

Contents

| | |
|---|---|
| Part I Abstract Model of a Distributed Control and Embedded Systems | |
| 1 | Introduction to Distributed Control and Embedded Systems (<i>DCES</i>) 3 |
| 1.1 | Motivations 5 |
| 1.1.1 | Communication Resources Limitations 5 |
| 1.1.2 | Computational Resources Limitations 6 |
| 1.2 | Goals and Contributions 7 |
| 1.3 | Methodology 7 |
| 2 | Resource Allocation in Distributed Control and Embedded Systems 9 |
| 2.1 | Real-Time Scheduling Theory 9 |
| 2.1.1 | Real-Time Single-Processor Scheduling 10 |
| 2.1.2 | Real-Time Medium Access Control in Communication Networks 13 |
| 2.1.3 | Real-Time Scheduling of Distributed Systems 17 |
| 2.2 | Integrated Approaches for Control and Resource Allocation 17 |
| 2.2.1 | Adaptive Sampling of Control Systems 18 |
| 2.2.2 | Allocation of Communication Resources: The “Per Symbol” Paradigm 19 |
| 2.2.3 | Allocation of Communication Resources: The “Per Message” Paradigm 21 |
| 2.2.4 | Allocation of Computational Resources 26 |
| 2.3 | Notes and Comments 28 |
| 3 | Modeling and Analysis of Resource-Constrained Systems 31 |
| 3.1 | Mixed-Logical Dynamical (<i>MLD</i>) Systems 31 |
| 3.2 | <i>MLD</i> Modeling of Resource-Constrained Systems 33 |
| 3.3 | Notion of Communication Sequence 38 |
| 3.4 | State Representation of Resource-Constrained Systems 39 |
| 3.5 | Stabilization with Limited Resources 39 |
| 3.6 | Trajectory Tracking with Limited Resources 40 |

| | | |
|--|---|-----------|
| 3.7 | Reachability and Observability with Limited Resources | 42 |
| 3.8 | Notes and Comments | 43 |
| Part II Optimal Co-design of Distributed Control and Embedded Systems | | |
| 4 | Optimal Integrated Control and Scheduling of Resource-Constrained Systems | 47 |
| 4.1 | Performance Index Definition | 48 |
| 4.2 | Optimal Control over a Finite Horizon for a Fixed Communication Sequence | 49 |
| 4.3 | Optimal Control over an Infinite Horizon for a Fixed Communication Sequence | 51 |
| 4.4 | Finite-Time Optimal Integrated Control and Scheduling | 53 |
| 4.4.1 | Problem Formulation | 54 |
| 4.4.2 | The Branch and Bound Method | 59 |
| 4.4.3 | An Illustrative Numerical Example | 63 |
| 4.5 | Notes and Comments | 66 |
| 5 | Optimal Integrated Control and Off-line Scheduling of Resource-Constrained Systems | 67 |
| 5.1 | Preliminaries | 67 |
| 5.2 | On Characterizing \mathcal{H}_2 Norm of Resource-Constrained Systems | 68 |
| 5.2.1 | Standard Extended Model Definition | 68 |
| 5.2.2 | Standard \mathcal{H}_2 Norm of a Continuous/Discrete-Time Linear Time Invariant (<i>LTI</i>) System | 70 |
| 5.2.3 | Computing \mathcal{H}_2 Norm of a Sampled-Data System | 71 |
| 5.2.4 | Introducing the \mathcal{H}_2 Norm of Periodically Scheduled Resource-Constrained Systems | 73 |
| 5.3 | Introducing the \mathcal{H}_2 Optimal Integrated Control and Off-line Scheduling Problem | 74 |
| 5.3.1 | Solving the Optimal Scheduling Subproblem | 74 |
| 5.3.2 | Solving the Optimal Control Subproblem | 76 |
| 5.3.3 | An Illustrative Numerical Example | 76 |
| 5.4 | Notes and Comments | 80 |
| 6 | Optimal Integrated Control and On-line Scheduling of Resource-Constrained Systems | 81 |
| 6.1 | Model Predictive Control (<i>MPC</i>) of Resource-Constrained Systems | 82 |
| 6.1.1 | Problem Formulation | 82 |
| 6.1.2 | Optimality | 83 |
| 6.1.3 | An Illustrative Numerical Example | 84 |
| 6.2 | Optimal Pointer Placement (<i>OPP</i>) Scheduling | 87 |
| 6.2.1 | Problem Formulation | 87 |
| 6.2.2 | An Illustrative Numerical Example | 89 |
| 6.2.3 | Optimal Pointer Placement over Infinite Horizon | 93 |

