Contents

Abbreviations xxi

1 Introduction 1
1.1 Motivations for Fault-tolerant Control Systems for Unmanned Aerial Vehicles 1
1.2 Book Outline 2

2 Review 3
2.1 Definition of Fault-tolerant Systems 3
2.1.1 Fault 3
2.1.2 Failure 4
2.1.3 Fault-tolerant Control System 5
2.1.4 Dealing with Faults and Failures in Practice 6
2.2 Challenges of Designing Reconfigurable Control Systems 7
2.2.1 Difficulties of Designing Reliable FDI Systems 7
2.2.2 Interaction Between Flight Controllers and FDI Systems 7
2.2.3 Other Practical Challenges 8
2.3 Different Approaches for FDI Systems 8
2.3.1 Trends in Filter Design for FDI System 8
2.3.2 Trends in Active Fault Detection 10
2.4 Different Approaches for Flight Control Systems 11
2.5 Techniques to Design Fault-tolerant Flight Control Systems 11
2.5.1 Multiple Model Techniques 12
2.5.2 Control Allocation Techniques 14
2.5.3 Model Reference Adaptive Control 15
2.5.4 Other Reconfigurable Control Methods 16
2.6 Reconfigurable Guidance Systems 17
2.7 Real Flight Tests 17
References 19

3 Nonlinear Aircraft Model 27
3.1 Definitions of the Frames 27
3.1.1 Navigation Frame 27
3.1.2 Body Frame 27
3.1.3 Euler Angles 28
3.1.4 Direction Cosine Matrix 29
3.1.5 Quaternion Representation 30
3.1.6 Wind Frame 31
3.2 Wind Disturbance 32
3.3 Model of the Low Altitude Atmosphere 33
3.4 Equations of Rigid-body Motion 33
3.4.1 Equations of Forces 34
3.4.2 Equations of Moments 37
3.5 Engine 37
3.5.1 Engine Rate 37
3.5.2 Thrust Force 38
3.6 Model of the Aerodynamic Forces 38
3.6.1 Lift Force 38
3.6.2 Lateral Force 38
3.6.3 Drag Force 38
3.7 Model of the Aerodynamic Torques 39
3.7.1 Roll Torque L^b 39
3.7.2 Pitch Torque M^b 40
3.7.3 Yaw Torque N^b 40
3.8 Summary of the Nonlinear Aircraft Model 41
References 41

4 Nonlinear Fault Detection and Isolation System 43
4.1 Introduction 43
4.2 FDI Using MMAE Schemes 44
4.2.1 Advantage of the MMAE Method 44
4.2.2 Limitations of the MMAE Method 45
4.2.3 New Extensions to the MMAE Method: The EMMAE Method 45
4.3 A New FDI Scheme Based on the EMMAE Method 46
4.3.1 Modeling Actuator Faults 46
4.3.2 The EMMAE Method 47
4.4 Aircraft Actuator Configuration and Nonlinear Dynamics 49
4.4.1 The Aircraft Configuration 49
4.4.2 Aircraft Nonlinear Dynamics 49
4.5 Design of the EKFs 51
4.5.1 EKF Equations 52
4.5.2 Designing the EKF for the No-fault Scenario 56
4.5.3 Augmenting the State Vector with the Faulty Actuator Parameter $\bar{\delta}_i$ 57

