Paul G. Fahlstrom, Thomas J. Gleason,
Mohammad H. Sadraey

Introduction to UAV Systems

Fifth Edition

Aerospace Series
Editors Peter Belobaba, Jonathan Cooper and Allan Seabridge

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Introduction to UAV Systems

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Introduction to UAV Systems

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Contents

Preface *xvii*
Series Preface *xxi*
Acknowledgments *xxiii*
List of Acronyms *xxv*
About the Companion Website *xxix*

Part I Introduction *1*

1 History and Overview *3*
1.1 Overview *3*
1.2 History *4*
1.2.1 Early History *4*
1.2.2 The Vietnam War *4*
1.2.3 Resurgence *5*
1.2.4 Joint Operations *6*
1.2.5 Desert Storm *6*
1.2.6 Bosnia *6*
1.2.7 Afghanistan and Iraq *7*
1.2.8 Long-Range Long-Endurance Operations *7*
1.3 Overview of UAV Systems *8*
1.3.1 Air Vehicle *9*
1.3.2 Mission Planning and Control Station *9*
1.3.3 Launch and Recovery Equipment *10*
1.3.4 Payloads *10*
1.3.5 Data Links *11*
1.3.6 Ground Support Equipment *11*
1.4 The Aquila *12*
1.4.1 Aquila Mission and Requirements *12*
1.4.2 Air Vehicle *13*
1.4.3 Ground Control Station *13*
1.4.4 Launch and Recovery *14*
1.4.5 Payload *14*
1.4.6 Other Equipment *14*
1.4.7 Summary *14*

1.5 Global Hawk *16*
1.5.1 Mission Requirements and Development *16*
1.5.2 Air Vehicle *16*
1.5.3 Payloads *17*
1.5.4 Communications System *17*
1.5.5 Development Setbacks *18*
1.6 Predator Family *19*
1.6.1 Predator Development *19*
1.6.2 Reaper *19*
1.6.3 Features *20*
1.7 Top UAV Manufacturers *21*
1.8 Ethical Concerns of UAVs *21*
Questions *22*

2 Classes and Missions of UAVs *27*
2.1 Overview *27*
2.2 Classes of UAV Systems *27*
2.2.1 Classification Criteria *27*
2.2.2 Classification by Range and Endurance *28*
2.2.3 Classification by Missions *29*
2.2.4 The Tier System *32*
2.3 Examples of UAVs by Size Group *33*
2.3.1 Micro-UAVs *34*
2.3.2 Mini-UAVs *34*
2.3.3 Very Small UAVs *35*
2.3.4 Small UAVs *36*
2.3.5 Medium UAVs *37*
2.3.6 Large UAVs *40*
2.4 Expendable UAVs *42*
Questions *43*

Part II The Air Vehicle *47*

3 Aerodynamics *49*
3.1 Overview *49*
3.2 Aerodynamic Forces *49*
3.3 Mach Number *51*
3.4 Airfoil *51*
3.5 Pressure Distribution *54*
3.6 Drag Polar *57*
3.7 The Real Wing and Airplane *58*
3.8 Induced Drag *58*
3.9 Boundary Layer *60*
3.10 Friction Drag *63*
3.11 Total Air-Vehicle Drag *63*

3.12 Flapping Wings *64*
3.13 Aerodynamic Efficiency *66*
Questions *67*

4 Performance *71*
4.1 Overview *71*
4.2 Cruising Flight *72*
4.3 Range *73*
4.3.1 Range for a Non-Electric-Engine Propeller-Driven Aircraft *74*
4.3.2 Range for a Jet-Propelled Aircraft *76*
4.4 Endurance *78*
4.4.1 Endurance for a Non-Electric-Engine Propeller-Driven Aircraft *78*
4.4.2 Endurance for a Jet-Propelled Aircraft *79*
4.5 Climbing Flight *80*
4.6 Gliding Flight *82*
4.7 Launch *83*
4.8 Recovery *84*
Questions *85*

