



Mohammad H. Sadraey

Design of Unmanned Aerial Systems

Aerospace Series

Editors **Peter Belobaba, Jonathan Cooper**
and **Allan Seabridge**



WILEY

Design of Unmanned Aerial Systems

Aerospace Series

- Helicopter Flight Dynamics: Including a Treatment of Tiltrotor Aircraft, 3rd Edition
Gareth D. Padfield, CEng, PhD, FRAeS
- Space Flight Dynamics, 2nd Edition
Craig A. Kluever
- Performance of the Jet Transport Airplane: Analysis Methods, Flight Operations, and Regulations
Trevor M. Young
- Small Unmanned Fixed-wing Aircraft Design: A Practical Approach
Andrew J. Keane, András Sóbester, James P. Scanlan
- Advanced UAV Aerodynamics, Flight Stability and Control: Novel Concepts, Theory and Applications
Pascual Marqués, Andrea Da Ronch
- Differential Game Theory with Applications to Missiles and Autonomous Systems Guidance
Farhan A. Faruqi
- Introduction to Nonlinear Aeroelasticity
Grigorios Dimitriadis
- Introduction to Aerospace Engineering with a Flight Test Perspective
Stephen Corda
- Aircraft Control Allocation
Wayne Durham, Kenneth A. Bordignon, Roger Beck
- Remotely Piloted Aircraft Systems: A Human Systems Integration Perspective
Nancy J. Cooke, Leah J. Rowe, Winston Bennett Jr., DeForest Q. Jorlmon
- Theory and Practice of Aircraft Performance
Ajoy Kumar Kundu, Mark A. Price, David Riordan
- Adaptive Aeroservoelastic Control
Ashish Tewari
- The Global Airline Industry, 2nd Edition
Peter Belobaba, Amedeo Odoni, Cynthia Barnhart
- Modeling the Effect of Damage in Composite Structures: Simplified Approaches
Christos Kassapoglou
- Introduction to Aircraft Aeroelasticity and Loads, 2nd Edition
Jan R. Wright, Jonathan Edward Cooper
- Theoretical and Computational Aerodynamics
Tapan K. Sengupta
- Aircraft Aerodynamic Design: Geometry and Optimization
András Sóbester, Alexander I. J. Forrester
- Stability and Control of Aircraft Systems: Introduction to Classical Feedback Control
Roy Langton
- Aerospace Propulsion
T. W. Lee
- Civil Avionics Systems, 2nd Edition
Ian Moir, Allan Seabridge, Malcolm Jukes
- Aircraft Flight Dynamics and Control
Wayne Durham
- Modelling and Managing Airport Performance
Konstantinos Zografos, Giovanni Andreatta, Amedeo Odoni
- Advanced Aircraft Design: Conceptual Design, Analysis and Optimization of Subsonic Civil Airplanes
Egbert Torenbeek
- Design and Analysis of Composite Structures: With Applications to Aerospace Structures, 2nd Edition
Christos Kassapoglou
- Aircraft Systems Integration of Air-Launched Weapons
Keith A. Rigby
- Understanding Aerodynamics: Arguing from the Real Physics
Doug McLean
- Design and Development of Aircraft Systems, 2nd Edition
Ian Moir, Allan Seabridge
- Aircraft Design: A Systems Engineering Approach
Mohammad H. Sadraey
- Introduction to UAV Systems, 4th Edition
Paul Fahlstrom, Thomas Gleason
- Theory of Lift: Introductory Computational Aerodynamics in MATLAB/Octave
G. D. McBain
- Sense and Avoid in UAS: Research and Applications
Plamen Angelov
- Morphing Aerospace Vehicles and Structures
John Valasek
- Spacecraft Systems Engineering, 4th Edition
Peter Fortescue, Graham Swinerd, John Stark
- Unmanned Aircraft Systems: UAVS Design, Development and Deployment
Reg Austin
- Gas Turbine Propulsion Systems
Bernie MacIsaac, Roy Langton
- Aircraft Systems: Mechanical, Electrical, and Avionics Subsystems Integration, 3rd Edition
Ian Moir, Allan Seabridge
- Basic Helicopter Aerodynamics, 3rd Edition
John M. Seddon, Simon Newman
- System Health Management: with Aerospace Applications
Stephen B. Johnson, Thomas Gormley, Seth Kessler, Charles Mott, Ann Patterson-Hine, Karl Reichard, Philip Scandura Jr.
- Advanced Control of Aircraft, Spacecraft and Rockets
Ashish Tewari
- Air Travel and Health: A Systems Perspective
Allan Seabridge, Shirley Morgan
- Principles of Flight for Pilots
Peter J. Swatton
- Handbook of Space Technology
Wolfgang Ley, Klaus Wittmann, Willi Hallmann
- Cooperative Path Planning of Unmanned Aerial Vehicles
Antonios Tsourdos, Brian White, Madhavan Shanmugavel
- Design and Analysis of Composite Structures: With Applications to Aerospace Structures
Christos Kassapoglou
- Introduction to Antenna Placement and Installation
Thereza Macnamara
- Principles of Flight Simulation
David Allerton
- Aircraft Fuel Systems
Roy Langton, Chuck Clark, Martin Hewitt, Lonnie Richards
- Computational Modelling and Simulation of Aircraft and the Environment, Volume 1: Platform Kinematics and Synthetic Environment
Dominic J. Diston
- Aircraft Performance Theory and Practice for Pilots, 2nd Edition
Peter J. Swatton
- Military Avionics Systems
Ian Moir, Allan Seabridge, Malcolm Jukes
- Aircraft Conceptual Design Synthesis
Denis Howe

Design of Unmanned Aerial Systems

Dr. Mohammad H. Sadraey
Southern New Hampshire University
Manchester, NH, USA

WILEY

This edition first published 2020
© 2020 John Wiley & Sons Ltd

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at <http://www.wiley.com/go/permissions>.

