

Contents

Acknowledgements	V
Contents	VII
List of Figures	XI
List of Tables	XIX
Abstract	XXI
1 Introduction	1
1.1 Unmanned Aerial Vehicles	1
1.2 Manual vs autonomous control	3
1.3 UAV Mishaps	4
1.4 Situational Awareness	6
1.5 Bilateral Teleoperation	8
1.6 Goal of the Thesis	9
1.7 Thesis outline	11
2 Haptic Systems Review and Classification	13
2.1 Robot Bilateral (Tele)operation Review	15

CONTENTS

2.1.1	Ground Mobile Robots	15
2.1.2	Manned and Unmanned Aerial Vehicles	16
2.2	Haptic aids analysis and classification	19
2.3	Reality-Based Haptic Aids	21
2.4	Time Delays	22
3	Conventional Aircraft Artificial Feel	25
3.1	FBW Aircrafts/UAVs Analogy	27
3.2	Mechanically Driven Aircrafts	28
3.2.1	A simplified stick force	30
3.2.2	Simplified Stick Force Proof	30
3.3	CAAF	34
3.3.1	Variable Stiffness CAAF	36
3.3.2	Force Injection CAAF	40
3.4	The Experimental Setup	44
3.5	Disturbance Rejection Experiments	48
3.5.1	The CAAF Experiment Simulators	49
3.5.2	The CAAF VS DHA Experiment Simulators	51
3.6	CAAF Evaluation	58
3.6.1	CAAF Experiment	59
3.6.2	CAAF Experimental Results	60
3.6.3	CAAF VS DHA Experiment	61
3.6.4	CAAF VS DHA Experimental Results	63
4	Obstacle Avoidance Feel	69
4.1	Simulation Environment	70
4.2	Aircraft Lateral Dynamics	72
4.3	The Stick Force	74
4.3.1	The haptic feedback	75
4.3.2	The Obstacle Force Field	76
4.4	The OAF VS DHA Experiment Simulators	80
4.4.1	NoEF Simulator	81
4.4.2	DHA Simulator	83
4.4.3	IHA-OAF Simulator	84
4.4.4	Isolated Obstacle Scenario	89
4.5	IHA-OAF Evaluation	90
4.5.1	Experimental Results	93

5	The Mixed CAAF/OAF	99
5.1	CAAF for lateral dynamics	101
5.1.1	The Wind Gust Simulation	101
5.1.2	β -CAAF	103
5.1.3	Lateral Acceleration-CAAF	105
5.2	Lateral Acceleration-DHA	105
5.3	Obstacle Avoidance Force Field	106
5.4	Haptic cueing for lateral dynamics	106
5.5	The Windy Obstacle Avoidance Simulators	107
5.5.1	NoEF Simulator	107
5.5.2	DHA Simulator	109
5.5.3	IHA-Mixed CAAF/OAF Simulator	111
5.6	Mixed CAAF/OAF Evaluation	114
5.6.1	Experimental Results	116
6	Delayed Bilateral Teleoperation	123
6.1	System Setup	125
6.2	F-P scheme	127
6.2.1	The Car-Driving Metaphor	129
6.2.2	The slave dynamics	130
6.2.3	The slave controller	131
6.2.4	The haptic feedback	132
6.2.5	Omega Device dynamic model	135
6.2.6	Master Compensator Design	135
6.2.7	Compensator Splitting and Pilot Simulation	136
6.2.8	F-P scheme: simulations	141
6.3	The Wave Variables Approach	143
6.4	Fa-P scheme	145
6.4.1	Admittance and local master controller	147
6.4.2	Fa-P scheme: simulations	151
6.4.3	The human force observer	152
7	Conclusions	161
Appendixes		168
A	Experiments Setup	169
A.1	The Aircraft Model	170

CONTENTS

A.1.1	Technical Data	172
A.1.2	Aircraft Natural Modes	174
A.2	The Haptic Device	176
A.3	The 3D Visualization System	178
B	Omega Device Identification	181
C	DHA Compensators Design	185
C.1	DHA for Longitudinal Disturbance Rejection	185
C.2	DHA for Lateral Disturbance Rejection	188
D	Experiments Background	191
D.1	The CAAF Experiment	191
D.1.1	Instruction to subjects	193
D.1.2	Subjects detailed results	193
D.2	The CAAF VS DHA Experiment	193
D.2.1	Instruction to professional pilots	196
D.2.2	Subjects detailed results	197
D.3	The OAF VS DHA Experiment	198
D.3.1	Instruction to subjects	199
D.3.2	Subjects detailed results	200
D.4	The MIXED-CAAF/OAF VS DHA Experiment	201
D.4.1	Instruction to subjects	201
D.4.2	Subjects detailed results	203
	Bibliography	203