
- 7.2 Noniterative Networked DMPC 126
  - *7.2.1 Problem Description* 126
  - *7.2.2 DMPC Formulation* 127
  - *7.2.3 Closed-Form Solution* 132
  - *7.2.4 Stability Analysis* 135
  - *7.2.5 Analysis of Performance* 135
  - *7.2.6 Numerical Validation* 137
- 7.3 Networked DMPC with Iterative Algorithm 144
  - *7.3.1 Problem Description* 144
  - *7.3.2 DMPC Formulation* 145
  - *7.3.3 Networked MPC Algorithm* 147
  - *7.3.4 Convergence and Optimality Analysis for Networked* 150

7.3.5 Nominal Stability Analysis for Distributed Control Systems 152
7.3.6 Simulation Study 153
7.4 Conclusion 159
Appendix 159
Appendix A. Proof of Lemma 7.1 159
Appendix B. Proof of Lemma 7.2 160
Appendix C. Proof of Lemma 7.3 160
Appendix D. Proof of Theorem 7.1 161
Appendix E. Proof of Theorem 7.2 161
Appendix F. Derivation of the QP problem (7.52) 164

Part III CONSTRAINT DISTRIBUTED PREDICTIVE CONTROL

8 Local Cost Optimization Based Distributed Predictive Control with Constraints 169
8.1 Introduction 169
8.2 Problem Description 170
8.3 Stabilizing Dual Mode Noncooperative DMPC with Input Constraints 171
8.3.1 Formulation 171
8.3.2 Algorithm Design for Resolving Each Subsystem-based Predictive Control 176
8.4 Analysis 177
8.4.1 Recursive Feasibility of Each Subsystem-based Predictive Control 177
8.4.2 Stability Analysis of Entire Closed-loop System 183
8.5 Example 184
8.5.1 The System 184
8.5.2 Performance Comparison with the Centralized MPC 185
8.6 Conclusion 187

9 Cooperative Distributed Predictive Control with Constraints 189
9.1 Introduction 189
9.2 System Description 190
9.3 Stabilizing Cooperative DMPC with Input Constraints 191
9.3.1 Formulation 191
9.3.2 Constraint C-DMPC Algorithm 193
9.4 Analysis 194
9.4.1 Feasibility 194
9.4.2 Stability 199
9.5 Simulation 201
9.6 Conclusion 208

10 Networked Distributed Predictive Control with Inputs and Information Structure Constraints 209
10.1 Introduction 209
10.2 Problem Description 210

10.3 Constrained N-DMPC 212
10.3.1 Formulation 212
10.3.2 Algorithm Design for Resolving Each Subsystem-based Predictive Control 218
10.4 Analysis 219
10.4.1 Feasibility 219
10.4.2 Stability 225
10.5 Formulations Under Other Coordination Strategies 227
10.5.1 Local Cost Optimization Based DMPC 227
10.5.2 Cooperative DMPC 228
10.6 Simulation Results 229
10.6.1 The System 229
10.6.2 Performance of Closed-loop System under the N-DMPC 230
10.6.3 Performance Comparison with the Centralized MPC and the Local Cost Optimization based MPC 231
10.7 Conclusions 236

Part IV APPLICATION

11 Hot-Rolled Strip Laminar Cooling Process with Distributed Predictive Control 239
11.1 Introduction 239
11.2 Laminar Cooling of Hot-rolled Strip 240
11.2.1 Description 240
11.2.2 Thermodynamic Model 241
11.2.3 Problem Statement 242
11.3 Control Strategy of HSLC 244
11.3.1 State Space Model of Subsystems 244
11.3.2 Design of Extended Kalman Filter 247
11.3.3 Predictor 247
11.3.4 Local MPC Formulation 248
11.3.5 Iterative Algorithm 249
11.4 Numerical Experiment 251
11.4.1 Validation of Designed Model 251
11.4.2 Convergence of EKF 252
11.4.3 Performance of DMPC Comparing with Centralized MPC 252
11.4.4 Advantages of the Proposed DMPC Framework Comparing with the Existing Method 253
11.5 Experimental Results 256
11.6 Conclusion 258