The right of Mohammad H. Sadraey to be identified as the author of this work has been asserted in accordance with law.

Registered Offices

John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office

The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Limit of Liability/Disclaimer of Warranty

In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of experimental reagents, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each chemical, piece of equipment, reagent, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. While the publisher and authors have used their best efforts in preparing this work, they make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives, written sales materials or promotional statements for this work. The fact that an organization, website, or product is referred to in this work as a citation and/or potential source of further information does not mean that the publisher and authors endorse the information or services the organization, website, or product may provide or recommendations it may make. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for your situation. You should consult with a specialist where appropriate. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

Library of Congress Cataloging-in-Publication Data

Names: Sadraey, Mohammad H., author.

Title: Design of unmanned aerial systems / Dr. Mohammad H. Sadraey.

Description: First edition. | Hoboken, NJ: John Wiley & Sons, 2020. |

Series: Aerospace series | Includes bibliographical references and index.

Identifiers: LCCN 2019024537 (print) | LCCN 2019024538 (ebook) | ISBN 9781119508700 (hardback) |

ISBN 9781119508694 (adobe pdf) | ISBN 9781119508625 (epub)

Subjects: LCSH: Drone aircraft--Design and construction.

Classification: LCC TL685.35 .S235 2019 (print) | LCC TL685.35 (ebook) | DDC 629.133/39--dc23

LC record available at <https://lcn.loc.gov/2019024537>

LC ebook record available at <https://lcn.loc.gov/2019024538>

Cover image: © NASA, © NASA/Tony Landis

Cover design by Wiley

Set in 10/12pt Warnock by SPi Global, Pondicherry, India

To Fatemeh Zafarani, Ahmad, and Atieh, for all their love and understanding

Contents

Preface	<i>xix</i>
Acronyms	<i>xxv</i>
Nomenclature	<i>xxix</i>
About the Companion Website	<i>xxxvii</i>
1 Design Fundamentals	<i>1</i>
1.1	Introduction <i>2</i>
1.2	UAV Classifications <i>5</i>
1.3	Review of a Few Successful UAVs <i>8</i>
1.3.1	Global Hawk <i>8</i>
1.3.2	RQ-1A Predator <i>9</i>
1.3.3	MQ-9 Predator B Reaper <i>9</i>
1.3.4	RQ-5A Hunter <i>10</i>
1.3.5	RQ-7 Shadow 200 <i>10</i>
1.3.6	RQ-2A Pioneer <i>11</i>
1.3.7	RQ-170 Sentinel <i>11</i>
1.3.8	X-45A UCAV <i>12</i>
1.3.9	Epson Micro-flying Robot <i>12</i>
1.4	Design Project Planning <i>12</i>
1.5	Decision Making <i>13</i>
1.6	Design Criteria, Objectives, and Priorities <i>15</i>
1.7	Feasibility Analysis <i>17</i>
1.8	Design Groups <i>17</i>
1.9	Design Process <i>18</i>
1.10	Systems Engineering Approach <i>19</i>
1.11	UAV Conceptual Design <i>21</i>
1.12	UAV Preliminary Design <i>27</i>
1.13	UAV Detail Design <i>28</i>
1.14	Design Review, Evaluation, Feedback <i>30</i>
1.15	UAV Design Steps <i>30</i>
Questions	<i>32</i>
2 Preliminary Design	<i>35</i>
2.1	Introduction <i>35</i>
2.2	Maximum Takeoff Weight Estimation <i>36</i>
2.3	Weight Buildup <i>36</i>
2.4	Payload Weight <i>37</i>

2.5	Autopilot Weight	37
2.6	Fuel Weight	39
2.7	Battery Weight	43
2.8	Empty Weight	47
2.9	Wing and Engine Sizing	48
2.10	Quadcopter Configuration	52
	Questions	60
	Problems	61

3 Design Disciplines 65

3.1	Introduction	66
3.2	Aerodynamic Design	67
3.3	Structural Design	69
3.4	Propulsion System Design	71
	3.4.1 General Design Guidelines	72
	3.4.2 Electric Engines	74
3.5	Landing Gear Design	75
3.6	Mechanical and Power Transmission Systems Design	78
3.7	Electric Systems	80
	3.7.1 Fundamentals	80
	3.7.2 Safety Recommendations	81
	3.7.3 Wiring Diagrams	82
	3.7.4 Wire Insulation and Shielding	83
	3.7.5 Batteries	83
	3.7.6 Generator	84
3.8	Control Surfaces Design	85
3.9	Safety Analysis	90
	3.9.1 Design Lessons Learned	91
	3.9.2 Likely Failure Modes of Sub-Systems/Components	93
3.10	Installation Guidelines	95
	3.10.1 GPS/Compass	95
	3.10.2 IMU	95
	3.10.3 Electric Motor	96
	Questions	96
	Design Questions	97
	Problems	99

4 Aerodynamic Design 101

4.1	Introduction	102
4.2	Fundamentals of Aerodynamics	103
4.3	Wing Design	104
	4.3.1 Wing Design Procedure	105
	4.3.2 Airfoil Selection/Design	106
	4.3.3 Wing Design Technique	108
	4.3.4 Wing Design Steps	113
4.4	Tail Design	113
	4.4.1 Design Procedure	113
	4.4.2 Tail Configuration	115

