

# Contents

## Part I Surviving the Improbable: Towards Resilient Aircraft Control

<b>1</b>	<b>Introduction . . . . .</b>	<b>3</b>
	Thomas Lombaerts, Hafid Smaili, Jan Breeman	
1.1	Towards More Resilient Flight Control . . . . .	3
1.2	History of Flight Control Systems, Source: [40] . . . . .	4
1.2.1	Mechanical [33], [35] . . . . .	6
1.2.2	Hydro-mechanical [33], [35] . . . . .	6
1.2.3	Fly-By-Wire Flight Control [33], [35], [34] . . . . .	7
1.2.4	Fault Tolerant Control in Fly-By-Wire Systems, Sources: [40] . . . . .	10
1.2.5	Airbus Philosophy, Sources: [22], [30] . . . . .	11
1.2.6	Boeing Philosophy, Sources: [24], [42] . . . . .	12
1.2.7	Short Case Study of Other Fault Tolerant Systems, Source: [24] . . . . .	14
1.2.8	A Final Note on Fault Tolerance Properties Incorporated in Current Fly by Wire Flight Control Systems . . . . .	20
1.3	Rationale of Damage Tolerant Control - Aircraft Accident Survey . . . . .	21
1.3.1	American Airlines Flight AA191, Source: [27] . . . . .	22
1.3.2	Japan Airlines Flight JL123, Source: [27] . . . . .	26
1.3.3	United Airlines Flight UA232, Source: [27] . . . . .	28
1.3.4	EL AL Cargo Flight LY1862, Source: [40] . . . . .	30
1.3.5	USAir Flight 427 and United Airlines Flight 585, Sources: [4], [9], [5] . . . . .	32
1.3.6	DHL Cargo Flight above Baghdad, Sources: [31], [32] . . . . .	36
1.3.7	Final Note on Accident Analysis . . . . .	38
1.4	Earlier Accomplishments in This Field, Source: [40] . . . . .	40

1.4.1	Self-Repairing Flight Control System (SRFCS) Program .....	40
1.4.2	MD-11 Propulsion Controlled Aircraft (PCA) .....	41
1.4.3	NASA Intelligent Flight Control System (IFCS) F-15 Program .....	41
1.5	Research Challenges and Objectives .....	42
	References .....	43
<b>2</b>	<b>Fault Tolerant Flight Control - A Survey</b> .....	47
	Michel Verhaegen, Stoyan Kanev, Redouane Hallouzi, Colin Jones, Jan Maciejowski, Hafid Smail	
2.1	Why Fault Tolerant Control? .....	47
2.2	Fault Classification .....	49
2.3	Modelling Faults .....	51
2.3.1	Multiplicative Faults .....	51
2.3.2	Additive Faults .....	53
2.3.3	Component Faults .....	54
2.4	Main Components in an FTC System .....	55
2.5	FTC Problem Formulation .....	58
2.5.1	Passive Fault Tolerant Control .....	61
2.5.2	Active Fault Tolerant Control .....	62
2.6	State-of-the-Art in Fault Tolerant Flight Control .....	63
2.6.1	Classification of Reconfigurable Control .....	63
2.6.2	Multiple Model Control .....	64
2.6.3	Control Allocation (CA) .....	69
2.6.4	Adaptive Feedback Linearization via Artificial Neural Network .....	71
2.6.5	Sliding Mode Control (SMC) .....	74
2.6.6	Eigenstructure Assignment (EA) .....	75
2.6.7	Model Reference Adaptive Control (MRAC) .....	78
2.6.8	Model Predictive Control .....	80
2.6.9	Model Following .....	81
2.6.10	Adaptive Control .....	82
2.7	Comparison of Fault Tolerant Flight Control Methods .....	83
	References .....	85
<b>3</b>	<b>Fault Detection and Diagnosis for Aeronautic and Aerospace Missions</b> .....	91
	David Henry, Silvio Simani, Ron J. Patton	
3.1	Introduction .....	91
3.2	Fault Detection and Diagnosis Approaches .....	94
3.2.1	The Parity-Space Methods .....	94
3.2.2	Particle Filtering Approach .....	97
3.2.3	Nonlinear EKF Approaches .....	99
3.2.4	Observer-Based Approaches .....	101
3.2.5	Norm-Based Approaches .....	103

