

Contents

<i>Preface</i>	<i>page</i> xiii
<i>Contributors</i>	xv
1 Introduction to UAV Systems	1
1.1 Introduction to UAV Types and Missions	2
1.1.1 Fixed-wing UAVs	3
1.1.2 Flapping-wing UAVs	5
1.1.3 Rotary-wing UAVs	8
1.1.4 Convertible UAVs	10
1.1.5 Hybrid UAVs	14
1.2 UAV Swarming and Miniaturization	16
1.3 UAV Miniaturization: Challenges and Opportunities	17
1.3.1 Gust Sensitivity	18
1.3.2 Energy Density	18
1.3.3 Aerodynamic Efficiency	19
1.3.4 Other Design Challenges	19
1.4 UAV Networks and Their Advantages	19
1.4.1 Unique Features of Airborne Networks	22
1.4.2 Mobility Models for UAV Networks	22
1.4.3 State of the art in UAV Networks	23
1.5 Summary	25
2 Air-to-Ground and Air-to-Air Data Link Communication	26
2.1 Air-to-Ground Communication for Manned Aviation	26
2.1.1 Radar for Ground-based Aircraft Identification	27
2.1.2 Distance and Direction Measurements Beyond Radar	30
2.1.3 Instrument Landing System for Precise Localization	31
2.1.4 Voice Communication between Air and Ground	31
2.2 Modernization of Aerial Communication for Future Growth	32
2.2.1 Modern Surveillance and Navigation	32
2.2.2 Digital Communication for ATM	33
2.3 Practical UAV and MUAV Data Links	35
2.3.1 Control and Telemetry	36
2.3.2 Payload or Application Data Communication	36

2.4	Analysis of Terrestrial Wireless Broadband Solutions for UAV Links	37
2.4.1	Single Antenna UAV System Analysis	38
2.4.2	Multiple Antenna UAV Air-to-Air Link Analysis	38
2.4.3	Multiple Antenna UAV Air-to-Ground Link Analysis	41
2.5	Conclusions	44
3	Aerial Wi-Fi Networks	45
3.1	Introduction	45
3.2	Aerial Network Characteristics	46
3.2.1	Vehicles	47
3.2.2	3D Nature	47
3.2.3	Mobility	48
3.2.4	Payload and Flight Time Constraints	48
3.3	Communication Demands of Autonomous Aerial Networks	49
3.3.1	Device Autonomy	49
3.3.2	Mission Autonomy	50
3.4	Quantitative Communication Requirements	51
3.5	Aerial Wi-Fi Networks: Results from Existing Real-World Measurements	52
3.5.1	Network Architecture	52
3.5.2	Experimental Results	54
3.6	Conclusions and Outlook	56
4	Disruption-Tolerant Airborne Networks and Protocols	58
4.1	Introduction	58
4.2	Airborne Network Environment	59
4.3	Related Work	62
4.3.1	Traditional Internet Protocols	62
4.3.2	Mobile Wireless Network Protocols	65
4.3.3	Transportation Network Protocols	67
4.3.4	Cross-Layering	69
4.4	Aeronautical Protocol Architecture	70
4.4.1	AeroTP: TCP-Friendly Transport Protocol	71
4.4.2	AeroNP: IP-Compatible Network Protocol	76
4.4.3	AeroRP: Location-Aware Routing Algorithm	78
4.5	Performance Evaluation	82
4.5.1	AeroTP Simulation Results	82
4.5.2	AeroRP and AeroNP Simulation Results	88
4.6	Summary	95
5	UAV Systems and Networks: Emulation and Field Demonstration	96
5.1	Unmanned Aerial Vehicle (UAV) Platform Systems	96
5.1.1	UAV Platform System	97
5.1.2	UAV Autopilot Control System	99
5.1.3	UAV Communication System	102