4.4.3	Horizontal Tail Design Technique	116
4.4.4	Tail Planform Area and Tail Arm	117
4.4.5	Tail Airfoil Section	118
4.4.6	Tail Incidence	119
4.4.7	Other Horizontal Tail Parameters	119
4.5	Vertical Tail Design	119
4.5.1	Parameters	119
4.5.2	Vertical Tail Location	120
4.5.3	Vertical Tail Moment Arm (l_{vt})	120
4.5.4	Planform Area (S_v)	120
4.5.5	Incidence (i_v)	121
4.5.6	Other Vertical Tail Parameters	122
4.5.7	Vertical Tail Design Technique	122
4.6	Fuselage Design	123
4.6.1	Fuselage Design Fundamentals	123
4.6.2	Fuselage Aerodynamics	123
4.6.3	Autopilot Compartment	126
4.6.4	Optimum Length-to-Diameter Ratio	126
4.6.5	Fuselage Aerodynamics	127
4.6.6	Lofting	128
4.6.7	Fuselage Design Steps	129
4.7	Antenna	130
4.7.1	Fixed Antenna	130
4.7.2	Radar Dish Antenna	131
4.7.3	Satellite Communication Antenna	131
4.7.4	Antenna Design/Installation	132
4.8	Aerodynamic Design of Quadcopters	132
4.9	Aerodynamic Design Guidelines	133
	Questions	134
	Problems	136
5	Fundamentals of Autopilot Design	141
5.1	Introduction	142
5.1.1	Autopilot and Human Operator	143
5.1.2	Primary Subsystems of an Autopilot	144
5.1.3	Autopilot Design or Selection	145
5.2	Dynamic Modeling	146
5.2.1	Modeling Technique	146
5.2.2	Fundamental Model	148
5.2.3	Transfer Function	150
5.2.4	State-Space Representation	152
5.3	Aerodynamic Forces and Moments	153
5.3.1	Forces and Moments Equations	153
5.3.2	Stability and Control Derivatives	154
5.3.3	Non-dimensional Stability and Control Derivatives	154
5.3.4	Dimensional Stability and Control Derivatives	155
5.3.5	Coupling Stability Derivatives	156

- 5.4 Simplification Techniques of Dynamic Models 157
 - 5.4.1 Linearization 157
 - 5.4.1.1 Taylor Series 158
 - 5.4.1.2 Direct Technique 159
 - 5.4.2 Decoupling 159
 - 5.5 Fixed-Wing UAV Dynamic Models 161
 - 5.5.1 Nonlinear Fully Coupled Equations of Motion 162
 - 5.5.2 Nonlinear Semi-Coupled Equations of Motion 162
 - 5.5.3 Nonlinear Decoupled Equations of Motion 163
 - 5.5.4 Linear Coupled Equations of Motion 163
 - 5.5.5 Linear Decoupled Equations of Motion 165
 - 5.5.6 Reformulated (Nonlinear Semi-Coupled) Equations of Motion 167
 - 5.5.7 Un-powered Gliding Equations of Motion 168
 - 5.6 Dynamic Model Approximation 169
 - 5.6.1 Pure Pitching Motion Approximation 169
 - 5.6.2 Pure Rolling Motion Approximation 169
 - 5.6.3 Pure Yawing Motion Approximation 169
 - 5.6.4 Longitudinal Oscillatory Modes Approximation 170
 - 5.7 Quadcopter (Rotary-Wing) Dynamic Model 170
 - 5.7.1 Overall Thrust of Four Motors 170
 - 5.7.2 Dynamic Model 174
 - 5.7.3 Simplified Dynamic Model 175
 - 5.8 Autopilot Categories 176
 - 5.8.1 Stability Augmentation 176
 - 5.8.2 Hold Functions 178
 - 5.8.3 Navigation Functions 180
 - 5.8.4 Command Augmentation Systems 180
 - 5.9 Flight Simulation – Numerical Methods 181
 - 5.9.1 Numerical Integration 182
 - 5.9.2 Matlab/Simulink 182
 - 5.9.3 Hardware-In-the-Loop Simulation 184
 - 5.10 Flying Qualities for UAVs 185
 - 5.10.1 Fundamentals 185
 - 5.10.2 Classes, Categories, and Acceptability Levels 186
 - 5.10.3 Force Restrictions 186
 - 5.11 Autopilot Design Process 187
 - Questions 188
 - Problems 190
-
- 6 Control System Design 195**
 - 6.1 Introduction 196
 - 6.2 Fundamentals of Control Systems 197
 - 6.2.1 Elements, Concepts and Definitions 197
 - 6.2.2 Root Locus Design Technique 199
 - 6.2.3 Frequency Domain Design Technique 200
 - 6.2.4 Controller Configurations and Control Architectures 201
 - 6.3 Servo/Actuator 203

6.3.1	Terminology	203
6.3.2	Electric Motors	204
6.3.3	Hydraulic Actuator	206
6.3.4	Delay	206
6.3.5	Saturation	207
6.4	Flight Control Requirements	207
6.4.1	Longitudinal Control Requirements	207
6.4.2	Roll Control Requirements	208
6.4.3	Directional Control Requirements	209
6.5	Control Modes	209
6.5.1	Coupled Control Modes	210
6.5.2	Cruise Control	212
6.5.3	Pitch-Attitude Hold	213
6.5.4	Wing Leveler	214
6.5.5	Yaw Damper	215
6.5.6	Auto-Landing	217
6.5.7	Turn Coordinator	218
6.6	Controller Design	223
6.6.1	PID Controller	223
6.6.2	Optimal Control – LQR	224
6.6.3	Gain Scheduling	229
6.6.4	Robust Control	231
6.6.5	Digital Control	233
6.7	Autonomy	234
6.7.1	Classification	234
6.7.2	Detect (i.e., Sense)-and-Avoid	235
6.7.3	Automated Recovery	236
6.7.4	Fault Monitoring	236
6.7.5	Intelligent Flight Planning	236
6.8	Manned–Unmanned Aircraft Teaming	237
6.8.1	Need for Teaming	237
6.8.2	Teaming Problem Formulation	237
6.8.3	Decision Making Process	239
6.8.4	Teaming Communication Process	241
6.8.5	Teaming Laws	242
6.9	Control System Design Process	243
	Questions	246
	Problems	249
7	Guidance System Design	255
7.1	Introduction	256
7.2	Fundamentals	257
7.2.1	Guidance Process	257
7.2.2	Elements of Guidance System	258
7.2.3	Guidance Components	259
7.2.4	Target Detection	260
7.2.5	Moving Target Tracking	262

