
Contents

1	Introduction	1
1.1	Flying like Animals	1
1.2	Flight Characteristics	1
1.3	Intelligence	3
1.4	Flapping Wing Micro Air Vehicles	5
	References	5
 Part I Design and Materials		
2	Introduction to Flapping Wing Design	9
2.1	Introduction	9
2.2	General Design Concept	10
2.3	Tail Configuration	11
2.4	Wing Configuration and Design	12
2.5	Control and Actuators	15
2.5.1	Actuation Strategies	15
2.5.2	Actuators	16
2.6	Energy and Power	18
2.6.1	Flight Efficiency	19
2.6.2	Energy Storage Materials	19
2.6.3	Trading Off Battery Mass and Payload Mass	22
2.7	Drive and Mechanism	25
2.8	Conclusions	27
	References	27
3	Mechanical Design and Materials	31
3.1	Introduction	31
3.2	General Concept	31
3.3	Crank Mechanism	32
3.4	Wings	34
3.5	Tail	36
3.6	Fuselage	37
3.7	Conclusions	38
	References	39

4	Electronics	41
4.1	Introduction	41
4.2	Power Source	42
4.3	Motor	42
4.3.1	Drive Mechanism	43
4.3.2	Development of the Motor	43
4.4	Radio Control System	47
4.5	Actuators	48
4.6	Video System	49
4.7	Onboard Sensor Processing	51
4.7.1	Autopilot	51
4.7.2	Vision Processing	52
4.8	Conclusions	53
	References	54

Part II Aerodynamics

5	Introduction to Fixed and Flapping Wing Aerodynamics	57
5.1	Introduction	57
5.2	Fixed Wing Aerodynamics	58
5.2.1	Generation of Circulatory Lift in Two Dimensional Airfoils	59
5.2.2	Aerodynamic Characteristics of Finite Span Wings	62
5.3	Flapping Wing Aerodynamics	64
5.3.1	Kinematics of Flapping Flight	64
5.3.2	Force Generation Mechanisms	68
5.4	Conclusion	77
	References	78
6	Research on the DelFly Aerodynamics	81
6.1	Introduction	81
6.2	Comparison of the Flapping Motion and Unsteady Forces in Air and Vacuum Conditions	82
6.3	Optimization of the Wing Geometry	90
6.3.1	Influence of the Stiffener Position	91
6.3.2	Influence of Stiffener Diameter	95
6.3.3	Comparison of the Original and the Improved Wing	97
6.4	Flow Visualization in the Wake of the DelFly in Forward Flight	103
6.4.1	Experimental Setup and Analysis Methods	104
6.4.2	Spatio-Temporal Wake Reconstruction	106
6.4.3	Spatial Wake Reconstruction	113
6.5	Conclusions	117
	References	119

Part III Autonomous Flight

7	Introduction to Autonomous Flight	125
7.1	Background Information on Artificial Intelligence for Robotics	125
7.2	Challenges for Autonomous Flight	130
7.3	Approaches to Autonomous Flight	130
7.3.1	Flapping Wing MAVs	132
7.3.2	Approach to Autonomous Flight of the DelFly	133
	References.	135
8	Monocular Obstacle Detection	139
8.1	Introduction	139
8.2	Appearance Variation as a Cue for Obstacle Proximity	140
8.2.1	Measuring Appearance Variation.	142
8.2.2	Experimental Setup	143
8.2.3	Results.	144
8.3	Sub-sampling	146
8.3.1	Effect on Computational Effort.	146
8.3.2	Effect on Performance	147
8.3.3	Effect on Accuracy	147
8.3.4	Accuracy of the Distribution Estimate \hat{p} .	148
8.3.5	Accuracy of the Entropy Estimate $H(\hat{p})$.	149
8.4	Classification Experiments	151
8.4.1	Optic Flow for Calculating Time-to-impact.	152
8.4.2	Classification Performance	153
8.5	Simulated Avoidance Experiments	156
8.5.1	Experimental Setup	156
8.5.2	Results.	158
8.6	Real-World Avoidance Experiments	160
8.7	Discussion	163
8.8	Conclusions	163
	References.	164
9	Optical Flow Based Turning Logic	167
9.1	Introduction	167
9.2	Turning Logic	169
9.3	Overview of the Control Algorithm.	170
9.4	Experiments	171
9.4.1	Simulation	171
9.4.2	Real World	174
9.5	Conclusion.	176
	References.	177

10 Autonomous Flight with Onboard Stereo Vision	179
10.1 Introduction	179
10.2 DelFly Explorer	180
10.3 Obstacle Avoidance Algorithm	182
10.3.1 Overview of Obstacle Avoidance Strategies	182
10.3.2 Proposed Obstacle Avoidance Strategy	184
10.4 Stereo Vision	186
10.4.1 LongSeq	186
10.4.2 Subsampling	190
10.5 Real-World Experiments	191
10.6 Conclusion	194
References	194
 Part IV Conclusions	
11 Conclusions and Future Research	199
11.1 Conclusions	199
11.2 Future	199
11.2.1 Design	200
11.2.2 Aerodynamics	200
11.2.3 System Identification	201
11.2.4 Artificial Intelligence	202
11.3 Application of Flapping Wing MAVs	204
11.3.1 Properties of Flapping Wing MAVs	204
11.3.2 Example Applications	206
References	206
 Appendix A: DelFly Versions	209
 Glossary	215
 Index	217

The DelFly

Design, Aerodynamics, and Artificial Intelligence of a
Flapping Wing Robot

de Croon, G.C.H.E.; Perçin, M.; Remes, B.D.W.; Ruijsink,
R.; De Wagter, C.

2016, XIV, 218 p. 124 illus., 11 illus. in color., Hardcover
ISBN: 978-94-017-9207-3