5 Flight Stability and Control *89*
5.1 Overview *89*
5.2 Trim *90*
5.2.1 Longitudinal Trim *91*
5.2.2 Directional Trim *93*
5.2.3 Lateral Trim *93*
5.2.4 Summary *94*
5.3 Stability *94*
5.3.1 Longitudinal Static Stability *95*
5.3.2 Directional Static Stability *97*
5.3.3 Lateral Static Stability *99*
5.3.4 Dynamic Stability *100*
5.4 Control *101*
5.4.1 Aerodynamic Control *101*
5.4.2 Pitch Control *102*
5.4.3 Directional Control *104*
5.4.4 Lateral Control *105*
Questions *106*

6 Propulsion *109*
6.1 Overview *109*
6.2 Propulsion Systems Classification *109*
6.3 Thrust Generation *110*
6.4 Powered Lift *111*
6.5 Sources of Power *114*
6.5.1 Four-Cycle Engine *115*
6.5.2 Two-Cycle Engine *116*

6.5.3 Rotary Engine *118*
6.5.4 Gas Turbine Engines *119*
6.5.5 Electric Motors *120*
6.6 Sources of Electric Energy *122*
6.6.1 Batteries *122*
6.6.2 Solar Cells *124*
6.6.3 Fuel Cells *126*
6.7 Power and Thrust *127*
6.7.1 Relation Between Power and Thrust *128*
6.7.2 Propeller *128*
6.7.3 Variations of Power and Thrust with Altitude *130*
Questions *131*

7 Air Vehicle Structures *135*
7.1 Overview *135*
7.2 Structural Members *135*
7.2.1 Skin *136*
7.2.2 Fuselage Structural Members *136*
7.2.3 Wing and Tail Structural Members *137*
7.2.4 Other Structural Members *138*
7.3 Basic Flight Loads *139*
7.4 Dynamic Loads *143*
7.5 Structural Materials *145*
7.5.1 Overview *145*
7.5.2 Aluminum *145*
7.6 Composite Materials *146*
7.6.1 Sandwich Construction *146*
7.6.2 Skin or Reinforcing Materials *147*
7.6.3 Resin Materials *147*
7.6.4 Core Materials *148*
7.7 Construction Techniques *148*
7.8 Basic Structural Calculations *149*
7.8.1 Normal and Shear Stress *150*
7.8.2 Deflection *152*
7.8.3 Buckling Load *153*
7.8.4 Factor of Safety *154*
7.8.5 Structural Fatigue *155*
Questions *155*

Part III Mission Planning and Control *159*

8 Mission Planning and Control Station *161*
8.1 Introduction *161*
8.2 MPCS Subsystems *161*
8.3 MPCS Physical Configuration *165*

8.4 MPCS Interfaces *169*
8.5 MPCS Architecture *170*
8.5.1 Fundamentals *170*
8.5.2 Local Area Networks *172*
8.5.3 Levels of Communication *172*
8.5.4 Bridges and Gateways *173*
8.6 Elements of a LAN *174*
8.6.1 Layout and Logical Structure (Topology) *174*
8.6.2 Communications Medium *175*
8.6.3 Network Transmission and Access *175*
8.7 OSI Standard *175*
8.7.1 Physical Layer *175*
8.7.2 Data-Link Layer *175*
8.7.3 Network Layer *176*
8.7.4 Transport Layer *176*
8.7.5 Session Layer *176*
8.7.6 Presentation Layer *176*
8.7.7 Application Layer *176*
8.8 Mission Planning *176*
8.9 Pilot-In-Command *179*
Questions *180*

9 Control of Air Vehicle and Payload *183*
9.1 Overview *183*
9.2 Levels of Control *184*
9.3 Remote Piloting the Air Vehicle *185*
9.3.1 Remote Manual Piloting *186*
9.3.2 Autopilot-Assisted Control *188*
9.3.3 Complete Automation *188*
9.3.4 Summary *189*
9.4 Autopilot *190*
9.4.1 Fundamental *190*
9.4.2 Autopilot Categories *191*
9.4.3 Inner and Outer Loops *191*
9.4.4 Overall Modes of Operation *192*
9.4.5 Control Process *193*
9.4.6 Control Axes *193*
9.4.7 Controller *194*
9.4.8 Actuator *195*
9.4.9 Open-Source Commercial Autopilots *195*
9.5 Sensors Supporting the Autopilot *196*
9.5.1 Altimeter *196*
9.5.2 Airspeed Sensor *196*
9.5.3 Attitude Sensors *197*
9.5.4 GPS *198*
9.5.5 Accelerometers *199*