- 7.3 Guidance Laws 263
- 7.4 Command Guidance Law 265
- 7.5 PN Guidance Law 269
- 7.6 Pursuit Guidance Law 273
- 7.7 Waypoint Guidance Law 274
 - 7.7.1 Waypoints 274
 - 7.7.2 Types of Waypoint Guidance 275
 - 7.7.3 Segments of a Horizontal (Level) Trajectory 276
 - 7.7.4 Waypoint Guidance Algorithm 278
 - 7.7.4.1 Trajectory Smoother 278
 - 7.7.4.2 Trajectory Tracking 279
 - 7.7.5 UAV Maneuverability Evaluation 281
- 7.8 Sense and Avoid 282
 - 7.8.1 Fundamentals 282
 - 7.8.2 Sensing Techniques 283
 - 7.8.3 Collision Avoidance 286
- 7.9 Formation Flight 291
- 7.10 Motion Planning and Trajectory Design 293
- 7.11 Guidance Sensor – Seeker 294
- 7.12 Guidance System Design 296
- Questions 298
- Problems 300

- 8 Navigation System Design 305**
 - 8.1 Introduction 306
 - 8.2 Classifications 307
 - 8.3 Coordinate Systems 309
 - 8.3.1 Fixed and Moving Frames 309
 - 8.3.2 World Geodetic System 310
 - 8.4 Inertial Navigation System 311
 - 8.4.1 Fundamentals 311
 - 8.4.2 Navigation Equations 313
 - 8.4.3 Navigation Basic Calculations 313
 - 8.4.4 Geodetic Coordinates Calculations 314
 - 8.5 Kalman Filtering 315
 - 8.6 Global Positioning System 317
 - 8.6.1 Fundamentals 317
 - 8.6.2 Earth Longitude and Latitude 319
 - 8.6.3 Ground Speed Versus Airspeed 322
 - 8.7 Position Fixing Navigation 322
 - 8.7.1 Map Reading 322
 - 8.7.2 Celestial Navigation 322
 - 8.8 Navigation in Reduced Visibility Conditions 323
 - 8.9 Inertial Navigation Sensors 323
 - 8.9.1 Primary Functions 323
 - 8.9.2 Accelerometer 324
 - 8.9.3 Gyroscope 326

8.9.4	Airspeed Sensor	329
8.9.5	Altitude Sensor	330
8.9.5.1	Radar Altimeter	330
8.9.5.2	Mechanical Altimeter	330
8.9.6	Pressure Sensor	332
8.9.7	Clock/Timer	332
8.9.8	Compass	332
8.9.9	Magnetometer	333
8.9.10	MEMS Inertial Module	333
8.9.11	Transponder	335
8.10	Navigation Disturbances	335
8.10.1	Wind	335
8.10.2	Gust and Disturbance	337
8.10.3	Measurement Noise	339
8.10.4	Drift	340
8.10.4.1	Drift Due to Rotation of Rotor/Propeller	340
8.10.4.2	Drift Due to Wind	342
8.10.5	Coriolis Effect	342
8.10.6	Magnetic Deviation	344
8.11	Navigation System Design	345
8.11.1	Design Requirements	345
8.11.2	Design Flowchart	346
8.11.3	Design Guidelines	347
	Questions	348
	Problems	351
9	Microcontroller	355
9.1	Introduction	356
9.2	Basic Fundamentals	358
9.2.1	Microcontroller Basics	358
9.2.2	Microcontroller Versus Microprocessor	361
9.2.3	Packaging Formats	361
9.2.4	Modules/Components	363
9.2.5	Atmel ATmega644P	365
9.3	Microcontroller Circuitry	367
9.3.1	Microcontroller Circuit Board	367
9.3.2	Electric Motor	367
9.3.3	Servo Motor	368
9.3.4	Sensors	368
9.3.5	Potentiometer	369
9.4	Embedded Systems	369
9.4.1	Introduction	369
9.4.2	Embedded Processors	369
9.4.3	Signal Flow	370
9.5	Microcontroller Programming	371
9.5.1	Software Development	371
9.5.2	Operating System	371

9.5.3	Management Software	371
9.5.4	Microcontroller Programing	372
9.5.5	Software Integration	372
9.5.6	High-Level Programming Languages	373
9.5.7	Compiler	374
9.5.8	Debugging	374
9.6	Programming in C	374
9.6.1	Introduction	374
9.6.2	General Structure of a C Program	374
9.6.3	Example Code – Detecting a Dead LED	375
9.6.4	Execution of a C Program	377
9.7	Arduino	378
9.7.1	Arduino Overview	378
9.7.2	Arduino Programming	379
9.7.3	Arduino Uno Board	380
9.7.4	Open-Loop Control of an Elevator	382
9.7.5	Arduino and Matlab	383
9.8	Open-Source Commercial Autopilots	384
9.8.1	ArduPilot	384
9.8.2	PX4 Pixhawk Autopilot	385
9.8.3	Micropilot	386
9.8.4	DJI WooKong Autopilot	387
9.9	Design Procedure	387
9.10	Design Project	388
9.10.1	Problem Statement	389
9.10.2	Design and Implementation	389
9.10.3	Arduino Code	389
9.10.4	Procedure	391
9.10.5	MATLAB Code for Real-Time Plotting	392
9.10.6	System Response and Results	393
	Questions	393
	Problems	395
	Design Projects	397