3.2.6	$H_\infty$ Fault Estimation Approach .....	104
3.2.7	Non-linear FDD Method .....	107
3.2.8	Sliding Mode Observer .....	109
3.3	Application Examples .....	109
3.3.1	Application to ‘Oscillatory Failure Case’ (OFC) .....	110
3.3.2	Simulated Aircraft Model FDD .....	110
3.3.3	Aerospace Mission Application Examples .....	113
3.3.4	Robust Diagnosis for Mars Express Satellite Thruster Faults .....	116
3.4	Conclusion .....	120
	References .....	121
<b>4</b>	<b>Real-Time Identification of Aircraft Physical Models for Fault Tolerant Flight Control .....</b>	<b>129</b>
	Ping Chu, Jan Albert (Bob) Mulder, Jan Breeman	
4.1	Introduction .....	129
4.2	History of Aircraft Model Identification at Delft University of Technology .....	130
4.3	The Two Step Method .....	135
4.3.1	Decomposition of Aircraft State and Parameter Estimation .....	136
4.3.2	Estimation Properties .....	144
4.3.3	Techniques to Cope with Estimation Biases .....	146
4.4	On-Line Parameter Estimation Using Least Squares and Total Least Squares Methods .....	146
4.4.1	Preliminaries .....	147
4.4.2	Sequential Total Least Squares (Ref. [34]) .....	148
4.4.3	Summary of TLS Method .....	149
4.5	Real-Time Identification of Aircraft Physical Model for Fault Tolerant Flight Control, [13] .....	149
4.6	Conclusions .....	152
	References .....	153
<b>5</b>	<b>Industrial Practices in Fault Tolerant Control .....</b>	<b>157</b>
	Philippe Goupil	
5.1	Introduction .....	157
5.2	Aircraft Development Process - The V-Cycle .....	157
5.3	Some ‘Golden Rules’ for Designing a Highly Dependable System .....	158
5.4	Flight Control Computer Functional Specification .....	161
5.5	System Validation and Verification .....	162
5.6	An Example of Monitoring: A380 Oscillatory Failure Case Detection .....	163
5.7	Conclusions .....	166
	References .....	166

## **Part II RECOVER: The Benchmark Challenge**

<b>6 RECOVER: A Benchmark for Integrated Fault Tolerant Flight Control Evaluation</b> . . . . .	171
Hafid Smaili, Jan Breeman, Thomas Lombaerts, Diederick Joosten	
6.1 Introduction . . . . .	171
6.2 Flight 1862 Accident Reconstruction and Simulation . . . . .	172
6.2.1 Sequence of Events . . . . .	173
6.2.2 Analysis of Flight 1862 . . . . .	176
6.2.3 Failure Mode Configuration . . . . .	180
6.2.4 Flight Data Reconstruction and Simulation . . . . .	181
6.3 GARTEUR RECOVER Benchmark . . . . .	194
6.3.1 Description . . . . .	194
6.3.2 Implementation . . . . .	197
6.3.3 Fault Scenarios Specification . . . . .	200
6.3.4 Graphical User Interface . . . . .	206
6.3.5 Aircraft Visualisation . . . . .	209
6.3.6 User Example . . . . .	210
6.3.7 Aircraft Characteristics . . . . .	212
6.4 GARTEUR RECOVER Benchmark Applications . . . . .	218
6.5 Conclusion . . . . .	219
References . . . . .	220
<b>7 Assessment Criteria as Specifications for Reconfiguring Flight Control</b> . . . . .	223
Thomas Lombaerts, Diederick Joosten, Hafid Smaili, Jan Breeman	
7.1 Introduction . . . . .	223
7.2 Specification Modelling . . . . .	224
7.2.1 General Evaluation Criteria . . . . .	225
7.2.2 Test Manoeuvres for Qualification . . . . .	227
7.3 Discussion . . . . .	239
References . . . . .	243

## **Part III Design Methods and Benchmark Analysis**

<b>8 Fault Tolerant Control Using Sliding Modes with On-Line Control Allocation</b> . . . . .	247
Halim Alwi, Christopher Edwards	
8.1 Introduction . . . . .	247
8.1.1 Sliding Mode Control . . . . .	247
8.1.2 Sliding Mode Control and Control Allocation . . . . .	248
8.2 Controller Design . . . . .	249
8.2.1 Problem Formulation . . . . .	249
8.2.2 Design Issues . . . . .	254