9.6 Navigation and Target Location *199*
9.7 Controlling Payloads *201*
9.7.1 Signal Relay Payloads *202*
9.7.2 Atmospheric, Radiological, and Environmental Monitoring *202*
9.7.3 Imaging and Pseudo-Imaging Payloads *203*
9.8 Controlling the Mission *204*
9.9 Autonomy *206*
Questions *208*

Part IV Payloads *213*

10 Reconnaissance/Surveillance Payloads *215*
10.1 Overview *215*
10.2 Imaging Sensors *216*
10.3 Target Detection, Recognition, and Identification *217*
10.3.1 Sensor Resolution *218*
10.3.2 Target Contrast *221*
10.3.3 Transmission Through the Atmosphere *222*
10.3.4 Target Signature *225*
10.3.5 Display Characteristics *225*
10.3.6 Range Prediction Procedure *226*
10.3.7 A Few Considerations *228*
10.3.8 Pitfalls *230*
10.4 The Search Process *231*
10.4.1 Types of Search *231*
10.4.2 Field of View *232*
10.4.3 Search Pattern *234*
10.4.4 Search Time *235*
10.5 Other Considerations *237*
10.5.1 Location and Installation *237*
10.5.2 Stabilization of the Line of Sight *238*
10.5.3 Gyroscope and Gimbal *238*
10.5.4 Gimbal-Gyro Configuration *240*
10.5.5 Thermal Design *241*
10.5.6 Environmental Conditions Affecting Stabilization *241*
10.5.7 Boresight *242*
10.5.8 Stabilization Design *242*
Questions *243*

11 Weapon Payloads *247*
11.1 Overview *247*
11.2 History of Lethal Unmanned Aircraft *249*
11.3 Mission Requirements for Armed Utility UAVs *251*
11.4 Design Issues Related to Carriage and Delivery of Weapons *252*
11.4.1 Payload Capacity *253*
11.4.2 Structural Issues *253*

11.4.3 Electrical Interfaces *255*
11.4.4 Electromagnetic Interference *256*
11.4.5 Launch Constraints for Legacy Weapons *257*
11.4.6 Safe Separation *257*
11.4.7 Data Links *258*
11.4.8 Payload Location *258*
11.5 Signature Reduction *258*
11.5.1 Acoustical Signatures *259*
11.5.2 Visual Signatures *263*
11.5.3 Infrared Signatures *264*
11.5.4 Radar Signatures *265*
11.5.5 Emitted Signals *269*
11.5.6 Active Susceptibility Reduction Measures *269*
11.6 Autonomy for Weapon Payloads *270*
11.6.1 Fundamental Concept *270*
11.6.2 Rules of Engagement *272*
Questions *273*

12 Other Payloads *277*
12.1 Overview *277*
12.2 Radar *277*
12.2.1 General Radar Considerations *277*
12.2.2 Synthetic Aperture Radar *280*
12.3 Electronic Warfare *280*
12.4 Chemical Detection *281*
12.5 Nuclear Radiation Sensors *282*
12.6 Meteorological and Environmental Sensors *282*
12.7 Pseudo-Satellites *283*
12.8 Robotic Arm *286*
12.9 Package and Cargo *287*
12.10 Urban Air Mobility *288*
Questions *288*

Part V Data Links *291*

13 Data Link Functions and Attributes *293*
13.1 Overview *293*
13.2 Background *293*
13.3 Data-Link Functions *295*
13.4 Desirable Data-Link Attributes *296*
13.4.1 Worldwide Availability *297*
13.4.2 Resistance to Unintentional Interference *298*
13.4.3 Low Probability of Intercept (LPI) *298*
13.4.4 Security *298*
13.4.5 Resistance to Deception *299*
13.4.6 Anti-ARM *299*

