

Contents

Kurzfassung	vii
Abstract	ix
List of Abbreviations	xi
1. Introduction	1
1.1. Optimized modern commercial air traffic	2
1.2. State of the art in aircraft trajectory optimization	5
1.3. Contributions	13
2. Trajectory Optimization Approach	19
2.1. Optimal control problem	21
2.1.1. Solution with indirect method	25
2.1.2. Solution by direct transcription	26
2.2. Numerical solution	27
2.2.1. Direct collocation	27
2.2.2. Direct shooting method	28
2.2.3. Multiobjective formulation	31
2.2.4. Genetic algorithms and Pareto optimality	33
2.3. Implementation with MOPS and TRAJOPT	36
2.3.1. Solver selection	40
2.3.2. Path constraints	40
2.3.3. Objective calculation	41
2.3.4. Simulation termination	44
3. Trajectory Modeling and Parameterization	47
3.1. Trajectory kinematics	47
3.1.1. Parameter-based trajectory description	53
3.2. Trajectory definition using the gnomonic projection	57

3.3.	Parameterization of the optimal control problem	62
3.3.1.	Bézier-Splines	65
3.3.2.	B-Splines	66
3.3.3.	NURBS	69
3.4.	Four-dimensional trajectory approximation with B-Splines	70
3.4.1.	Knot averaging	73
3.4.2.	Degree elevation	75
3.4.3.	Influence of degree elevation on simulation performance	77
3.5.	Implementation in MODELICA	81
3.5.1.	Trajectory definition	82
3.5.2.	Parameter translation module	84
4.	Aircraft Modeling and Flight Control	93
4.1.	Rigid-body model	96
4.2.	Mass-point model	99
4.3.	Total energy model	99
4.4.	Model inversion	101
4.5.	4-D trajectory tracking	103
4.5.1.	Longitudinal time tracking	107
4.5.2.	Lateral position tracking	109
4.6.	Pseudo-control hedging	109
4.7.	Controller structures for different model fidelity	114
4.8.	Implementation in MODELICA	116
4.8.1.	Aircraft models	116
4.8.2.	Environment models	118
4.8.3.	Control system	120
5.	Case Studies	125
5.1.	City pair optimization with inverse model	126
5.1.1.	Results	127
5.1.2.	Discussion	130
5.2.	Reactive trajectory following for a high altitude pseudo satellite	130
5.2.1.	Results	133
5.2.2.	Discussion	134
5.3.	Approach trajectory optimization with 6-DoF model	135
5.3.1.	Results	136

5.4. Comparison of open- and closed-loop optimization	140
5.4.1. Open-loop optimization setup of 3-DoF forward model	143
5.4.2. Closed-loop optimization setup of 3-DoF forward model	148
5.4.3. Comparison of optimization results	148
5.5. Transatlantic route optimization with BADA model . . .	152
5.5.1. Results	154
5.5.2. Discussion	156
6. Conclusions and Future Work	159
Bibliography	165
A. Optimization Runscripts	181
B. Interpolation for Irregular Grids	189
C. Controller Block Diagrams	193
C.1. Longitudinal movement	194
C.2. Lateral movement	197
D. System and Criteria Models	203
D.1. Emissions model	203
D.2. Contrails model	205
D.3. Noise model	209
E. Scenario Definitions	213