12 High-Speed Train Control with Distributed Predictive Control 263
12.1 Introduction 263
12.2 System Description 264

12.3 N-DMPC for High-Speed Trains 264
12.3.1 Three Types of Force 264
12.3.2 The Force Analysis of EMUs 266
12.3.3 Model of CRH2 267
12.3.4 Performance Index 271
12.3.5 Optimization Problem 272
12.4 Simulation Results 272
12.4.1 Parameters of CRH2 273
12.4.2 Simulation Matrix 273
12.4.3 Results and Some Comments 274
12.5 Conclusion 278

13 Operation Optimization of Multitype Cooling Source System Based on DMPC 279
13.1 Introduction 279
13.2 Structure of Joint Cooling System 279
13.3 Control Strategy of Joint Cooling System 280
13.3.1 Economic Optimization Strategy 281
13.3.2 Design of Distributed Model Predictive Control in Multitype Cold Source System 283
13.4 Results and Analysis of Simulation 286
13.5 Conclusion 292

References 293

Index 299

Preface

There is a class of complex plant-wide systems which are composed of many physically or geographically divided subsystems. Each subsystem interacts with some so-called neighboring subsystems by their states and inputs. The technical target is to achieve a specific global performance of the entire system.

The classical centralized control solution, which could obtain a good global performance, is often impractical for application to a plant-wide system for computational reasons and lack of error tolerance. When the centralized controller fails or a control component fails, the entire system is out of control and the control integrity cannot be guaranteed.

The distributed (or decentralized) framework, where each subsystem is controlled by an independent controller, has the advantages of error-tolerance, less computational effort, and flexibility to system structure. Thus the distributed control framework is usually adopted in this class of system, in spite of the fact that the dynamic performance of centralized framework is better. Thus, how to improve the global performance under distributed control framework is a valuable problem.

Model predictive control (MPC), as a highly practical control technology with high performance, has been successfully applied to various linear and nonlinear systems in the process industries, and is becoming more widespread. The distributed framework of MPC, distributed MPC (DMPC), is also gradually developed with the development of communication network technologies in process industries that allow the control technologies and methodologies to utilize their potentials for improving control.

For the MPC algorithm applied to the plant-wide systems, the system's architectures can be divided as follows:

1. Centralized MPC, which is a MIMO system architecture;
2. Decentralized MPC, one controller-one subsystem, but no information exchange between controllers, and
3. Distributed MPC, which assumes that each subsystem can exchange information with its neighbor's subset of other subsystems.

Since the centralized MPC is forbidden for the large-scale plant-wide system with hundreds (or thousands) of inputs and outputs variables due to its lesser flexibility, weak error tolerance and the large cost of computation, the distributed framework is usually adopted despite its lower global performance. The schematic of distributed MPC is shown in Figure 1, the whole system is composed by many spatial distributed interconnected sub-systems. Each

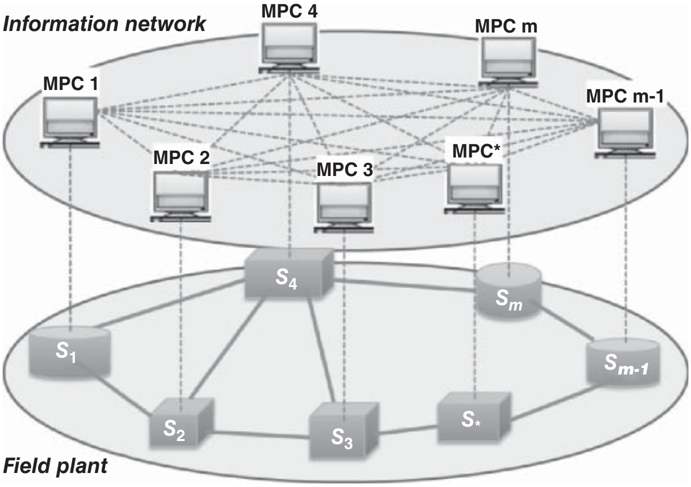

Figure 1 The schematic of distributed model predictive control

subsystem is controlled by a subsystem-based MPC and these controllers are interconnected by the network.