13.4.7 Anti-Jam *300*
13.4.8 Digital Data Links *301*
13.4.9 Signal Strength *301*
13.5 System Interface Issues *302*
13.5.1 Mechanical and Electrical *302*
13.5.2 Data-Rate Restrictions *302*
13.5.3 Control-Loop Delays *303*
13.5.4 Interoperability, Interchangeability, and Commonality *305*
13.6 Antennas *307*
13.6.1 Omnidirectional Antenna *307*
13.6.2 Parabolic Reflectors *307*
13.6.3 Array/Directional Antennas *308*
13.6.4 Lens Antennas *308*
13.7 Data Link Frequency *309*
Questions *311*

14 Data-Link Margin *315*
14.1 Overview *315*
14.2 Sources of Data-Link Margin *316*
14.2.1 Transmitter Power *316*
14.2.2 Antenna Gain *316*
14.2.3 Processing Gain *322*
14.3 Anti-Jam Margin *327*
14.3.1 Definition of Anti-Jam Margin *327*
14.3.2 Jammer Geometry *328*
14.3.3 System Implications of AJ Capability *331*
14.3.4 Anti-Jam Uplinks *334*
14.4 Propagation *334*
14.4.1 Obstruction of the Propagation Path *334*
14.4.2 Atmospheric Absorption *336*
14.4.3 Precipitation Losses *336*
14.5 Data-Link Signal-to-Noise Budget *336*
Questions *339*

15 Data-Rate Reduction *343*
15.1 Overview *343*
15.2 Compression Versus Truncation *343*
15.3 Video Data *344*
15.3.1 Gray Scale *344*
15.3.2 Encoding of Gray Scale *345*
15.3.3 Effects of Bandwidth Compression on Operator Performance *346*
15.3.4 Frame Rate *348*
15.3.5 Control Loop Mode *348*
15.3.6 Forms of Truncation *350*
15.3.7 Summary *351*
15.4 Non-Video Data *352*
15.5 Location of the Data-Rate Reduction Function *353*
Questions *354*

16 Data-Link Tradeoffs *357*
16.1 Overview *357*
16.2 Basic Tradeoffs *357*
16.3 Pitfalls of "Putting Off" Data-Link Issues *359*
16.4 Future Technology *360*
Questions *360*

Part VI Launch and Recovery *363*

17 Launch Systems *365*
17.1 Overview *365*
17.2 Conventional Takeoff *365*
17.3 Basic Considerations *366*
17.4 Launch Methods for Fixed-Wing Air Vehicles *370*
17.4.1 Overview *370*
17.4.2 Rail Launchers *372*
17.4.3 Pneumatic Launchers *373*
17.4.4 Hydraulic-Pneumatic Launchers *374*
17.4.5 Zero Length RATO Launch of UAVs *375*
17.4.6 Tube Launch *375*
17.5 Rocket-Assisted Takeoff *376*
17.5.1 RATO Configuration *376*
17.5.2 Ignition Systems *376*
17.5.3 Expended RATO Separation *376*
17.5.4 Other Launch Equipment *377*
17.5.5 Energy (Impulse) Required *377*
17.5.6 Propellant Weight Required *378*
17.5.7 Thrust, Burning Time, and Acceleration *379*
17.6 Vertical Takeoff *379*
Questions *379*

18 Recovery Systems *383*
18.1 Overview *383*
18.2 Conventional Landing *383*
18.3 Vertical Net Systems *384*
18.4 Parachute Recovery *385*
18.5 VTOL UAVs *386*
18.6 Mid-Air Retrieval *388*
18.7 Shipboard Recovery *389*
18.8 Break-Apart Landing *392*
18.9 Skid and Belly Landing *393*
18.10 Suspended Cables *394*
Questions *395*

