

CONTENTS

| | |
|---|----|
| PREFACE | V |
| 1. INTRODUCTION | 1 |
| 2. FUNDAMENTALS OF DUAL CONTROL | 6 |
| 2.1. Dual Control Problem of Feldbaum | 6 |
| 2.1.1. Formulation of the Optimal Dual Control Problem | 6 |
| 2.1.2. Formal Solution Using Stochastic Dynamic Programming | 7 |
| 2.2. Features of Adaptive Dual Control Systems | 7 |
| 2.3. Simple Example of Application of the Bicriterial Approach | 9 |
| 2.4. Simple Example of a Continuous-Time Dual Control System..... | 11 |
| 2.5. General Structure of the Adaptive Dual Control System | 12 |
| 3. SURVEY OF DUAL CONTROL METHODS | 14 |
| 3.1. Classification of Adaptive Controllers | 14 |
| 3.2. Dual Effect and Neutral Systems | 20 |
| 3.3. Simplifications of the Original Dual Control Problem..... | 24 |
| 3.4. Implicit Dual Control | 26 |
| 3.5. Explicit Dual Control | 27 |
| 3.6. Brief History of Dual Control and its Applications..... | 32 |
| 4. BICRITERIAL SYNTHESIS METHOD FOR DUAL CONTROLLERS | 33 |
| 4.1. Parameter Estimation | 33 |
| 4.1.1. Algorithms for Parameter Estimation | 33 |
| 4.1.2. Simulation Example of Parameter Estimation | 35 |
| 4.2. The Bicriterial Synthesis Method and the Dual Version of the STR | 37 |
| 4.3. Design of the Dual Version of the GMV Controller..... | 40 |
| 4.4. Computer Simulations..... | 45 |
| 4.4.1. The Plant without Time Delay $d=1$ | 45 |
| 4.4.2. GMV Controller for the Plant with Time Delay $d=4$ | 45 |
| 4.4.3. GMV Controller for the Plant with Time Delay $d=7$ | 49 |
| 4.5. Summary | 53 |
| 5. CONVERGENCE AND STABILITY OF ADAPTIVE DUAL CONTROL | 55 |
| 5.1. The Problem of Convergence Analysis..... | 55 |
| 5.2. Preliminary Assumptions for the System..... | 55 |
| 5.3. Global Stability and Convergence of the System..... | 57 |

| | |
|---|-----|
| 5.4. Conclusion | 61 |
| 6. DUAL POLE-PLACEMENT CONTROLLER WITH DIRECT ADAPTATION | 62 |
| 6.1. Design of a Direct Adaptive Pole-Placement Controller Using the Standard Approach | 63 |
| 6.2. Design of Dual Pole-Placement Controller with Direct Adaptation | 66 |
| 6.3. Simulation Examples | 69 |
| 6.3.1 Example 1: Unstable Minimum Phase Plant | 70 |
| 6.3.2. Example 2: Unstable Nonminimum Phase Plant | 71 |
| 6.3.3. Comparison of Controllers Based on Standard and Adaptive Dual Approaches | 72 |
| 7. DUAL MODEL REFERENCE ADAPTIVE CONTROL (MRAC) | 75 |
| 7.1. Formulation of the Bicriterial Synthesis Problem for Dual MRAC | 75 |
| 7.2. Design of Dual MRAC (DMRAC) | 78 |
| 7.3. Controller for Nonminimum Phase Plants | 80 |
| 7.4. Standard and Dual MRAC Schemes (DMRAC) | 81 |
| 7.5. Simulations and Comparisons | 82 |
| 8. DUAL CONTROL FOR MULTIVARIABLE SYSTEMS IN STATE SPACE REPRESENTATION | 85 |
| 8.1. Synthesis Problem Formulation by Applying Lyapunov Functions | 85 |
| 8.2. Synthesis of Adaptive Dual Controllers | 88 |
| 8.3. Implementation of the Designed Controller and the Relation to the Linear Quadratic Control Problem | 90 |
| 8.4. Simulation Results for Controllers Based on Lyapunov Functions | 91 |
| 8.5. Partial Certainty Equivalence Control for Linear Systems | 94 |
| 8.6. Design of Dual Controllers Using the Partial Certainty Equivalence Assumption and Bicriterial Optimization | 97 |
| 8.7. Simulation Examples | 98 |
| 8.7.1. Example 1: Underdamped Plant | 98 |
| 8.7.2. Example 2: Nonminimum Phase Plant | 101 |
| 9. A SIMPLIFIED APPROACH TO THE SYNTHESIS OF DUAL CONTROLLERS WITH INDIRECT ADAPTATION | 105 |
| 9.1. Modification of Certainty-Equivalence Adaptive Controllers | 105 |
| 9.2. Controllers for SIMO Systems | 109 |
| 9.3. Controllers for SISO Systems with Input-Output Models | 110 |
| 9.4. An Example for Applying the Method to Derive the Dual Version of an STR ... | 111 |

