
Contents

- 1 Introduction** 1
 - 1.1 Motivations for Fault-Tolerant Control Systems for UAVs 1
 - 1.2 Thesis Outline 2

- 2 Literature Review** 5
 - 2.1 Definition of Fault-Tolerant Systems 5
 - 2.1.1 Fault-Tolerant Control System 7
 - 2.1.2 Dealing with Faults and Failures in Practice 8
 - 2.2 Different Approaches for Fault-Tolerant Control 9
 - 2.2.1 Multiple Model Techniques 9
 - 2.2.2 Control Allocation Techniques 11
 - 2.2.3 Model Reference Adaptive Control (MRAC) 12
 - 2.2.4 Other Reconfigurable Control Methods 13
 - 2.3 Reconfigurable Guidance Systems 13
 - 2.4 New Trends 14
 - 2.5 Real Flight Testing of Fault-Tolerant Control (FTC) Algorithms 15

- 3 Nonlinear Aircraft Model** 17
 - 3.1 Definitions of the Frames 17
 - 3.2 Wind Disturbance 21
 - 3.3 Model of the Low Altitude Atmosphere 22
 - 3.4 Equations of Rigid-Body Motion 23
 - 3.5 Engine 26
 - 3.5.1 Engine Rate 26
 - 3.5.2 Thrust Force 27
 - 3.6 Model of the Aerodynamic Forces 27
 - 3.6.1 Lift Force 27
 - 3.6.2 Lateral Force 27
 - 3.6.3 Drag Force 28

3.7	Model of the Aerodynamic Torques	28
3.7.1	Roll Torque L^b	28
3.7.2	Pitch Torque M^b	29
3.7.3	Yaw Torque N^b	29
3.8	Summary of the Nonlinear Aircraft Model	29
4	Nonlinear Fault Detection and Isolation System	31
4.1	Introduction	31
4.2	FDI using Multiple Model Adaptive Estimation (MMAE) Schemes	32
4.2.1	Advantage of the MMAE Method	32
4.2.2	Limitations of the MMAE Method	33
4.2.3	New Extensions to the MMAE Method: the EMMAE Method	33
4.3	A New FDI Scheme based on the EMMAE Method	34
4.3.1	Modeling Actuator Faults	34
4.3.2	The EMMAE Method	35
4.4	Aircraft Actuator Configuration and Nonlinear Dynamics	37
4.4.1	The Aircraft Configuration	37
4.4.2	Aircraft Nonlinear Dynamics	37
4.5	Design of the Extended Kalman Filters	39
4.5.1	Extended Kalman Filter Equations	39
4.5.2	Designing the EKF for the No-Fault Scenario	44
4.5.3	Augmenting the State Vector with the Faulty Actuator Parameter $\bar{\delta}_i$	44
4.5.4	Designing the EKF for the Case of a Failure on Aileron 1	45
4.6	Actuator Fault Isolation	46
4.6.1	Hypothesis Testing	46
4.6.2	Gaussian Conditional Probability Density	48
4.7	Simulation Results of the EMMAE-FDI with no Supervision System	50
4.7.1	Simulation Conditions	50
4.7.2	Comments on the Simulation Results	52
4.7.3	Remarks on the First Attempt of Using the EMMAE-FDI System	53
4.8	Improvements to the EMMAE-FDI System	54
4.8.1	Design of an Active Supervision Module (Supervisor)	54
4.8.2	Performance of the EMMAE-FDI with the Supervision System	56
4.9	A Realistic Flight Scenario	58
4.9.1	No-Wind and No-Actuator-Fault Conditions	58
4.9.2	Wind Conditions and No Actuator Faults	61
4.9.3	Strong Winds, Actuator Faults and Active Supervision Module	62
4.10	An Additional Filtering Stage for the EMMAE-FDI System	66