10	Launch and Recovery Systems Design	399
10.1	Introduction	400
10.2	Launch Technologies and Techniques	402
10.2.1	Rocket Assisted Launch	402
10.2.2	Bungee Cord Catapult Launch	403
10.2.3	Pneumatic Launchers	406
10.2.4	Hydraulic Launchers	407
10.2.5	Air Launch	408
10.2.6	Hand Launch	409
10.3	Launcher Equipment	410
10.3.1	Elements	410
10.3.2	Ramp/Slipway	410
10.3.3	Push Mechanism	412

10.3.4	Elevation Platform	412
10.3.5	Power Supply	415
10.4	Fundamentals of Launch	415
10.4.1	Fundamental Principles	415
10.4.2	Governing Launch Equations	416
10.4.3	Wing and Horizontal Tail Contributions	419
10.4.4	UAV Longitudinal Trim	420
10.5	Elevation Mechanism Design	422
10.5.1	Elevation Mechanism Operation	422
10.5.2	Hydraulic and Pneumatic Actuators	423
10.6	VTOL	424
10.7	Recovery Technologies and Techniques	424
10.7.1	Fundamentals	424
10.7.2	Net Recovery	425
10.7.3	Arresting Line	426
10.7.4	Skyhook	427
10.7.5	Windsock	427
10.7.6	Parachute	429
10.8	Recovery Fundamentals	429
10.8.1	Parachute	429
10.8.2	Impact Recovery	431
10.9	Launch/Recovery Systems Mobility	431
10.9.1	Mobility Requirements	431
10.9.2	Conventional Wheeled Vehicle	432
10.10	Launch and Recovery Systems Design	433
10.10.1	Launch and Recovery Techniques Selection	433
10.10.2	Launch System Design	434
10.10.3	Recovery System Design	436
	Questions	437
	Problems	440
	Design Projects	443
11	Ground Control Station	445
11.1	Introduction	446
11.2	GCS Subsystems	448
11.3	Types of Ground Stations	448
11.3.1	Handheld Radio Controller	449
11.3.1.1	General Structure	449
11.3.1.2	Stick	450
11.3.1.3	Potentiometer	452
11.3.2	Portable GCS	453
11.3.3	Mobile Truck	454
11.3.4	Central Command Station	458
11.3.5	Sea Control Station	459
11.3.6	General GCS	459
11.4	GCS of a Number of UAVs	460
11.4.1	Global Hawk	460

- 11.4.2 Predator 461
- 11.4.3 MQ-5A Hunter 462
- 11.4.4 Shadow 200 462
- 11.4.5 DJI Phantom 463
- 11.4.6 Yamaha RMAX Unmanned Helicopter 464
- 11.5 Human-Related Design Requirements 464
 - 11.5.1 Number of Pilots/Operators in Ground Station 464
 - 11.5.2 Ergonomics 464
 - 11.5.3 Features of a Human Pilot/Operator 466
 - 11.5.4 Console Dimensions and Limits 467
- 11.6 Support Equipment 469
 - 11.6.1 Introduction 469
 - 11.6.2 Transportation Equipment 470
 - 11.6.3 Power Generator 471
 - 11.6.4 HVAC System 471
 - 11.6.5 Other Items 471
- 11.7 GCS Design Guidelines 472
- Questions 473
- Problems 475
- Design Problems 476
- Laboratory Experiments 477

- 12 Payloads Selection/Design 481**
 - 12.1 Introduction 482
 - 12.2 Elements of Payload 483
 - 12.2.1 Payload Definition 483
 - 12.2.2 Payloads Classifications 484
 - 12.3 Payloads of a Few UAVs 484
 - 12.3.1 RQ-4 Global Hawk 485
 - 12.3.2 MQ-9 Predator B Reaper 485
 - 12.3.3 RQ-7 Shadow 200 486
 - 12.3.4 RQ-5A Hunter 486
 - 12.3.5 DJI Phantom Quadcopter 486
 - 12.3.6 X-45 UCAV 487
 - 12.3.7 Yamaha RMAX 487
 - 12.4 Cargo or Freight Payload 487
 - 12.5 Reconnaissance/Surveillance Payload 488
 - 12.5.1 Electro-Optical Camera 489
 - 12.5.2 Infra-Red Camera 494
 - 12.5.3 Radar 495
 - 12.5.3.1 Fundamentals 495
 - 12.5.3.2 Radar Governing Equations 497
 - 12.5.3.3 An Example 498
 - 12.5.3.4 A Few Applications 500
 - 12.5.4 Lidar 502
 - 12.5.5 Range Finder 502
 - 12.5.6 Laser Designator 504