19 Launch and Recovery Tradeoffs *397*
19.1 UAV Launch Method Tradeoffs *397*
19.2 Recovery Method Tradeoffs *400*

19.3 Overall Conclusions *402*
Questions *402*

20 Rotary-Wing UAVs and Quadcopters *405*
20.1 Overview *405*
20.2 Rotary-Wing Configurations *406*
20.2.1 Single Rotor *406*
20.2.2 Twin Co-axial Rotors *407*
20.2.3 Twin Tandem Rotors *408*
20.2.4 Multicopters *408*
20.3 Hybrid UAVs *409*
20.3.1 Tilt Rotor *409*
20.3.2 Tilt Wing *409*
20.3.3 Thrust Vectoring *410*
20.3.4 Fixed-Wing Quadcopter Combination *410*
20.4 Quadcopters *411*
20.4.1 Overview *411*
20.4.2 Aerodynamics *413*
20.4.3 Control *414*
Questions *416*

References *419*

Index *421*

Preface

Introduction to UAV Systems, Fifth Edition, has been written to meet the needs of both newcomers to the world of unmanned aerial vehicle (UAV) systems and experienced members of the UAV community who desire an overview and who, though they may find the treatment of their particular discipline elementary, will gain valuable insights into the other disciplines that contribute to a UAV system. The material has been presented such that it is readily understandable to college freshman and to both technical and nontechnical persons working in the UAV field, and is based on standard engineering texts as well as material developed by the authors while working in the field. Most equations have been given without proof and the reader is encouraged to refer to standard texts of each discipline when engaging in actual design or analysis as no attempt is made to make this book a complete design handbook.

This book is also not intended to be the primary text for an introductory course in aerodynamics or imaging sensors or data links. Rather, it is intended to provide enough information in each of those areas, and others, to illustrate how they all play together to support the design of complete UAV systems and to allow the reader to understand how the technology in all of these areas affect the system-level tradeoffs that shape the overall system design. As such, it might be used as a supplementary text for a course in any of the specialty areas to provide a system-level context for the specialized material.

For a beginning student, we hope that it will whet the appetite for knowing more about at least one of the technology areas and demonstrate the power of even the simplest mathematical treatment of these subjects in allowing understanding of the tradeoffs that must occur during the system design process.

For a UAV user or operator, we hope that it will provide understanding of how the system technology affects the manner in which the UAV accomplishes its objectives and the techniques that the operator must use to make that happen.

For a "subject matter expert" in any of the disciplines involved in the design of a UAV system, we hope that it will allow better understanding of the context in which his or her specialty must operate to produce success for the system as a whole and why other specialists may seem preoccupied with things that seem unimportant to him or her.

Finally, for a technology manager, we hope that this book can help him or her understand how everything fits together, how important it is to consider the system-integration issues early in the design process so that the integration issues are considered during the basic selection of subsystem designs, and help him or her understand what the specialists are talking about and, perhaps, ask the right questions at critical times in the development process.

Part One contains a brief history and overview of UAVs in Chapter 1 and a discussion of classes and missions of UAVs in Chapter 2.

Part Two is devoted to the design of the air vehicle including basic aerodynamics, performance, stability and control, propulsion and loads, structures and materials in Chapters 3 through 7.

Part Three discusses the mission planning, control function, and autopilot in Chapter 8 and operational control in Chapter 9.

Part Four has three chapters addressing payloads. Chapter 10 discusses the most universal types of payloads, reconnaissance, and surveillance sensors. Chapter 11 discusses weapons payloads, a class of payloads that has become prominent since its introduction about 10 years ago. Chapter 12 discusses a few of the many other types of payloads that may be used on UAVs.

Part Five covers data links, the communication subsystems used to connect the air vehicle to the ground controllers, and delivers the data gathered by the air-vehicle payloads. Chapter 13 describes and discusses basic data-link functions and attributes. Chapter 14 covers the factors that affect the performance of a data link, including the effects or intentional and unintentional interference. Chapter 15 addresses the impact on the operator and system performance of various approaches to reducing the data-rate requirements of the data link to accommodate limitations on available bandwidth. Chapter 16 summarizes data-link tradeoffs, which are one of the key elements in the overall system tradeoffs.