As mentioned before, how to improve the global performance under distributed control framework is a valuable problem. It is exactly true for the DMPC. There are many DMPC strategies and design methods in the literature, all to different ends. We have done extensive research in this topic for more than 10 years, and have proposed some strategies, e.g., the Nash optimization-based DMPC and the impacted region optimization based DMPC, etc. We found that the DMPC is definitely a useful method for large-scale plant-wide systems. Thus, we decided to write this book.

This book systematically introduces different distributed predictive control methods for plant-wide systems, including system decomposition, classification of distributed predictive control, unconstrained distributed predictive control, and the stabilized distributed predictive control with different coordinating strategies for different purposes, as well as the implementation examples of distributed predictive control. The major new contribution of this book is to show how the distributed MPCs can be coordinated efficiently for different control requirements, namely network connectivity, error tolerance, performance of entire closed-loop system, calculation speed, etc., and how to design distributed MPC. The remaining contents of this book are structured into four parts.

In the first part, we recall the main concepts and some fundamental results of the predictive control for discrete-time linear systems. The system structure model and some decomposition methods to present how to divide the entire system into interacting subsystems according to the specific control requirements is also introduced. Our intent is to provide the necessary background knowledge to understand the rest of the book.

The second part introduces the unconstrained distributed MPCs with different coordination strategies. The simplest and most practical local cost optimization based distributed MPC, Nash optimization based distributed MPC, the cooperative distributed MPC that can obtain very good performance of the entire system but each subsystem-based MPC of which requires the information of the whole system, and the networked distributed MPC with information constraints, which is a tradeoff between the two methods mentioned above. For primary readers, the major ideas and characteristics of distributed MPCs are clearly explained in a simple way without constraints.

The third part focuses on introducing the design of the stabilizing distributed MPCs with constraints for the three types of DMPCs: the local cost optimization based DMPC, the cooperative DMPC, and the networked DMPC with information constraint, respectively. The designed DMPCs can guarantee recursive feasibility and the asymptotic stability of the closed-loop system if the initial feasible solution exists.

In the last part, three practical examples are given to illustrate how to implement the introduced distributed MPC into industrial processes, they are the nonlinear networked DMPC for accelerated cooling processes in heavy plate steel mills, the speed train control with unconstrained networked DMPC, and the hierarchical DMPC for load control of a high building with multicooling resources.

In conclusion, this book tries to give a systematic overview of the latest distributed predictive control technologies to readers. We hope this book can help engineers to design control systems in their daily work or in their new projects. In addition, we believe that this book is fit for the graduate students who are pursuing their master or doctor degree in control theory and control engineering. We will be very pleased if this book is of use to you if you are interested in the control of plant-wide systems or predictive control.

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List of Figures

Figure 1 The schematic of distributed model predictive control xii
Figure 1.1 The wind farm 2
Figure 1.2 The multizone building temperature regulation system 3
Figure 1.3 Distributed power generation power network 3
Figure 1.4 Hierarchical control system for the plant-wide system 4
Figure 1.5 Centralized control 5
Figure 1.6 Decentralized control 6
Figure 1.7 Hierarchical coordinated decentralized control 7
Figure 1.8 Distributed control 7
Figure 1.9 Distributed control in the hierarchical control system 8
Figure 1.10 Distributed predictive control 10
Figure 1.11 Content of this book 14
Figure 2.1 A state observer with measurable disturbances 30
Figure 3.1 The centralized MPC control structure 40
Figure 3.2 The single-layer decentralized/distributed MPC control structure 41
Figure 3.3 The hierarchical decentralized/distributed MPC control structure 43
Figure 3.4 Simplified process flow diagram of a hydrocracking plant and its hierarchical distributed MPC control structure 44
Figure 4.1 The schematic of the distributed system 48
Figure 4.2 A multizone building temperature regulation system 51
Figure 4.3 The two-input−two-output system (TITO) 59
Figure 4.4 Distillation column controlled with the LV-configuration 62
Figure 5.1 Maximum closed-loop eigenvalues with LCO-DMPC when $\alpha = 0.1$ 81
Figure 5.2 Performance with $\gamma = 1$ and $P = 20$ of a closed-loop system under the control of LCO-DMPC with $\alpha = 0.1$ 82
Figure 5.3 Maximum closed-loop eigenvalues with LCO-DMPC when $\alpha = 1$ 83
Figure 5.4 Performance with $\gamma = 1$ and $P = 20$ of a closed-loop system under the control of LCO-DMPC with $\alpha = 1$ 84