12.5.7	Radar Warning Receiver	505
12.6	Scientific Payloads	505
12.6.1	Classifications	505
12.6.2	Temperature Sensor	507
12.7	Military Payloads	508
12.8	Electronic Counter Measure Payloads	509
12.9	Payload Installation	511
12.9.1	Payload Wiring	511
12.9.2	Payload Location	512
12.9.3	Payload Aerodynamics	513
12.9.4	Payload-Structure Integration	517
12.9.5	Payload Stabilization	519
12.10	Payload Control and Management	520
12.11	Payload Selection/Design Guidelines	520
	Questions	523
	Problems	525
	Design Problems	527
13	Communications System Design	531
13.1	Fundamentals	532
13.2	Data Link	534
13.3	Transmitter	536
13.4	Receiver	537
13.5	Antenna	539
13.6	Radio Frequency	541
13.7	Encryption	544
13.8	Communications Systems of a Few UAVs	545
13.9	Installation	547
13.10	Communications System Design	547
13.11	Bi-directional Communications Using Arduino Boards	548
13.11.1	Communications Modules	548
13.11.2	NRF24L01 Module	549
13.11.3	Bluetooth Module	553
13.11.4	An Application	554
	Questions	558
	Problems	560
	Laboratory Experiments	561
	Design Projects	562
14	Design Analysis and Feedbacks	565
14.1	Introduction	566
14.2	Design Feedbacks	567
14.3	Weight and Balance	569
14.3.1	UAV Center of Gravity	569
14.3.2	Weight Distribution	571
14.4	Stability Analysis	573
14.4.1	Fundamentals	573

- 14.4.2 Static Longitudinal Stability 574
- 14.4.3 Dynamic Longitudinal Stability 574
- 14.4.4 Static Lateral-Directional Stability 575
- 14.4.5 Dynamic Lateral-Directional Stability 576
- 14.4.6 Typical Values for Stability Derivatives 577
- 14.5 Controllability Analysis 579
 - 14.5.1 Longitudinal Control 579
 - 14.5.2 Lateral Control 580
 - 14.5.3 Directional Control 581
 - 14.5.4 Typical Values for Control Derivatives 582
- 14.6 Flight Performance Analysis 582
 - 14.6.1 Maximum Speed 582
 - 14.6.2 Maximum Range 584
 - 14.6.3 Maximum Endurance 584
 - 14.6.4 Climb Performance 585
 - 14.6.4.1 Fastest Climb 585
 - 14.6.4.2 Steepest Climb 586
 - 14.6.5 Takeoff Performance 587
 - 14.6.6 Turn Performance 588
 - 14.6.7 Absolute Ceiling 590
 - 14.6.7.1 UAV with Jet Engine(s) 591
 - 14.6.7.2 UAV with Propeller-driven Engine(s) 591
- 14.7 Cost Analysis 591
- Questions 593
- Problems 595

- References 601**
- Index 609**

Preface

Definitions

An Unmanned Aerial System (UAS) is a group of coordinated multidisciplinary elements for an aerial mission by employing various payloads in flying vehicle(s). In contrast, an Unmanned Aerial Vehicle (UAV) is a remotely piloted or self-piloted aircraft that can carry payloads such as camera, radar, sensor, and communications equipment. All flight operations (including takeoff and landing) are performed without on-board human pilot. In news and media reports, the expression “drone” – as a short term – is preferred.

A UAS basically includes five main elements: 1. Air vehicle; 2. Control station; 3. Payload; 4. Launch and recovery system, 5. Maintenance and support system. Moreover, the environment in which the UAV(s) or the systems elements operate (e.g., the airspace, the data links, relay aircraft, etc.) may be assumed as the sixth (6) inevitable element.

A UAV is much more than a reusable air vehicle. UAVs are to perform critical missions without risk to personnel and more cost effectively than comparable manned system. UAVs are air vehicles; they fly like airplanes and operate in an airplane environment. They are designed like air vehicles; they have to meet flight critical air vehicle requirements. A designer needs to know how to integrate complex, multi-disciplinary systems, and to understand the environment, the requirements and the design challenges.

UAVs are employed in numerous flight missions; in scientific projects and research studies such as hurricane tracking, volcano monitoring, and remote sensing; and in commercial applications such as tall building and bridge observation, traffic control, tower maintenance, and fire monitoring. UAVs also present very unique opportunities for filmmakers in aerial filming/photography.

The UAVs are about to change how directors make movies in capturing the perfect aerial shot. In military arenas, UAVs may be utilized in flight missions such as surveillance, reconnaissance, intelligent routing, offensive operations, and combat. A UAV must typically be flexible, adaptable, capable of performing reconnaissance work, geo-mapping ready, able to collect samples of various pollutants, ready to conduct “search and destroy” missions, and prepared to research in general.

There is no consensus for the definition of autonomy in UAV community. The main systems drivers for autonomy are that it should provide more flexible operation, in that the operator tells the system what is wanted from the mission (not how to do it) with the flexibility of dynamic changes to the mission goals being possible in flight with minimal operation re-planning. Autonomy is classified in 10 levels, from remotely piloted, to fully autonomous swarm. Autonomy includes a level of artificial intelligence. An

autopilot is the main element by which the level of autonomy is determined. For instance, stabilization of an unstable UAV is a function for autopilot.

In 2018, at least 122000 people in the U.S. are certified to fly UAVs professionally, according to the Federal Aviation Administration (FAA), which sparked the UAVs explosion in 2016 when it simplified its process for allowing their commercial use. FAA has ruled that commercial UAV flight outside a pilot's line of sight is not allowed. About three million UAVs were sold [1] worldwide in 2017, according to Time Magazine, and more than one million UAVs are registered for US use with the FAA.

By January 2019, at least 62 countries are developing or using over 1300 various UAVs. The contributions of unmanned UAV in sorties, hours, and expanded roles continue to increase. These diverse systems range in cost from a few hundred dollars (Amazon sells varieties) to tens of millions of dollars. Range in capability from Micro Air Vehicles (MAV) weighing less than 1 lb to aircraft weighing over 40000lbs. UAVs will have to fit into a pilot based airspace system. Airspace rules are based on manned aircraft experience.