Part Six describes approaches for the launch and recovery of UAVs, including ordinary takeoff and landing, but extending to many approaches not used for manned aircraft. Chapter 17 describes launch systems and Chapter 18 recovery systems. Chapter 19 summarizes the tradeoffs between the many different launch and recovery approaches. Chapter 20 – a new chapter in this edition – is dedicated to fundamentals, control, and characteristics of rotary-wing UAVs and quadcopters.

Introduction to UAV Systems was first published in 1992. Much has happened in the UAV world in the 30 years since the first edition was written. In the Preface to the second edition (1998), we commented that there had been further problems in the development process for tactical UAVs but that there had been some positive signs in the use of UAVs in support of the Bosnian peace-keeping missions and that there even was some talk of the possible use of "uninhabited" combat vehicles within the US Air Force that was beginning for the first time to show some interest in UAVs. At that time, we concluded that "despite some interest, and real progress in some areas, however, we believe that the entire field continues to struggle for acceptance, and UAVs have not come of age and taken their place as proven and established tools."

In the 30 years since we made that statement, the situation has changed dramatically. UAVs have been widely adopted in the military world, unmanned combat vehicles have been deployed and used in highly visible ways, often featured on the evening news, and unmanned systems now appear to be serious contenders for the next generation of fighters and bombers.

While civilian applications still lag, impeded by the very-real issues related to mixing manned and unmanned aircraft in the general airspace, the success of military applications has encouraged attempts to resolve these issues and establish unmanned aircraft in nonmilitary roles.

The Fifth Edition has been extensively revised and restructured. The revisions have, we hope, made some of the material clearer and easier to understand and have added a number of new subjects in areas that have become more prominent in the UAV world during the last two decades, such as quadcopter, automatic flight control systems, new payloads, and the various levels of autonomy that may be given to an air vehicle. It also revises a number of details that have clearly been overtaken by events, and all chapters have been brought up to date to introduce some of the new terminology, concepts, and specific UAV systems that have appeared over the last 12 years. However, the basic subsystems that make up a UAV "system of systems" have not greatly changed, and at the level that this text addresses them, the basic issues and design principles have not changed since the first edition was published.

The first two authors – sadly, now deceased - met while participating in a "red team" that was attempting to diagnose and solve serious problems in an early UAV program. The eventual diagnosis was that there had been far too little "systems engineering" during the design process and that various subsystems did not work together as required for system-level success. This book grew out of a desire to write down at least some of the "lessons learned" during that experience and make them available to those who design UAV systems in the future.

Supplementary materials, including answers to end-of-chapter questions, are available for registered instructors who adopt this book as a course text. Please visit www.wiley.com/go/fahlstrom/uavsystems5e for information and to register for access to these resources.

We believe that most of those lessons learned are universal enough that they are just as applicable today as they were when they were learned years ago, and hope that this book can help future UAV system designers apply them and avoid having to learn them again the "hard way."

