Mohammad H. Sadraey

Design of Unmanned Aerial Systems

Aerospace Series
Editors Peter Belobaba, Jonathan Cooper and Allan Seabridge

with website

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. Joralmon

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
Wilfried 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

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.

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://lccn.loc.gov/2019024537
LC ebook record available at https://lccn.loc.gov/2019024538

Cover image: © NASA, © NASA/Tony Landis
Cover design by Wiley

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

10 9 8 7 6 5 4 3 2 1

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

Contents

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 122 000 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 40 000 lbs. 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 Fassioms, 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