Objectives

The objective of this book is to provide a basic text for courses in the design of UASs and UAVs at both the upper division undergraduate and beginning graduate levels. Special effort has been made to provide knowledge, lessons, and insights into UAS technologies and associated design techniques across various engineering disciplines. The author has attempted to comprehensively cover all the main design disciplines that are needed for a successful UAS design project. To cover such a broad scope in a single book, depths in many areas have to be sacrificed.

UAVs share much in common with manned aircraft. The design of manned aircraft and the design of UAVs have many similarities; and some differences. The similarities include: 1. Design process; 2. Constraints (e.g., g-load, pressurization); and 3. UAV main components (e.g., wing, tail, fuselage, propulsion system, structure, control surfaces, and landing gear). The differences include: 1. Autopilot, 2. Communication system, 3. Sensors, 4. Payload, 5. Launch and recovery system, and 6. Ground control station.

The book is primarily written with the objective to be a main source for a UAS chief designer. The techniques presented in this book are suitable for academic study, and teaching students. The book can be adopted as the main text for a single elective course in UAS and UAV design for engineering programs. This text is also suitable for professional continuing education for individuals who are interested in UASs. Industries engineers with various backgrounds can learn about UAS and prepare themselves for new roles in UAS design project.

Approach

The process of UAS design is a complex combination of numerous disciplines which have to be blended together to yield the optimum design to meet a given set of requirements. This is a true statement "the design techniques are not understood unless practiced." Therefore, the reader is highly encouraged to experience the design techniques and concepts through application projects. The instructors are also encouraged to

define an open-ended semester-/year-long UAS design project to help the students to practice and learn through the application and experiencing the iterative nature of the design technique. It is my sincere wish that this book will help aspiring students and design engineers to learn and create more efficient and safer UASs, and UAVs.

In this text, the coverage of the topics which are similar to that of a manned aircraft is reviewed. However, the topics which are not covered in a typical manned aircraft design book, are presented in detail. The author has written a book on manned aircraft design – *Aircraft Design, a Systems Engineering Approach* – published by Wiley. In several topics, the reader recommends the reader to study that text for the complete details. Some techniques (e.g., matching plot) deviate from traditional aircraft design. Throughout the text, the systems engineering approach is examined and implemented.

A UAV designer must: (a) be knowledgeable on the various related engineering topics; (b) be aware of the latest UAV developments; (c) be informed of the current technologies; (d) employ lessons learned from past failures; and (e) appreciate breadth of UAV design options.

A design process requires both integration and iteration. A design process includes: 1. Synthesis: the creative process of putting known things together into new and more useful combinations. 2. Analysis: the process of predicting the performance or behavior of a design candidate. 3. Evaluation: the process of performance calculation and comparing the predicted performance of each feasible design candidate to determine the deficiencies.

UAVs are typically smaller than manned aircraft, have a reduced radar signature, and an increased range and endurance. A UAV designer is also involved in mission planning. Payload type has a direct effect of mission planning. For any mission, the commander seeks to establish criteria that maximize his probability of success. Planning considerations are cost dependent. A UAV can be designed for both scientific purposes and for the military. Their once reconnaissance only role is now shared with strike, force protection, and signals collection.

Beyond traditional aircraft design topics, this text presents detail design of launchers, recovery systems, communication systems, electro-optic/infrared cameras, ground control station, autopilot, radars, scientific sensors, flight control system, navigation system, guidance system, and microcontrollers.

Outline

The objective of the book is to review the design fundamentals of UAVs, as well as the coverage of the design techniques of the UASs. The book is organized into 14 Chapters. Chapter 1 is devoted to design fundamentals including design process, and three design phases (i.e., conceptual, preliminary, and detail). The preliminary design phase is presented in Chapter 2 to determine maximum takeoff weight, wing reference planform area, and engine thrust/power. Various design disciplines including propulsion system, electric system, landing gear, and safety analysis are covered in Chapter 3. The aerodynamic design of wing, horizontal tail, vertical tail, and fuselage is provided in Chapter 4.

Fundamentals of autopilot design including UAV dynamic modeling, autopilot categories, flight simulation, flying qualities for UAVs, and autopilot design process is discussed in Chapter 5. The detail design of control system, guidance system, and

navigation system are covered in Chapters 6, 7, and 8 respectively. As the heart of autopilot, the design and application of microcontrollers are explained in Chapter 9. In this Chapter, topics such as microcontroller circuitry, microcontroller elements, embedded systems, and programming are described. Moreover, features of a number of open-source commercial microcontrollers and autopilots (e.g., Arduino and Ardupilot) are introduced. Chapters 10 and 11 are dedicated to two subsystems of a UAS; namely launch and recovery systems, and ground control station. In both chapters, fundamentals, equipment, types, governing equations, ergonomics, technologies, and design techniques are presented.

The payload selection and design is provided in Chapter 12. Various types of payloads including cargo, electro-optic cameras, infrared sensors, range finders, radars, lidars, scientific payloads, military payloads, and electronic counter measure equipment are considered in this chapter. The communications system (including transmitter, receiver, antenna, datalink, frequencies, and encryption) design is discussed in Chapter 13. Finally, in Chapter 14, various design analysis and evaluation techniques; mainly weight and balance, stability analysis, control analysis, performance analysis, and cost analysis techniques are discussed.

Special effort has been made to provide example problems so that the reader will have a clear understanding of the topic discussed. The book contains many fully solved examples in various chapters to exhibit the applications of the design techniques presented. Each chapter concludes with questions and problems; and some chapters with design problems and lab experiments. A solutions manual and figures library are available for instructors who adopt this book.

Quadcopters

Due to the popularity and uniqueness of quadcopters in aeronautics/aviation and commercial applications, this type of UAV is specially treated in this book. A number of sections in various chapters are dedicated to the configuration design, aerodynamic design, and control of quadcopters as follows: Section 2.10. Quadcopter configuration, Section 4.8. Aerodynamic design of quadcopters, and Section 5.7. Quadcopter dynamic model.