Mohammad Hashem Sadraey
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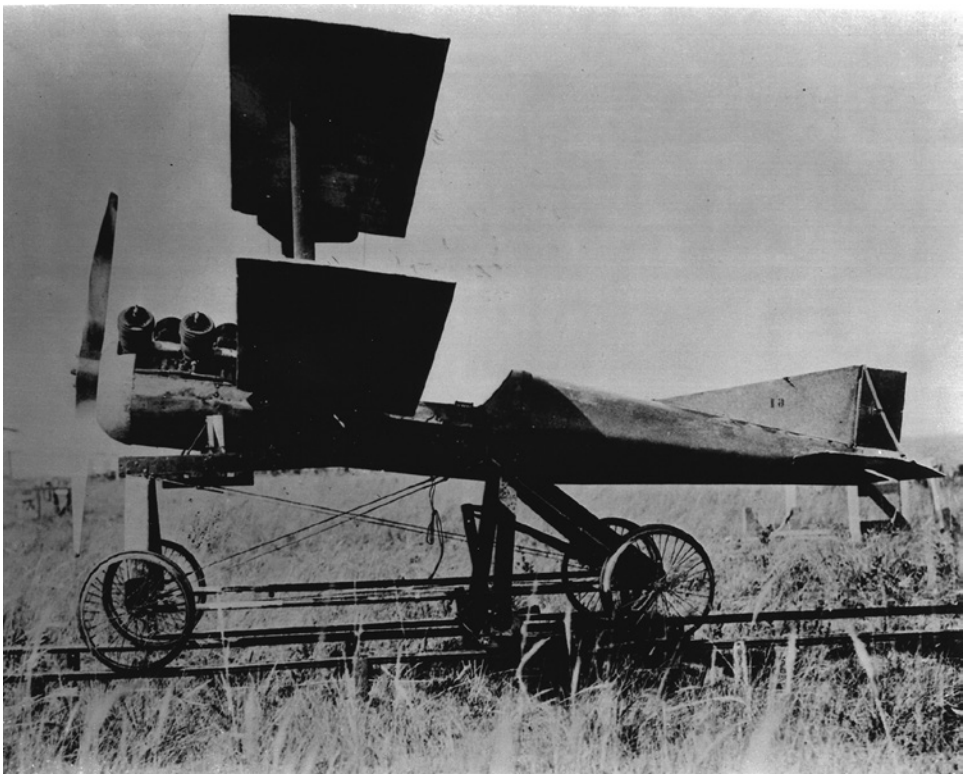

The Kettering Bug (Photograph courtesy of Norman C. “Dutch” Heilman)

Series Preface

This book is a welcome addition to the Aerospace Series, continuing the tradition of the Series in providing clear and practical advice to practitioners in the field of aerospace. This book will appeal to a wide readership and is an especially good introduction to the subject by extending the range of titles on the topic of unmanned air vehicles, and more importantly presenting a systems viewpoint of unmanned air systems. This is important as the range of vehicles currently available provides a diverse range of capabilities with differing structural designs, propulsions systems, payloads, ground systems, and launch/recovery mechanisms. It is difficult to see any rationalization or standardization of vehicles or support environment in the range of available solutions.

The book covers the history of unmanned flight and describes the range of solutions available world-wide. It then addresses the key aspects of the subsystems such as structure, propulsion, navigation, sensor payloads, launch and recovery, and associated ground systems in a readable and precise manner, pulling them together as elements of a total integrated system. In this way it is complementary to other systems books in the Series.

It is important for engineers and designers to visualize the totality of a system in order to gain an understanding of all that is involved in designing new vehicles or in writing new requirements to arrive at a coherent design of vehicle and infrastructure. Even more important if the new vehicle needs to interact and inter-operate with other vehicles or to operate from different facilities.

If unmanned air systems are going to become accepted in civilian airspace and in commercial applications then it is vital that a set of standards and design guidelines is in place to ensure consistency, to aid the certification process, and to provide a global infrastructure similar to that existing for today's manned fleets. Without that understanding, certification of unmanned air vehicles to operate in civilian controlled airspace is going to be a long and arduous task.

This book sets the standard for a definitive work on the subject of unmanned air systems by providing a measure of consistency and a clear understanding of the topic.

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List of Acronyms

AC	alternating current, aerodynamic center
ADC	analog-to-digital converter
ADT	air data terminal
AFCS	automatic flight control systems
AGL	above ground level
Ah	ampere-hours
AI	artificial intelligence
AJ	anti jam
AOA	angle of attack
AR	aspect ratio
ARM	antiradiation munition
AV	air vehicle
BD	bi-directional
BIT	built-in test
BVLOS	beyond visual line of sight
BLOS	beyond line of sight
C2	command and control
CARS	common automatic recovery system
CBR	chemical, biological, radiological
CCD	charge-coupled device
CFD	computational fluid dynamics
CG	center of gravity
CLRS	central launch and recovery section
CP	center of pressure
CPU	central processing unit
COMINT	communication intelligence
CW	continuous wave
DAA	detect and avoid
DAC	digital-to-analog converter
dB	decibel
dBA	dBs relative to the lowest pressure difference that is audible to a person
dBmv	dBs relative to 1 mV
dBsm	dB relative to 1 m^2
DC	direct current
DF	direction finding