4.5.4 Designing the EKF for the Case of a Failure on Aileron 1 . . . 58
4.6 Actuator Fault Isolation . . . 59
4.6.1 Hypothesis Testing . . . 59
4.6.2 Gaussian Conditional Probability Density . . . 61
4.7 Simulation Results of the EMMAE-FDI with no Supervision System . . . 64
4.7.1 Simulation Conditions . . . 64
4.7.2 Scenario . . . 64
4.7.3 Comments on the Simulation Results . . . 66
4.7.4 Remarks on the First Attempt to Use the EMMAE-FDI System . . . 67
4.8 Improvements to the EMMAE-FDI System . . . 68
4.8.1 Design of an Active Supervision Module (Supervisor) . . . 68
4.8.2 Performance of the EMMAE-FDI with the Supervision System . . . 69
4.9 A Realistic Flight Scenario . . . 72
4.9.1 No-wind and No-actuator-fault Conditions . . . 72
4.9.2 Wind Conditions and No Actuator Faults . . . 76
4.9.3 Strong Winds, Actuator Faults and Active Supervision Module . . . 77
4.10 An Additional Filtering Stage for the EMMAE-FDI System . . . 80
4.11 Detection and Isolation of Simultaneous Failures . . . 81
4.12 Use of the EMMAE-FDI for a Reconfigurable Flight Control System . . . 84
4.12.1 Control Allocation . . . 84
4.12.2 Benefits of the Supervision Module for Control Allocation . . . 85
4.13 Computational Complexity of the EMMAE-FDI . . . 85
4.14 Conclusions . . . 86
References . . . 86

5 Control Allocation . . . 89
5.1 Introduction to Control Allocation . . . 89
5.2 Reconfigurable Flight Control System . . . 90
5.3 Behavior Mode of Ailerons and Elevators . . . 95
5.3.1 Nominal Mode: Mode 0 . . . 95
5.3.2 Single Actuator Fault Modes: Modes 1 to 4 . . . 97
5.4 Multiple Failures . . . 99
5.4.1 Case of Two Simultaneous Failures: Mode 5 . . . 99
5.4.2 More Than Two Simultaneous Failures: Modes 6 and 7 99
5.5 Extensions of the Method . . . 99
5.6 Computational Load of the Method . . . 100
5.7 Simulation Results . . . 100
5.7.1 Impact of the Control Allocator on the Controller . . . 101

5.7.2 Comparison of Computational Effort for Control Allocation . . . 103
5.8 Conclusions . . . 104
References . . . 105

6 Nonlinear Control Design . . . 107
6.1 Concept of Dynamic Inversion . . . 107
6.1.1 Derivation of a Dynamic Inversion Controller . . . 107
6.1.2 General Case . . . 108
6.1.3 Formulation of the Signal for the Desired Output Dynamics $\dot{y}_{des}(t)$ . . . 108
6.2 Ideal or Perfect Dynamic Inversion . . . 109
6.3 Architecture of the Controller of Desired Dynamics . . . 111
6.3.1 Selection of a PI Controller . . . 111
6.3.2 Feedforward of the Command Signal y_c . . . 112
6.3.3 Open-loop Gain . . . 113
6.3.4 Design Rules for the Command-feedforward Gain f_c . . . 114
6.3.5 Feedforward of the Rate of Change of the Command Signal $\dot{y}_c$ . . . 116
6.3.6 Reference Model and Explicit Model Following . . . 117
6.3.7 Integrator Anti-windup . . . 118
References . . . 119

7 Autopilot for the Longitudinal Motion . . . 121
7.1 Equations for Longitudinal Mode Analysis . . . 121
7.1.1 Pitch Rate Differential Equation . . . 122
7.1.2 Airspeed Differential Equation . . . 122
7.1.3 Differential Equation for the Angle of Attack . . . 123
7.1.4 Differential Equation for the Pitch Angle . . . 123
7.1.5 Matrices for the Longitudinal Mode . . . 123
7.2 Dynamic Modes of the Longitudinal Plant . . . 124
7.2.1 Short-period Mode . . . 124
7.2.2 Phugoid Mode . . . 125
7.3 Validation of the Linear Longitudinal Model . . . 125
7.3.1 Perturbation on the Elevator Command . . . 126
7.3.2 Perturbation on the Engine Speed n_{mot} . . . 127
7.4 Stability Analysis of the Uncertain Dynamic Inversion . . . 128
7.4.1 Uncertain Model Parameters and Measurement Data . 129
7.4.2 Linear Modeling of the Uncertain Dynamic Inversion . 130
7.4.3 Model Simplification for the Longitudinal Motion . . . 131
7.4.4 Linear Model of the Pitch Axis and Dynamic Inversion Process . . . 132
7.4.5 Evaluation of the Uncertainty Terms in the Matrix A_{DI} 135
7.4.6 Effect of Uncertainties on Dynamic Inversion . . . 137