4.11	Detection and Isolation of Simultaneous Failures	68
4.12	Usage of the EMMAE-FDI for a Reconfigurable Flight Control System . . .	70
4.12.1	Control Allocation	70
4.12.2	Benefits of the Supervision Module for Control Allocation	70
4.13	Computational Complexity of the EMMAE-FDI	71
4.14	Conclusion about the EMMAE-FDI System	72
5	Control Allocation	73
5.1	Introduction to Control Allocation	73
5.2	Reconfigurable Flight Control System	74
5.3	Behavior Mode of Ailerons and Elevators	78
5.3.1	Nominal Mode: Mode 0	79
5.3.2	Single Actuator Fault Modes: Modes 1 to 4	80
5.4	Multiple Failures	82
5.4.1	Case of Two Simultaneous Failures: Mode 5	82
5.4.2	More Than Two Simultaneous Failures: Modes 6 and 7	83
5.5	Extensions of the Method	83
5.6	Computational Load of the Method	83
5.7	Simulation Results	83
5.7.1	Impact of the Control Allocator on the Controller	86
5.7.2	Comparison of Computational Effort for Control Allocation	87
5.8	Conclusion on Control Allocation	88
6	Nonlinear Control Design	89
6.1	Concept of Dynamic Inversion	89
6.1.1	Derivation of a Dynamic Inversion Controller	89
6.1.2	General Case	89
6.1.3	Formulation of the Signal for the Desired Output Dynamics $\dot{y}_{des}(t)$. .	90
6.2	Ideal or Perfect Dynamic Inversion	91
6.3	Architecture of the Controller of Desired Dynamics	92
6.3.1	Selection of a PI Controller	92
6.3.2	Feedforward of the Command Signal y_c	93
6.3.3	Open-Loop Gain	95
6.3.4	Design Rules for the Command-Feedforward Gain f_c	95
6.3.5	Feedforward of the Rate of Change of the Command Signal \dot{y}_c	97
6.3.6	Reference Model and Explicit Model Following	98
6.3.7	Integrator Anti-Windup	98

7	Autopilot for the Longitudinal Motion	101
7.1	Equations for Longitudinal Mode Analysis	101
7.1.1	Pitch Rate Differential Equation	102
7.1.2	Airspeed Differential Equation	102
7.1.3	Differential Equation for the Angle of Attack	103
7.1.4	Differential Equation for the Pitch Angle	103
7.1.5	Matrices for the Longitudinal Mode	103
7.2	Dynamic Modes of the Longitudinal Plant	104
7.2.1	Short-Period Mode	104
7.2.2	Phugoid Mode	104
7.3	Validation of the Linear Longitudinal Model	105
7.3.1	Perturbation on Elevator Command	105
7.3.2	Perturbation on n_{mot}	105
7.4	Stability Analysis of the Uncertain Dynamic Inversion	108
7.4.1	Uncertain Model Parameters and Measurement Data	109
7.4.2	Linear Modeling of the Uncertain Dynamic Inversion	109
7.4.3	Model Simplification for the Longitudinal Motion	110
7.4.4	Linear Model of the Pitch Axis and Dynamic Inversion Process	111
7.4.5	Evaluation of the Uncertainty Terms in the Matrix A_{DI}	114
7.4.6	Effect of Uncertainties on Dynamic Inversion	116
7.4.7	Mathematical Selection of the Uncertain Model Parameters	120
7.5	General Control Architecture for the Longitudinal Motion	123
7.5.1	Nonlinear Transformation T_3	124
7.5.2	Nonlinear Transformation T_2	124
7.5.3	Nonlinear Transformation T_1	124
7.6	Pitch Rate Control	124
7.6.1	Stability/Robustness Requirements	125
7.6.2	Pitch Rate Closed-Loop Transfer Function	130
7.7	Angle-of-attack Control Loop	132
7.7.1	Open-Loop and Closed-Loop Gains	133
7.7.2	Comments on the Results	133
7.8	Rate-of-Climb Controller	138
7.8.1	Open-Loop Gain	139
7.8.2	Closed-Loop Gain	140
7.9	Altitude Controller	143
7.9.1	Open-Loop Gain	143
7.9.2	Closed-Loop Gain	144

7.9.3	Performance of the Altitude Controller	144
7.10	Airspeed Controller	148
7.10.1	Content of this Section	148
7.10.2	Motivation	148
7.10.3	Engine Speed	150
7.10.4	Thrust Force	150
7.10.5	Nonlinear Transformations	150
7.10.6	Controller of the Desired Airspeed Dynamics	152
7.10.7	Simulation Results	152
8	Autopilot for the Lateral Motion	155
8.1	Equations for Lateral Motion Analysis	155
8.1.1	Differential Equation for the Roll Rate p	156
8.1.2	Differential Equation for the Yaw Rate r	156
8.1.3	Differential Equation for the Sideslip Angle β	156
8.1.4	Differential Equation for the Roll Angle ϕ	157
8.1.5	Matrices for the Lateral Mode	157
8.2	Dynamic Modes of the Lateral Plant	158
8.2.1	Dutch Roll Mode	158
8.2.2	Roll Subsidence Mode	158
8.2.3	Spiral Mode	159
8.3	Validation of the Linear Lateral Model	159
8.3.1	Perturbation on the Aileron Command	159
8.3.2	Perturbation on the Rudder Command	159
8.3.3	Linearization at Different Operating Points	161
8.4	Stability Analysis of the Uncertain Dynamic Inversion	162
8.4.1	Uncertain Model Parameters and Measurement Data	162
8.4.2	Modeling of the Uncertain Dynamic Inversion	163
8.4.3	Linear Representation of the Lateral-Directional Motion	163
8.4.4	Definition of the Matrices A_{DI} , B_{DI} , and C_{DI} for the Lateral Mode	164
8.4.5	Stability on the Channel \dot{p}_{des} to p_{meas}	166
8.4.6	Stability on the Channel \dot{r}_{des} to r_{meas}	169
8.5	Roll and Yaw Rate Controllers	170
8.5.1	Architecture of the Controllers	171
8.5.2	Open-loop Analysis of the Roll and Yaw Rate Controllers	172
8.5.3	Frequency-Domain Stability and Robustness Bounds	173
8.6	Coordinated-Turn Controllers	175
8.6.1	Sideslip Angle Controllers	175