DOF	degrees of freedom
ECCM	electronic counter-countermeasures
ECM	electronic countermeasure
ELINT	electronic intelligence
EMI	electromagnetic interference
EO	electro optic
ERP	effective radiated power
ESM	electronic support measure
eVTOL	electric vertical take-off and landing
EW	electronic warfare
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FCS	forward control section
FEM	finite element method
FLIR	forward-looking infrared
FLOT	Forward Line of Own Troops
FOV	field of view
fps	frames per second
FPV	first-person view
FSED	Full Scale Engineering Development
GCS	ground control station
GDT	ground data terminal
GHz	giga hertz
GNC	Guidance-Navigation-Control
GPS	global positioning system
GSE	ground support equipment
Gyro	gyroscope
HALE	high-altitude, long endurance
HELLFIRE	helicopter launched fire and forget missile
HERO	Hazards of Electromagnetic Radiation to Ordnance
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HP	hydraulic-pneumatic
HTOL	horizontal takeoff and landing
IAI	Israeli Aircraft Industries
IC	integrated circuit
IFF	identification friend or foe
IMC	Image Motion Compensation
iOS	iPhone operating system
IR	infrared
ISR	Intelligence, Surveillance, Reconnaissance
ISO	International Organization for Standardization
JATO	Jet Assisted Take-Off
JII	Joint Integration Interface
JPEG	Joint Photographic Experts Group
JPO	joint project office
JSTARS	Joint Surveillance Target Attack Radar System
KE	kinetic energy

LAN	local area network
Li-ion	lithium ion
Li-poly	lithium polymer
LOS	line of sight
LPI	low-probability of intercept
LQR	linear quadratic regulator
mAh	milli ampere hour
MALE	medium-altitude, long endurance
MARS	mid-air recovery system
MART	Mini Avion de Reconnaissance Telepilot
Mbps	mega bits per second
MDO	multidisciplinary design optimization
MEMS	Micro-Eectro-Mechanical System
MET	meteorological
MICNS	Modular Integrated Communication and Navigation System
MPCS	mission planning and control station
MRC	minimum resolvable contrast
MRDT	minimum resolvable delta in temperature
MRT	minimum resolvable temperature
MSL	mean sea level
MTF	modulation transfer function
MTI	Moving Target Indicator
NACA	National Advisory Committee for Aeronautics
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NDI	non-developmental item
NiCd	nickel cadmium
NiMH	nickel metal hydride
nm	nautical mile
NOAA	National Oceanic and Atmospheric Administration
NP	neutral point
OBC	optical bar camera
OSD	on-screen display
OSI	Open System Interconnection
OT	operational test
PGM	precision guided munition
PIC	Pilot In Command
PID	Proportional, Integral, Derivative
PIN	positive intrinsic negative
PLSS	Precision Location and Strike System
QFT	quantitative feedback theory
RAM	radar-absorbing material
RAP	radar-absorbing paint
RATO	rocket-assisted takeoff
RC Plane	radio-controlled airplane, remotely controlled airplane
R&D	Research and Development
RCS	radar cross-section

RF	radio frequency
RGT	remote ground terminal
RMS	root mean square
ROC	rate of climb
RPG	rocket propelled grenade
RPM	revolutions per minute
RPA	remotely piloted aircraft
RPV	remotely piloted vehicle
SAR	synthetic aperture radar
SEAD	Suppression of Enemy Air Defense
SF	safety factor
shp	shaft horsepower
SIGINT	signal intelligence
SLAR	side-looking airborne radar
SOTAS	Stand-Off Target Acquisition System
SPARS	Ship Pioneer Arresting System
sUAS	small unmanned aircraft systems
TADARS	Target Acquisition/Designation and Aerial Reconnaissance System
TUAV	tactical UAV
UAM	Urban Air Mobility
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
UCAV	unmanned combat aerial vehicle
UD	unidirectional
VLOS	visual line-of-sight
VTOL	vertical takeoff and landing