7.4.7 Mathematical Selection of the Uncertain Model Parameters . . . 141
7.5 General Control Architecture for the Longitudinal Motion . . . 143
7.5.1 Nonlinear Transformation T_3 . . . 144
7.5.2 Nonlinear Transformation T_2 . . . 145
7.5.3 Nonlinear Transformation T_1 . . . 145
7.6 Pitch Rate Control . . . 145
7.6.1 Stability/Robustness Requirements . . . 146
7.6.2 Pitch Rate Closed-loop Transfer Function . . . 150
7.7 Angle-of-attack Control Loop . . . 152
7.7.1 Open-loop and Closed-loop Gains . . . 153
7.7.2 Comments on the Results . . . 153
7.8 Rate-of-climb Controller . . . 158
7.8.1 Open-loop Gain . . . 160
7.8.2 Closed-loop Gain . . . 160
7.9 Altitude Controller . . . 161
7.9.1 Open-loop Gain . . . 163
7.9.2 Closed-loop Gain . . . 164
7.9.3 Performance of the Altitude Controller . . . 165
7.10 Airspeed Controller . . . 167
7.10.1 Content of this Section . . . 167
7.10.2 Motivation . . . 167
7.10.3 Engine Speed . . . 169
7.10.4 Thrust Force . . . 169
7.10.5 Nonlinear Transformations . . . 169
7.10.6 Controller of the Desired Airspeed Dynamics . . . 171
7.10.7 Simulation Results . . . 171
References . . . 172

8 Autopilot for the Lateral Motion . . . 175
8.1 Equations for Lateral Motion Analysis . . . 175
8.1.1 Differential Equation for the Roll Rate p . . . 176
8.1.2 Differential Equation for the Yaw Rate r . . . 176
8.1.3 Differential Equation for the Sideslip Angle β . . . 176
8.1.4 Differential Equation for the Roll Angle ϕ . . . 177
8.1.5 Matrices for the Lateral Mode . . . 177
8.2 Dynamic Modes of the Lateral Plant . . . 178
8.2.1 Dutch Roll Mode . . . 179
8.2.2 Roll Subsidence Mode . . . 179
8.2.3 Spiral Mode . . . 179
8.3 Validation of the Linear Lateral Model . . . 179
8.3.1 Perturbation on the Aileron Command . . . 180
8.3.2 Perturbation on the Rudder Command . . . 181
8.3.3 Linearization at Different Operating Points . . . 182
8.4 Stability Analysis of the Uncertain Dynamic Inversion . . . 183

8.4.1 Uncertain Model Parameters and Measurement Data . 183
8.4.2 Modeling of the Uncertain Dynamic Inversion 183
8.4.3 Linear Representation of the Lateral-directional Motion 185
8.4.4 Definition of the Matrices A_{DI}, B_{DI}, and C_{DI} for the Lateral Mode 185
8.4.5 Stability of the Channel $\dot{p}_{des}$ to p_{meas} 187
8.4.6 Stability of the Channel $\dot{r}_{des}$ to r_{meas} 190
8.5 Roll and Yaw Rate Controllers 191
8.5.1 Architecture of the Controllers 193
8.5.2 Open-loop Analysis of the Roll and Yaw Rate Controllers 193
8.5.3 Frequency-domain Stability and Robustness Bounds . . 194
8.6 Coordinated-turn Controllers 197
8.6.1 Sideslip Angle Controllers 197
8.6.2 Desired Dynamics of the Bank Angle 197
8.6.3 Desired Dynamics of the Sideslip Angle 198
8.6.4 Simulation Results 198
References 200