8.3	Controller Design .....	254
8.3.1	Fault Tolerant Controller Design .....	256
8.3.2	Heading and Altitude Control and EPR Control Mixing .....	260
8.3.3	ILS Landing .....	261
8.3.4	Fault Tolerant Control Simulation Results .....	264
8.4	Conclusions .....	270
	References .....	270
<b>9</b>	<b>An Adaptive Fault-Tolerant FCS for a Large Transport Aircraft</b> .....	<b>273</b>
	Adolfo Sollazzo, Gianfranco Morani, Andrea Giovannini	
9.1	Fault-Tolerant FCS .....	273
9.1.1	Adaptive Model-Following .....	274
9.1.2	The SCAS Architecture .....	277
9.1.3	Limitations and Practical Solutions .....	279
9.2	The Classic A/P .....	280
9.3	Numerical Validation .....	280
9.4	Future Development .....	287
9.5	Conclusions .....	289
	References .....	290
<b>10</b>	<b>Subspace Predictive Control Applied to Fault-Tolerant Control</b> .....	<b>293</b>
	Redouane Hallouzi, Michel Verhaegen	
10.1	Introduction .....	293
10.2	Architecture of the Fault-Tolerant Control System .....	295
10.2.1	Control Loops .....	295
10.2.2	Fault Isolation .....	296
10.3	Closed-Loop Subspace Predictive Control .....	297
10.3.1	Closed-Loop Subspace Predictor (CLSP) .....	297
10.3.2	Closed-Loop Subspace Predictor Integrated with a Predictive Control Law .....	301
10.4	SPC (Re-)configuration .....	303
10.5	Simulation Results .....	305
10.5.1	Trajectory Following for the Nominal Case .....	306
10.5.2	Trajectory Following for Elevator Lock-in-Place .....	307
10.5.3	Trajectory Following for Rudder Runaway .....	309
10.5.4	Trajectory Following for “Bijlmerramp” Condition .....	310
10.5.5	Discussion of the Simulation Results .....	312
10.6	Real-Time Implementation .....	313
10.7	Conclusions .....	315
	References .....	315

<b>11 Fault-Tolerant Control through a Synthesis of Model-Predictive Control and Nonlinear Inversion</b>	319
D.A. Joosten, T.J.J. van den Boom, M. Verhaegen	
11.1 Introduction	319
11.2 Overall Control-Setup	320
11.2.1 Model Structure	322
11.2.2 Nonlinear Dynamic Inversion	322
11.2.3 Model Predictive Control	324
11.2.4 Control Allocation	327
11.3 Modeling and Dynamic Inversion of the Benchmark Model	327
11.4 Simulation Results	331
11.4.1 Reference Tracking: Stabiliser Runaway	331
11.4.2 Right Turn and Localiser Intercept	332
11.5 Conclusion	335
References	335
<b>12 A FTC Strategy for Safe Recovery against Trimmable Horizontal Stabilizer Failure with Guaranteed Nominal Performance</b>	337
Jérôme Cieslak, David Henry, Ali Zolghadri	
12.1 Introduction	337
12.2 Nomenclature	339
12.3 Problem Statement	340
12.4 Model-Based FDI Schemes: Some Assumptions for an Integrated FDI/FTC Design Approach	344
12.4.1 Analysis of the FTC Loop	344
12.4.2 Some Outlines for the Design	345
12.4.3 The Case of an Observer-Based FDI Scheme	346
12.5 Important Issues about Stability and Performance in Faulty Situations	346
12.6 FM-AG16 FTC Problem	347
12.6.1 Modelling the Aircraft Dynamics	347
12.6.2 Modeling the Autoflight and FCS Systems	350
12.6.3 Design of $\bar{K}(s)$	350
12.6.4 Nonlinear Simulation Results	354
12.7 Concluding Remarks	356
Appendix A: Bumpless Switching Scheme	356
Appendix B: Computed Controller $\hat{K}(s) = \hat{C}_K(sI - \hat{A}_K)^{-1}\hat{B}_K + \hat{D}_K$	359
References	360
<b>13 Flight Control Reconfiguration Based on Online Physical Model Identification and Nonlinear Dynamic Inversion</b>	363
Thomas Lombaerts, Ping Chu, Jan Albert (Bob) Mulder	
13.1 Introduction	363

13.2	On Line Nonlinear Damaged Aircraft Model Identification:	
	Two Step Method .....	364
13.2.1	Aircraft State Estimation .....	366
13.2.2	Aerodynamic Model Identification .....	368
13.3	Real Time Aerodynamic Model Identification .....	371
13.4	Application on the Boeing 747 Simulator .....	372
13.4.1	Trim Horizontal Stabilizer (THS) Runaway .....	373
13.4.2	Loss of the Vertical Tail .....	373
13.4.3	Feedback of Aircraft Stability and Control Effector Information to the Pilot.....	375
13.5	Trigger for Reconfiguration .....	376
13.6	Reconfiguring Control: Adaptive Nonlinear Dynamic Inversion .....	377
13.6.1	Autopilot Control: Assessment Criteria .....	382
13.7	Computational Load .....	395
13.8	Conclusions .....	395
13.9	Current and Future Work .....	396
	References .....	396
<b>14</b>	<b>A Combined Fault Detection, Identification and Reconfiguration System Based around Optimal Control Allocation</b> .....	<b>399</b>
	Nicholas Swain, Shadhanan Manickavasagar	
14.1	Background .....	399
14.1.1	Control Allocation.....	399
14.1.2	Fault Detection and Identification .....	402
14.1.3	Software and Hardware Testing .....	403
14.2	Introduction .....	403
14.3	Fault Tolerant Control System Overview .....	405
14.3.1	Sensors .....	405
14.3.2	Outer-Loop Controller/Autopilot.....	406
14.3.3	Non-linear Dynamic Inversion .....	406
14.3.4	Direct Control Allocation .....	407
14.3.5	Aerodynamic FDI .....	411
14.3.6	Actuator FDI .....	414
14.3.7	Flight Envelope Protection .....	416
14.4	Benchmark Tests .....	418
14.4.1	Longitudinal Control Failure Test .....	418
14.4.2	Lateral Control Failure Test .....	419
14.4.3	El-AL Case .....	420
14.5	Conclusion .....	421
	References .....	422