Figure 5.5 Shell heavy oil fractionator benchmark control problem 95

Figure 5.6 Closed-loop system output responses and manipulated/control signals with no communication failure under the disturbance pattern $\mathbf{d}^1 = [0.5\ 0.5]^\mathrm{T}$ 97

Figure 5.7 Closed-loop system output responses and manipulated/control signals with no communication failure under the disturbance pattern $\mathbf{d}^2 = [-0.5 - 0.5]^\mathrm{T}$ 97

Figure 5.8 Closed-loop system output responses and manipulated/control signals with mixed communication failure under the disturbance pattern $\mathbf{d}^1 = [0.5\ 0.5]^\mathrm{T}$ 98

Figure 5.9 Closed-loop system output responses and manipulated/control signals with mixed communication failure under the disturbance pattern $\mathbf{d}^2 = [-0.5 - 0.5]^\mathrm{T}$ 98

Figure 6.1 Plant with $\alpha = 0.1$: (a) maximum closed-loop eigenvalues with LCO-DMPC and C-DMPC; (b) control performance with $\gamma = 1$ for LCO-DMPC (blue line, MSE = 0.2568) and C-DMPC (red line, MSE = 0.2086) 115

Figure 6.2 Plant with $\alpha = 1$: (a) maximum closed-loop eigenvalues with LCO-DMPC and C-DMPC; (b) control performance with $\gamma = 1$ for LCO-DMPC (blue line, MSE = 0.2277) and C-DMPC (red line, MSE = 0.2034) 116

Figure 6.3 Plant with $\alpha = 10$: (a) maximum closed-loop eigenvalues with LCO-DMPC and C-DMPC; (b) control performance with $\gamma = 1$ for LCO-DMPC (blue line, unstable) and C-DMPC (red line, MSE = 0.1544) 117

Figure 6.4 The outputs and inputs of each subprocess 122

Figure 6.5 The outputs and inputs of the second subprocess 122

Figure 7.1 ACC process for middle and heavy plates 138

Figure 7.2 Control strategy of ACC 140

Figure 7.3 Equilibriums of states of entire system 141

Figure 7.4 Performance of close-loop subsystems using centralized MPC, N-DMPC, and the LCO-MPC 142

Figure 7.5 Flux of each header unit using centralized MPC, N-DMPC, and LCO-MPC 143

Figure 7.6 Diagram of a serially connected process 144

Figure 7.7 Diagram of the MPC unit for each subsystem 148

Figure 7.8 Diagram of networked MPC algorithm 149

Figure 7.9 Outputs and control signals under the decentralized MPC 155

Figure 7.10 Outputs and control signals under the LCO-DMPC with Nash optimization 155

Figure 7.11 Outputs and control signals under the N-DMPC iterative algorithm 156

Figure 7.12 Performance index comparisons for three schemes 156

Figure 7.13 Structure of a walking beam reheating furnace 157

Figure 7.14 Furnace temperature and fuel feed flow for each zone 158

Figure 8.1 The interaction relationship among subsystems 184

Figure 8.2 The evolution of the states under the LCO-DMPC 185

Figure 8.3 The evolution of the control inputs under the LCO-DMPC 186

Figure 8.4 The evolution of the states under the centralized MPC 186

Figure 8.5 The evolution of the control inputs under the centralized MPC 187

Figure 9.1 Schematic of the discrepancy among feasible state sequence and presumed state sequence 196

Figure 9.2 The multizones building temperature regulation system 202

Figure 9.3 The evolution of the states under the centralized MPC, LCO-DMPC, and C-DMPC 204

Figure 9.4 The evolution of the inputs under the centralized MPC, LCO-DMPC, and C-DMPC 205

Figure 9.5 Differences of the absolute value of the state and inputs of each subsystem between under the control of LCO-DMPC and under the control of centralized MPC, and between under the control of C-DMPC and under the control centralized DMPC 206

Figure 9.6 The difference between the input of each subsystem produced by the LCO-DMPC and the input of each subsystem calculated by the centralized MPC, and between the input of each subsystem produced by the C-DMPC and the input of each subsystem calculated by the centralized MPC 207