Unit System

In this text, the emphasize is on the SI units or metric system; which employs the meter (m) as the unit of length, the kilogram (kg) as the unit of mass, and the second (s) as the unit of time. The metric unit system is taken as fundamental, this being the educational basis in the most parts of the world. It is true that metric units are more universal and technically consistent than British units. However, currently, many Federal Aviation Regulations (FARs) are published in British Units; where the foot (ft) is the unit of length/altitude, the slug is the unit of mass, pound (lb) is the unit of force (weight), and the second (s) as the unit of time. British/imperial units are still used extensively, particularly in the USA, and by industries and other federal agencies and organizations in aviation, such as FAA and NASA.

In FARs, the unit of pound (lb) is used as the unit for force and weight, knot for airspeed, and foot for altitude. Thus, in various locations, the knot is mainly used as the unit of airspeed, lb for weight and force and, ft as the unit of altitude. Therefore, in this text, a combination of SI unit and British unit systems is utilized. For dimensional examples in the text and diagrams, both units are used which it is felt have stood the test of time and may well continue to do so.

In many cases, units in both systems are used, in other cases reference may need to be made to the conversion tables. In either system, units other than the basic one are sometimes used, depending on the context; this is particularly so for weight/mass and airspeed. For instance, the UAV airspeed is more conveniently expressed in kilometers/hour or in knots than in meters/second or in feet/second. For the case of weight/mass, the unit of kg is employed for maximum takeoff mass, while the unit of pound (lb) is utilized for the maximum takeoff weight.

Acknowledgment

Putting a book together requires the talents of many people, and talented individuals abound at Wiley Publishers. My sincere gratitude goes to Eric Willner and Steven Fassions, executive editors of engineering, Thilagavathy Mounisamy, production editor, and Sashi Samuthiram for composition. My special thanks go to Mary Malin, as outstanding copy editor and proof-reader that are essential in creating an error-free text. I especially owe a large debt of gratitude to my students and the reviewers of this text. Their questions, suggestions, and criticisms have helped me to write more clearly and accurately and have influenced markedly the evolution of this book.

January 2019

Mohammad H. Sadraey

Acronyms

2d	Two dimensional
3d	Three dimensional
AC	Alternating Current, aerodynamic center
ADF	Automatic direction finder
AI	Artificial intelligence
AIA	Aerospace Industries Association
AFCS	Automatic flight control systems
APU	Auxiliary power unit
ATC	Air Traffic Control
C2	Command and Control
C3	Command, Control, and Communications
C4ISR	Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance
CFD	Computational Fluid Dynamics
cg	Center of gravity
CMOS	Complementary metal oxide semiconductor; sensors
COTS	Commercial off-the-shelf
DARPA	Defense Advanced Research Projects Agency
DC	Direct Current
DOD	Department of Defense
DOF	Degree of freedom
DoS	Denial of Service
EO/IR	Electro-Optic/Infra-Red
ECM	Electronic Counter Measures
EM	Electro Magnetic
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FBW	Fly-by-wire
FLIR	Forward looking infrared
FOV	Field of view
fps	ft/sec, frame/sec
GA	General aviation
GCS	Ground control station
GIS	Geographic Information System
GNC	Guidance-Navigation-Control

GPS	Global Positioning System
GUI	Graphical user interface
HALE	High altitude long endurance
HLD	High Lift Device
HTOL	Horizontal takeoff and landing
HVAC	Heating, Ventilation, and Air Conditioning
IC	Integrated Circuit
I2C	Inter-Integrated Circuit
ILS	Instrument landing system
IMU	Inertial measurement unit
INS	Inertial navigation system
IR	Infra-Red
ISA	International Standard Atmosphere
JATO	Jet assisted takeoff
KEAS	Knot Equivalent Air Speed
KTAS	Knot True Air Speed
LED	Light emitting diode
LIDAR	Light detection and ranging
LOS	Line-of-sight
LQR	Linear Quadratic Regulator
MAC	Mean Aerodynamic Chord
mAh	mili Ampere hour
MAV	Micro Air Vehicle
MCE	Mission control element
MDO	Multidisciplinary design optimization
MEMS	Microelectromechanical system
MIL-STD	Military Standards
MIMO	Multiple-input multiple-output
MTBF	Mean time between failures
MTI	Moving Target Indicator
MTOW	Maximum takeoff weight
NACA	National Advisory Committee for Aeronautics
NASA	National Administration for Aeronautics and Astronautics
NTSB	National Transportation Safety Board
OS	Operating System
PIC	Pilot-in-Command
Pot	Potentiometer
PRF	Pulse-repetition frequency
PWM	Pulse Width Modulation
rad	Radian
RC	Remote control, Radio control
RCS	Radar Cross Section
rpm	Revolution per minute
RPV	Remotely piloted vehicle
SAR	Synthetic aperture radar
SAS	Stability augmentation system
Satcom	Satellite Communication

SDRAM	Synchronous dynamic random access memory
SFC	Specific fuel consumption
SIGINT	Signals Intelligence
SISO	Single-Input Single-Output
sUAS	small unmanned aircraft system
sUAV	small unmanned aerial vehicle
TCA	Traffic collision avoidance
TCAS	Traffic Alert and Collision Avoidance System
TE	Trailing Edge
UAS	Unmanned aerial system
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned combat air vehicle
USB	Universal Serial Bus
VHF	Very High Frequency
UHF	Ultra High frequency
VOR	Very High Frequency Omni-Directional Range
VTOL	Vertical takeoff and landing
WGS	World Geodetic System