9 Reconfigurable Guidance System 201
9.1 Introduction 201
9.2 Lateral Guidance System 203
9.2.1 Lateral Guidance Control Law for Trajectory Tracking 203
9.2.2 Advantages and Properties of the Method 204
9.2.3 Drawback of the Method 205
9.2.4 Selection of L_1 205
9.2.5 Path-planning Objective 206
9.3 Regular Waypoint Tracking 206
9.3.1 Computation of the Reference Point P 206
9.3.2 Logic for Segment Switching 207
9.3.3 Computation of the Roll Angle Command ϕ_{com} 208
9.4 Altitude Guidance Law 210
9.5 NFZ and Obstacles 211
9.5.1 Definition of an NFZ 211
9.5.2 Choice of an Appropriate Look-ahead Distance R_{LA} . . 212
9.6 Detection of the NFZ 214
9.7 NFZ Avoidance Algorithm 216
9.7.1 On-line Selection of an Avoidance Path Template 218
9.7.2 Entering the Circular Path Template 219
9.7.3 Choice of the Avoidance Side 219
9.7.4 Generating the Template Path 220
9.7.5 Leaving the Circular Path Template 221
9.7.6 Properties of the Guidance Schedule 223
9.8 Simulation 223
9.8.1 Simulation Set-up 223

9.8.2 Simulation Results . . . 225
9.9 Conclusions . . . 228
References . . . 228

10 Evaluation of the Reduction in the Performance of a UAV 229
10.1 Introduction . . . 229
10.2 FDI System . . . 230
10.2.1 FDI with Control Surface Deflection Sensor . . . 230
10.2.2 FDI Without Control Surface Deflection Sensor . . . 230
10.3 Degraded Turn Performance Evaluation . . . 230
10.3.1 Determination of the Maximum Bank Angle for Left/Right Turn . . . 232
10.3.2 Determination of the Minimum Radius of Right/Left Turns . . . 234
10.3.3 Determination of the Maximum Roll Rates . . . 234
10.3.4 Determination of the Maximum Time τ_{roll} to Roll to ϕ_{max} . . . 235
10.4 Interface with the Guidance System . . . 235
10.5 Stability Discussion . . . 236
10.6 Simulation Results . . . 236
10.6.1 No Failure . . . 236
10.6.2 With Failure but No Reconfiguration . . . 237
10.6.3 With Failure and With Reconfiguration . . . 237
10.7 Performance Degradation Around the Pitch and Yaw Axes . . 238
10.7.1 Pitch Axis . . . 238
10.7.2 Yaw Axis . . . 239
10.8 Conclusion . . . 239
References . . . 240

11 Conclusions and Outlook . . . 241
11.1 Future Work . . . 241
11.1.1 FDI System . . . 241
11.1.2 Reconfigurable Guidance System . . . 241
11.2 The Future of Fault-tolerant Flight Control Systems for UAVs 242
11.3 General Conclusion . . . 242

A V_T, α, and β Differential Equations . . . 245

B Discretization of Linear State Space Models . . . 247
B.1 Continuous Model . . . 247
B.2 Discrete Model . . . 248
B.2.1 Derivation of the Discrete Process-noise Covariance Matrix Q_k . . . 249
B.2.2 Transition Matrix for KFs . . . 250

C Nonlinear Transformations Used in the Longitudinal Controllers 251
C.1 Nonlinear Transformation $T1$ Between Second Time Derivative of Altitude $\ddot{h}$ and the Aircraft Normal Acceleration a_n 251
C.2 Nonlinear Transformation $T2$ Between the Angle of Attack α and the Aircraft Normal Acceleration a_n 252
C.3 Nonlinear Transformation $T3$ Between $\dot{\alpha}$ and the Pitch Rate q 253

D Nonlinear Transformation Used in the Lateral-directional Controller 255
D.1 Dynamics of the Sideslip Angle 255
D.2 Roll Angle Command Signal and Equation Governing a Coordinated Turn 256
D.3 Law of Cosines 257

E Linearization of the Aircraft Model at 30 m/s 259
E.1 Longitudinal Linear Model 259
E.2 Lateral Linear Model 260

F Nomenclature 261

Index 265