Figure 10.1 The interaction relationship among subsystems 229

Figure 10.2 The evolution of the states under the N-DMPC 231

Figure 10.3 The evolution of the control inputs under the N-DMPC 232

Figure 10.4 The evolution of the states under the centralized MPC 232

Figure 10.5 The evolution of the control inputs under the centralized MPC 233

Figure 10.6 The evolution of the states under the LCO-DMPC 233

Figure 10.7 The evolution of the control inputs under the LCO-DMPC 233

Figure 10.8 The errors between the absolute value of the state of each subsystem under the centralized MPC and the absolute value of the state of each subsystem under the N-DMPC 234

Figure 10.9 The difference between the input of each subsystem produced by the centralized MPC and the input of each subsystem calculated by the N-DMPC 234

Figure 10.10 The errors between the absolute value of the state of each subsystem under the local cost optimization based DMPC and the absolute value of the state of each subsystem under the N-DMPC 234

Figure 10.11 The difference between the input of each subsystem produced by the LCO-DMPC and the input of each subsystem calculated by the N-DMPC 235

Figure 11.1 Hot-rolled strip laminar cooling process 241
Figure 11.2 Desired temperature profile 242
Figure 11.3 The structure of DMPC framework for HSLC 244
Figure 11.4 The division of each subsystem 245
Figure 11.5 Comparison between the predictive CT and the measurement of CT 252
Figure 11.6 Initial states of process model and observer 252
Figure 11.7 Comparison of temperatures estimated by process model and observer 253
Figure 11.8 Performance comparison of different control strategies (centralized MPC and DMPC framework proposed) 254
Figure 11.9 Flux of each header group with centralized MPC and DMPC framework proposed 255
Figure 11.10 The cooling curve of each strip-point with existing method 256
Figure 11.11 The cooling curve of each strip-point with proposed DMPC framework 257
Figure 11.12 The structure of experimental system 257
Figure 11.13 Runout table pilot apparatus 258
Figure 11.14 Finishing rolling temperature of strip 258
Figure 11.15 Output of each closed-loop subsystem with DMPC framework 259
Figure 11.16 Flux of each header group with DMPC framework 260
Figure 12.1 Traction characteristics of the CRH2 [140] 265
Figure 12.2 Groups of CRH2 (“M” means motor coach and “T” means trailer coach) 266
Figure 12.3 Analysis of the force of the CRH2 267
Figure 12.4 Spring−mass model 267
Figure 12.5 The structure diagram of the distributed model predictive control 270
Figure 12.6 Half of the CRH2 EMUs schematic diagram 273
Figure 12.7 Velocity track 274
Figure 12.8 Driving force optimal scheduling 275
Figure 12.9 The relative displacement of the coaches 275
Figure 12.10 Velocity track of the first coach 276
Figure 12.11 Velocity track 276
Figure 12.12 Driving force optimal scheduling of the second coach 277
Figure 12.13 Driving force optimal scheduling of the third coach 277
Figure 13.1 Structure of joint cooling system 280
Figure 13.2 Control strategy of joint cooling system 281
Figure 13.3 Load forecasting curve 288
Figure 13.4 Comparison of power cost in every half an hour between the two strategies 289
Figure 13.5 Simulation results of dynamic performance optimization 290

List of Tables

Table 4.1 The meaning of the value for RGA elements 61

Table 5.1 Notations used in this chapter 70

Table 6.1 Notations definition 105

Table 7.1 Notations used in this chapter 128

Table 7.2 The plate parameters and the operating points 141

Table 8.1 Notations in this chapter 172

Table 8.2 Parameters of the LCO-DMPC 185

Table 8.3 State square errors of the closed-loop system under the control of the centralized MPC (CMPC) and the LCO-DMPC 187

Table 9.1 Notations in this chapter 191

Table 9.2 Parameters of C-DMPC 203

Table 9.3 State square errors of the closed-loop system under the control of the centralized MPC (CMPC), the LCO-DMPC, and the C-DMPC 208

Table 10.1 Notations in this chapter 213

Table 10.2 Parameters of the N-DMPC 231

Table 10.3 State square errors of the closed-loop system under the control of the centralized MPC(CMPC), the LCO-DMPC, and the N-DMPC 235