| | |
|---|-----|
| 9.5. Simulation Examples for Controllers with Dual Modification | 112 |
| 9.5.1. Example 1: LQG Controller | 112 |
| 9.5.2. Example 2: Pole-Placement Controller | 113 |
| 9.5.3. Example 3: Pole-Placement Controller for a Plant with Integral Behaviour | 116 |
| 10. DUAL POLE-PLACEMENT AND LQG CONTROLLERS WITH INDIRECT ADAPTATION | 119 |
| 10.1. Indirect Adaptive Pole-Placement Controller and the Corresponding LQG Controller | 119 |
| 10.2. Dual Modification of the Controller | 124 |
| 10.3. Computation of the Covariance Matrix of the Controller Parameters | 126 |
| 10.4. Simplified Dual Versions of the Controllers | 128 |
| 11. APPLICATION OF DUAL CONTROLLERS TO THE SPEED CONTROL OF A THYRISTOR-DRIVEN DC-MOTOR | 130 |
| 11.1. Speed Control of a Thyristor-Driven DC Motor | 130 |
| 11.2. Application Results for the Pole-Placement Controller | 132 |
| 11.3. Application Results for the LQG Controller | 132 |
| 12. APPLICATION OF DUAL CONTROLLERS TO A LABORATORY SCALE VERTICAL TAKE-OFF AIRPLANE | 135 |
| 12.1. Pole-Zero-Placement Adaptive Control Law | 135 |
| 12.1.1. Modification for Cautious and Dual Control | 136 |
| 12.1.2. Modification for Nonminimum Phase Systems | 139 |
| 12.2. Experimental Setup and Results | 140 |
| 12.2.1. Description of the Plant | 140 |
| 12.2.2. Comparison of Standard and Dual Control | 142 |
| 13. ROBUSTNESS AGAINST UNMODELED EFFECTS AND SYSTEM STABILITY | 148 |
| 13.1. Description of the Plant with Unmodeled Effects | 148 |
| 13.2. Design of the Dual Controller | 149 |
| 13.2.1. Adaptive Pole-Placement Controller Based on the CE Assumption | 149 |
| 13.2.2. Incorporation of the Dual Controller | 151 |
| 13.3. Robustness against Unmodeled Nonlinearity and System Stability | 154 |
| 13.3.1. Adaptation Scheme | 154 |
| 13.3.2. Stability of the Adaptive Control System | 156 |
| 14. DUAL MODIFICATION OF PREDICTIVE ADAPTIVE CONTROLLERS | 160 |
| 14.1. Model Algorithmic Control (MAC) | 160 |

| | |
|--|-----|
| 14.1.1. Modelling of the Plant and Parameter Estimation..... | 160 |
| 14.1.2. Cautious and Dual MAC | 161 |
| 14.2. Generalized Predictive Control (GPC)..... | 162 |
| 14.2.1. Equations for the Plant Model and Parameter Estimation..... | 162 |
| 14.2.2. Generalized Predictive Controller (GPC)..... | 163 |
| 14.2.3. Dual Modification of the GPC | 164 |
| 14.3. Other Predictive Controllers..... | 165 |
| 15. SIMULATION STUDIES AND REAL-TIME CONTROL USING MATLAB/SIMULINK | 166 |
| 15.1. Simulation Studies of Adaptive Dual Controllers Using MATLAB..... | 166 |
| 15.1.1. Generalized Minimum Variance Controller..... | 166 |
| 15.1.2. Direct Adaptive Pole-Placement Controller..... | 171 |
| 15.1.3. Model Reference Adaptive Controller | 177 |
| 15.2. Simulation Studies of Adaptive Controllers Using MATLAB/ SIMULINK.... | 179 |
| 15.3. Real-Time Robust Adaptive Control of a Hydraulic Positioning System using MATLAB/SIMULINK | 188 |
| 15.3.1. Description of the Laboratory Equipment..... | 188 |
| 15.3.2. Program Listing..... | 192 |
| 15.4. Real-Time ANN-Based Adaptive Dual Control of a Hydraulic Drive | 195 |
| 15.4.1. Plant Identification Using an ANN | 195 |
| 15.4.2. ANN-Based Design of a Standard Adaptive LQ Controller | 197 |
| 15.4.3. Extension to the Design of the ANN-Based Adaptive Dual Controller..... | 199 |
| 15.4.4. Real-Time Experiments..... | 203 |
| 16. CONCLUSION..... | 206 |
| APPENDIX A..... | 207 |
| Derivation of the PCE Control for Linear Systems..... | 207 |
| APPENDIX B | 210 |
| Proof of Lemmas and Theorem of Stability of Robust Adaptive Dual Control | 210 |
| APPENDIX C | 214 |
| MATLAB Programs for Solving the Diophantine Equation..... | 214 |
| APPENDIX D..... | 217 |
| Calculation of Mathematical Expectation | 217 |
| REFERENCES..... | 220 |
| INDEX | 229 |



<http://www.springer.com/978-3-540-21373-4>

Adaptive Dual Control
Theory and Applications
Filatov, N.M.; Unbehauen, H.
2004, XIV, 234 p., Softcover
ISBN: 978-3-540-21373-4