<b>15 Detection and Isolation of Actuator/Surface Faults for a Large Transport Aircraft .....</b>	423
Andras Varga	
15.1 Introduction .....	423
15.2 Design of Least Order Scalar Output Detectors .....	424
15.3 Solving Fault Isolation Problems .....	426
15.4 Computational Aspects .....	429
15.5 Monitoring Actuator Failures .....	430
15.5.1 Component Level Monitoring .....	431
15.5.2 System Level Monitoring .....	433
15.5.3 Pitch Axis Fault Monitoring .....	435
15.5.4 Gear and Roll Axes Fault Monitoring .....	439
15.6 Summary of Achieved Results and Needs for Further Analysis .....	441
References .....	442
<b>Part IV Real-Time Flight Simulator Assessment</b>	
<b>16 Real-Time Assessment and Piloted Evaluation of Fault Tolerant Flight Control Designs in the SIMONA Research Flight Simulator .....</b>	451
Olaf Stroosma, Thomas Lombaerts, Hafid Smaili, Mark Mulder	
16.1 Introduction .....	451
16.2 Evaluation Method .....	453
16.2.1 Experiment Design .....	453
16.2.2 Dependent Measures .....	455
16.2.3 Participants .....	457
16.2.4 Simulator Configuration .....	457
16.2.5 Procedure .....	463
16.3 Results .....	468
16.4 Conclusions .....	471
Appendix 1: Failure mode test matrix .....	472
Appendix 2: Cooper Harper Handling Qualities Rating Scale .....	474
References .....	475
<b>17 Piloted Evaluation Results of a Nonlinear Dynamic Inversion Based Controller Using Online Physical Model Identification .....</b>	477
Thomas Lombaerts, Ping Chu, Hafid Smaili, Olaf Stroosma, Jan Albert (Bob) Mulder	
17.1 Introduction .....	477
17.2 Fly-by-Wire ANDI Control Law Design .....	478
17.3 Fly-by-Wire ANDI Control Law Evaluation .....	479
17.4 Analysis Results .....	481
17.4.1 FTC and Pilot Performance Analysis Results: Time Histories .....	481

17.4.2	Handling Qualities Analysis Results: CH Ratings .....	486
17.4.3	Pilot Workload Analysis Results .....	491
17.5	Conclusions .....	498
	References .....	499
<b>18</b>	<b>Model Reference Sliding Mode FTC with SIMONA Simulator Evaluation: EL AL Flight 1862 Bijlmermeer Incident Scenario . . . . .</b>	<b>501</b>
	Halim Alwi, Christopher Edwards, Olaf Stroosma, Jan Albert (Bob) Mulder	
18.1	Introduction .....	501
18.2	A Model Reference Sliding Mode Control Allocation Scheme .....	502
18.3	Controller Design .....	506
18.3.1	Lateral Controller Design .....	507
18.3.2	Longitudinal Controller Design .....	508
18.4	SIMONA Implementation .....	510
18.5	SIMONA Flight Simulator Results with Experienced Pilots .....	510
18.5.1	SMC Controller Evaluation .....	511
18.6	Conclusions .....	517
	References .....	517
<b>Part V Conclusions</b>		
<b>19</b>	<b>Industrial Review . . . . .</b>	<b>521</b>
	Philippe Goupil, Andres Marcos	
19.1	Introduction .....	521
19.2	Considerations for Commercial Aircraft - AIRBUS .....	522
19.2.1	Industrial Limitations and Constraints .....	523
19.2.2	An Aircraft Manufacturer Perspective .....	524
19.2.3	Conclusion .....	528
19.3	Perspectives for Aerospace Applications - Deimos Space .....	528
19.3.1	Context and Significance of the FM-AG16 for Space Systems .....	530
19.3.2	Assessment of the Techniques and Results .....	532
19.3.3	Conclusion .....	535
	References .....	535
<b>20</b>	<b>Concluding Remarks . . . . .</b>	<b>537</b>
	Christopher Edwards, Thomas Lombaerts, Hafid Smaili	
20.1	Summary of Achievements .....	537
20.2	Future Research .....	538
	<b>Appendix . . . . .</b>	<b>541</b>