Table 11.1 Thermal and physical properties of the strip 251

Table 11.2 Computational burdens of DMPC and centralized MPC 256

Table 12.1 Coefficients 266

Table 13.1 Power consumption functions of refrigerators under air conditioning operation 287

Table 13.2 Time-of use power price 287

Table 13.3 Dynamic parameters of refrigerators under air conditioning operation 288

Table 13.4 Effect of dynamic optimization 291

1

Introduction

1.1 Plant-Wide System

There is a class of systems which are composed of many interacted subsystems' industrial fields. Especially with the development of the advanced technology and the increase in the requirement of products, many new distributed processes have appeared, the processes of producing products have become more and more complex, and the scales of industrial processes have become more and more large. The automation structure for this kind of systems has changed from the traditional centralized automation system to a decentralized and centralized automation system, and then to a distributed automation system.

Correspondingly, the control algorithm and control structure for this kind of system change from centralized control and decentralized control to the distributed control system. The distributed control refers to a control system where each subsystem is controlled by an individual controller, and these controllers communicate with other subsystem-based controllers and are coordinated according to the exchanged information for obtaining good global performance or some special common goals. So far, the distributed control, especially the DMPC, has been studied and are still being studied by many scientists, and many theories and algorithms have been developed. We think it is the right time to introduce the distributed control to more students and engineers.

To make it more clear which kind of system is suitable for distributed control, we give some examples as follows.

1. **Wind power generation farm**
   In a wind turbine power generation farm, as shown in Figure 1.1, wind turbines are spatially distributed. The output wind flow rate of each wind turbine decreases with increasing generated power. It affects the input wind flow rate of the downstream wind turbines, and then their dynamics. In this way, these wind turbines interact with each other. For the automation system, each wind turbine is controlled by an individual controller. And these controllers are connected by a network (fieldbus) and are able to communicate with each other by the network.

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Figure 1.1 The wind farm

2. **Multizone building temperature regulation system**
   Multizone building temperature regulation systems are a class of typical spatially distributed systems, as shown in Figure 1.2, which are composed of many physically interacted subsystems (rooms or zones) labeled as $\mathcal{S}_1$, $\mathcal{S}_2$, …, $\mathcal{S}_m$, respectively. The thermal influences between rooms of the same building occur through internal walls (the internal walls' isolation is weak) and/or door openings. A thermal meter and a heater (or air conditioner) are installed in each zone, which is used to measure and adjust the temperature of the multizone building.
3. **Distributed power network**
   Power networks are large networks consisting of a large number of components. The dynamics of the power network as a whole are the result of interactions between the individual components. The generators produce power that is injected into the network on the one side, while the loads consume power from the network on the other. If we consider each power plant, load, and station as a subsystem, it is a typical distributed system, whose subsystems interacted with each other and controlled separately.

In addition, since the number of players involved in the generation and distribution of power has increased significantly, in the near future, the number of source nodes of the power distribution network will increase even further as large-scale industrial suppliers and small-scale individual household will also start to feed electricity into the network. As a consequence, the structure of the power distribution network will change into a much more decentralized system with many generating sources and distribution agencies (Figure 1.3).