| | | |
|----------|--|------------|
| 6.3 | Real-Time Implementation Aspects of the <i>OPP</i> over Infinite Horizon Algorithm | 95 |
| 6.4 | Optimal Pointer Placement Scheduling: Application to a Car Suspension System | 96 |
| 6.4.1 | The Suspension Control System | 96 |
| 6.4.2 | Active Suspension Control Law | 98 |
| 6.4.3 | Simulation Setup and Results | 99 |
| 6.4.4 | Embedded Computing Implementation Aspects of the Distributed Suspension Model | 102 |
| 6.5 | Optimal Pointer Placement Scheduling: Application to a Quadrotor | 102 |
| 6.6 | Notes and Comments | 105 |
| 7 | Optimal Relation Between Quantization Precision and Sampling Rates | 109 |
| 7.1 | Modeling and Computation Issues | 110 |
| 7.1.1 | Quantization Aspects | 111 |
| 7.1.2 | Information Pattern | 112 |
| 7.1.3 | Notion of Quantization Sequence | 113 |
| 7.1.4 | Performance Index Definition | 114 |
| 7.2 | Static Strategy | 114 |
| 7.2.1 | Algorithm Description | 114 |
| 7.2.2 | Practical Stabilization Using the Static Strategy | 115 |
| 7.3 | Model Predictive Control <i>MPC</i> | 119 |
| 7.3.1 | Algorithm Description | 119 |
| 7.3.2 | A Heuristic Approach for the Choice of Quantization Sequences | 121 |
| 7.3.3 | Attraction Properties of the <i>MPC</i> | 122 |
| 7.4 | Simulation Results | 126 |
| 7.5 | Notes and Comments | 129 |
| 8 | Optimal State-Feedback Resource Allocation | 135 |
| 8.1 | Optimal Off-line Scheduling | 136 |
| 8.1.1 | Problem Formulation | 136 |
| 8.1.2 | Decomposability of the Optimal Integrated Control and Off-line Scheduling Problem | 140 |
| 8.1.3 | Formal Definition of the \mathcal{H}_2 Norm | 140 |
| 8.1.4 | Solving of the Optimal Scheduling Sub-problem | 142 |
| 8.1.5 | Solving the Optimal Control Sub-problem | 144 |
| 8.1.6 | An Illustrative Numerical Example | 148 |
| 8.2 | On-line Scheduling of Control Tasks | 151 |
| 8.2.1 | Execution of the Feedback Scheduler | 153 |
| 8.2.2 | Adaptive Scheduling of Control Tasks | 153 |
| 8.2.3 | Reduction of the Feedback Scheduler Overhead | 154 |
| 8.2.4 | Stability and Performance Improvements | 158 |
| 8.2.5 | Reduction of Input Readings Overhead | 160 |
| 8.2.6 | A Numerical Example | 161 |

| | | |
|---|---|-----|
| 8.3 | Application to a <i>DC</i> Motor Associated to an Embedded Processor | 164 |
| 8.4 | Notes and Comments | 167 |
| Part III Insight on Stability and Optimization of Distributed Control and Embedded Systems | | |
| 9 | Insight in Delay System Modeling of <i>DCEs</i> | 173 |
| 9.1 | Preliminaries | 174 |
| 9.2 | Hyper-Sampling Period and Induced Mathematical Model | 177 |
| 9.3 | Macroscopic Time-Delay Model of <i>DCEs</i> | 180 |
| 9.4 | Control Input Missings | 181 |
| 9.5 | Some Specific Problems of <i>DCEs</i> and Related Approaches | 181 |
| 9.6 | Notes and Comments | 183 |
| 10 | Stability of <i>DCEs</i> Under the Hyper-Sampling Mode | 185 |
| 10.1 | Introduction | 185 |
| 10.2 | Problem Formulation | 186 |
| 10.3 | Insights in Computing Stability Regions | 188 |
| 10.3.1 | Constant Delay Case | 188 |
| 10.3.2 | Time-Varying Delay Case | 190 |
| 10.3.3 | Time-Varying Hyper-Sampling Periods | 197 |
| 10.4 | An Illustrative Application | 200 |
| 10.5 | Notes and Comments | 203 |
| 11 | Optimization of the Hyper-Sampling Sequence for <i>DCEs</i> | 207 |
| 11.1 | Introduction | 207 |
| 11.2 | Problem Formulation | 208 |
| 11.3 | Design of the Standard Single-Sampling Period | 210 |
| 11.4 | Design of the Hyper-Sampling Sequence | 213 |
| 11.5 | An Experimental Platform | 217 |
| 11.6 | Notes and Comments | 219 |
| 12 | A Switched Sampled-Data Control Strategy for <i>DCEs</i> | 223 |
| 12.1 | Introduction | 224 |
| 12.2 | Intersample Dynamics: A Delay-System Perspective | 226 |
| 12.3 | A Switched Sampled-Data (<i>SD</i>) Control Approach | 227 |
| 12.4 | Stability Analysis | 227 |
| 12.5 | Optimization of the Dynamic Performance | 230 |
| 12.6 | An Illustrative Application | 233 |
| 12.7 | Notes and Comments | 236 |
| 13 | A Switched Hold-Zero Compensation Strategy for <i>DCEs</i> Subject to Control Input Missings | 239 |
| 13.1 | Modeling and Problem Formulation | 240 |
| 13.1.1 | Mathematical Expressions of Control Input Missings | 240 |
| 13.1.2 | A Switched Hold-Zero (<i>HZ</i>) Compensation Strategy | 242 |
| 13.2 | Problem Analysis and Solution | 243 |
| 13.2.1 | <i>ACIMR</i> Under the Zero-Control Strategy | 244 |

| | |
|---|------------|
| 13.2.2 Dynamics Under the Hold-Control Strategy | 250 |
| 13.2.3 Optimization of the Switched Hold-Zero (<i>HZ</i>) Control . . | 251 |
| 13.3 Notes and Comments | 258 |
| Resumé | 261 |
| Appendix A Four-Wheels Active Suspension System Model | 263 |
| A.1 Model Description | 263 |
| A.2 Vehicle Parameters | 264 |
| A.3 State Equations | 265 |
| Appendix B Quadrotor | 269 |
| B.1 Introduction to Quaternions | 269 |
| B.2 Quadrotor Attitude Modeling | 270 |
| References | 273 |
| Index | 285 |

Optimal Design of Distributed Control and Embedded
Systems

Çela, A.; Ben Gaid, M.; Li, X.-G.; Niculescu, S.-I.

2014, XXIV, 288 p. 94 illus., 60 illus. in color., Hardcover

ISBN: 978-3-319-02728-9