8.6.2	Desired Dynamics of the Bank Angle	175
8.6.3	Desired Dynamics of the Sideslip Angle	175
8.6.4	Simulation Results	176
9	Reconfigurable Guidance System	179
9.1	Introduction	179
9.2	Lateral Guidance System	181
9.2.1	Lateral Guidance Control Law for Trajectory Tracking	181
9.2.2	Advantages and Properties of the Method	182
9.2.3	Drawback of the Method	183
9.2.4	Selection of L_1	183
9.2.5	Path Planning Objective	183
9.3	Regular Waypoint Tracking	184
9.3.1	Computation of the Reference Point P	184
9.3.2	Logic for Segment Switching	185
9.3.3	Computation of the Roll Angle Command ϕ_{com}	187
9.4	Altitude Guidance Law	188
9.5	No-Fly Zones (NFZ) and Obstacles	189
9.5.1	Definition of a No-Fly Zone	189
9.5.2	Choice of an Appropriate Look-Ahead Distance R_{LA}	190
9.6	Detection of the No-Fly Zone	191
9.7	No-Fly Zone Avoidance Algorithm	195
9.7.1	On-Line Selection of an Avoidance Path Template	195
9.7.2	Entering the Circular Path Template	196
9.7.3	Choice of the Avoidance Side	196
9.7.4	Generating the Template Path	196
9.7.5	Leaving the Circular Path Template	198
9.7.6	Properties of the Guidance Schedule	198
9.8	Simulation	201
9.8.1	Simulation Set-Up	201
9.8.2	Simulation Results	201
9.9	Conclusions	204
10	Evaluation of the Reduction in the Performance of a UAV	205
10.1	Introduction	205
10.2	Fault Detection and Isolation System	206
10.2.1	FDI with Control Surface Deflection Sensor	206
10.2.2	FDI without Control Surface Deflection Sensor	206

10.3 Degraded Turn Performance Evaluation	207
10.3.1 Determination of the Maximum Bank Angle for Left/Right Turn ...	208
10.3.2 Determination of the Minimum Radius of Right/Left Turns	209
10.3.3 Determination of the Maximum Roll Rates	210
10.3.4 Determination of the Maximum Time τ_{roll} to Roll to ϕ_{max}	210
10.4 Interface with the Guidance System	210
10.5 Stability Discussion	210
10.6 Simulation Results	211
10.6.1 No Failure	211
10.6.2 With Failure but No Reconfiguration	211
10.6.3 With Failure and With Reconfiguration	212
10.7 Performance Degradation around the Pitch and Yaw Axes	212
10.7.1 Pitch Axis	212
10.7.2 Yaw Axis	214
10.8 Conclusion	214
11 Conclusions and Outlook	217
11.1 Hardware and Software Design	217
11.1.1 Mini Control Unit (MCU)	217
11.1.2 Software Suite	218
11.2 Future Work	219
11.2.1 Fault Detection and Isolation (FDI) System	219
11.2.2 Reconfigurable Guidance System	219
11.3 The Future of Fault-Tolerant Flight Control Systems for UAVs	219
11.4 General Conclusion	220
A Appendix	223
A.1 Parameters of the Nonlinear Plant	224
A.2 V_T , α , and β Differential Equations	225
A.3 Discretization of Linear State Space Models	227
A.3.1 Continuous Model	227
A.3.2 Discrete Model	228
A.3.3 Derivation of the Discrete Process-Noise Covariance Matrix Q_k	229
A.4 Transition Matrix for Kalman Filters	230
A.5 Nonlinear Transformations used in the Longitudinal Controllers	231
A.6 Nonlinear Transformation used in the Lateral-Directional Controller	234
A.7 Roll Angle Command Signal and Equation Governing a Coordinated Turn .	235
A.8 Linearization of the Aircraft Model at 30 m/s	236

A.8.1 Longitudinal Linear Model	236
A.8.2 Lateral Linear Model	237
A.9 Nomenclature	238
References	241