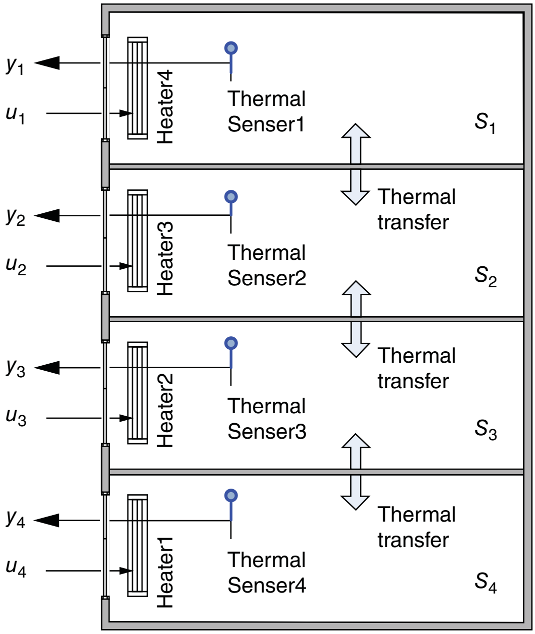

Figure 1.2 The multizone building temperature regulation system

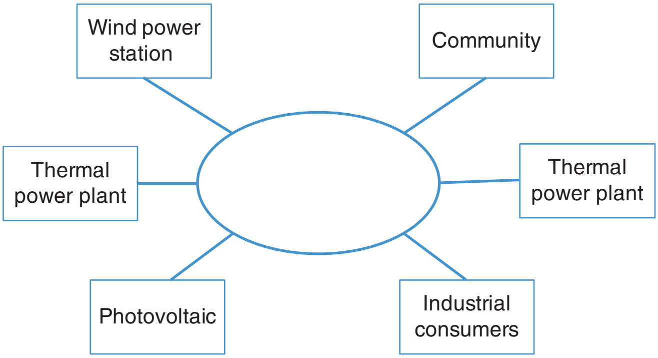

Figure 1.3 Distributed power generation power network

1.2 Control System Structure of the Plant-Wide System

The control structure is a very general concept. It includes how to schedule the controllers, and the inputs/outputs of each controller. The control system structure of the plant-wide system is shown in Figure 1.4, which is a hierarchical structure. The top layer, denoted as layer 4, is a steady economic optimization layer which is used to optimize the key process parameters, e.g., the product quantity, product quality, feeding material quality, etc. Layer 3 is a real-time optimization layer which dynamically optimizes the set-point of the multivariable layers.

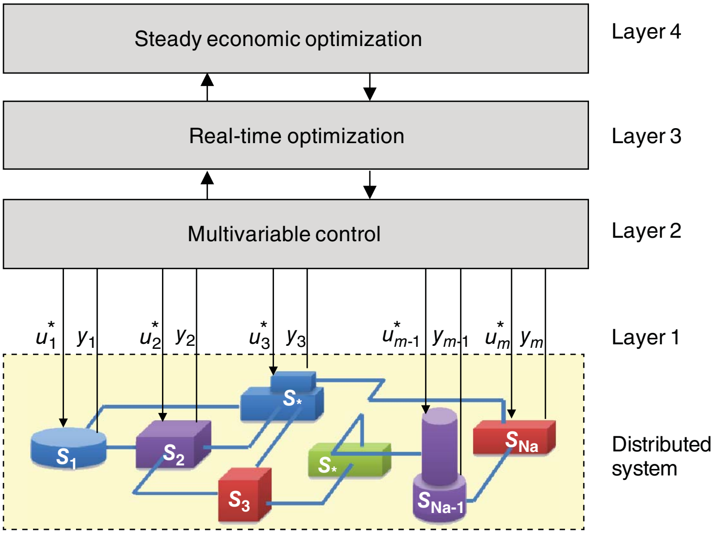

Figure 1.4 Hierarchical control system for the plant-wide system

This layer considers the dynamic economic performance and efficiency. The slow time variation of the process condition is taken into account in this layer. Below this layer is a multivariable layer which coordinates the interaction between each control loop and gives a set-point for the field control loop. The lowest layer, a field control loop layer, which is not drawn in this figure, is used to regulate the process variable, e.g., the temperature, flow rate, or pressure. In some cases, the multivariable takes some work of the field control loop layer when the control problem is complicated. In this structure, with an increase in the layer level, the information to communicate is deduced, and the computing interval is increased.

Here, we consider the multivariable control layer. For a plant-wide system, there are many inputs and outputs. With the development of a network, communication technology, and field-bus product, as well as intelligent meters, the control theory for a multivariable system is developed correspondingly. Many advanced control methods appear in the literature works, and the control structure in a multivariable layer changes from the centralized control to the decentralized control, to the distributed control. In addition, recently, the distributed structures for the real-time dynamic optimization layer and steady-state optimization layer have also appeared in the literature works. The real-time optimization layer and multivariable control loop are combined together in some cases. This is out of the scope of discussion in this book. In the following, three types of control structures, centralized control structure, decentralized control structure, and distributed control structure, in a multivariable control layer are specified to show the advantage of the distributed control framework.

1.2.1 Centralized Control

As shown in Figure 1.5, the centralized multivariable controller gets all the information of the plant-wide system, and then calculates the control law of all the inputs together, and sends the