5.1.4	UAV Monitoring System	103
5.1.5	UAV System Integration and Safety	105
5.2	Unmanned Aerial Vehicle (UAV) Networked Systems	107
5.2.1	UAV Internetworking Operational Concept (CONOPS)	107
5.2.2	Network Configuration	108
5.2.3	Network Emulation	108
5.2.4	Network Protocols	110
5.2.5	Network Systems Integration	112
5.2.6	Field Demonstration and Analysis	115
5.3	Related Works	117
5.4	Summary	118
6	Integrating UAS into the NAS – Regulatory, Technical, and Research Challenges	120
6.1	Regulatory Framework For Civil Aviation – Past and Present	120
6.1.1	Airworthiness Certification	121
6.1.2	Regulations for Continuing Airworthiness	124
6.1.3	Certification for Crew and Operators	124
6.2	Regulatory Bodies and UAS Legislation – Present and Future	126
6.2.1	European Union (EU)	127
6.2.2	United States of America	131
6.2.3	Canada	132
6.2.4	Australia	133
6.2.5	Brazil	135
6.2.6	South Africa	135
6.2.7	Japan	136
6.2.8	Summary	136
6.3	Standards Organizations	137
6.3.1	International Civil Aviation Organization (ICAO)	137
6.3.2	Radio Technical Commission for Aeronautics: SC-228	138
6.3.3	European Organization for Civil Aviation Equipment: WG 73/WG 93	139
6.3.4	Joint Authorities for Rulemaking on Unmanned Systems	139
6.3.5	Summary	140
6.4	Social Implications – Privacy and Security	140
6.4.1	Privacy	140
6.5	Gaps between Regulatory Needs and Technical State-of-the-Art	145
6.6	Technical Challenges	146
6.6.1	Research Questions	147
6.6.2	Minimum Transmission Range Needed by the UAVs to Keep the Airborne Backbone Network Connected at all Times	147
6.6.3	Minimum Number of UAVs Needed to Monitor all Suspect Mobile Targets at all Times	154
6.6.4	Modified Minimum Flow Problem	158
6.7	Summary	159
6.8	Acknowledgements	159

7	Safety, Security, and Privacy Aspects in UAV Networks	160
7.1	Introduction	160
7.2	Safety in the Sky	161
7.2.1	Automatic Dependent Surveillance – Broadcast (ADS-B)	162
7.2.2	FLARM	163
7.2.3	ADS-B Versus FLARM for Gliders	163
7.2.4	L-Band Digital Aeronautical Communications System (LDACS)	164
7.2.5	Aeronautical Mobile Aircraft Communication System (AeroMACS)	164
7.2.6	Self-organized Airborne Network (SOAN)	164
7.2.7	Beyond the Radio Line of Sight (BRLoS)	166
7.2.8	Benefits of Self-organized Airborne Networks	166
7.3	Privacy on the Ground	166
7.3.1	Fourth Amendment in the Context of UAVs	167
7.4	Information Security	168
7.5	Security Requirements at UAV Level	169
7.6	Security Requirements at UAV Network Level	172
7.6.1	Security Requirements for Standalone Swarms	173
7.6.2	Security Requirements in Ground-Controlled UAV Fleets	174
7.7	Ongoing Research and Products Related to UAV Security	175
7.8	Summary	176
8	Collaboration Between Autonomous Drones and Swarming	177
8.1	Introduction and Background	177
8.2	Why Use Swarms of Unmanned Aerial Systems?	178
8.2.1	Continuous Flight/Mission	179
8.2.2	Increased Mission Flexibility	180
8.2.3	Increased Capabilities	181
8.2.4	Additional Features	182
8.2.5	Summary	183
8.3	Major Issues and Research Directions	183
8.3.1	Localization, Proximity Detection, and Positioning	183
8.3.2	Man Swarm Interaction	186
8.3.3	Degraded Mode of Operation	187
8.3.4	Safety and Legal Issues	189
8.3.5	Security	190
8.4	Conclusion	192
9	Real-World Applications	194
9.1	Introduction	194
9.2	Wildlife Detection	194
9.2.1	Aerial Wildlife Counts	195
9.2.2	Raven RQ-11A Small Unmanned Aircraft System	196

9.2.3	Using the Raven RQ-11A sUAS to Estimate the Abundance of Sandhill Cranes (<i>Grus canadensis</i>) at Monte Vista National Wildlife Refuge, Colorado, USA	198
9.2.4	Evaluation of the Raven sUAS to Detect Greater Sage-Grouse (<i>Centrocercus urophasianus</i>) on Leks, Middle Park, Colorado, USA	201
9.3	Enabling Emergency Communications	204
9.3.1	Aerial Base Stations	204
9.3.2	Cyber Physical System Perspective	205
9.3.3	Scientific and Engineering Challenges	206
9.3.4	Disaster Response and Emergency Communications	207
9.3.5	Research Challenges	208
9.3.6	Deriving Theoretical Models	210
9.4	Summary	213
	<i>References</i>	214
	<i>Index</i>	242