



**Andrew J. Keane  
András Sóbester  
James P. Scanlan**

# **Small Unmanned Fixed-wing Aircraft Design**

**A Practical Approach**

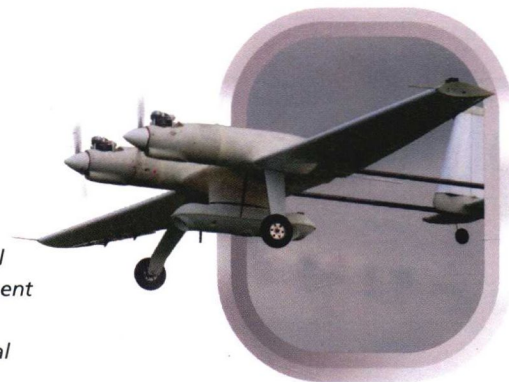
**Aerospace Series**

Editors Peter Belobaba, Jonathan Cooper  
and Allan Seabridge

**WILEY**

# Small Unmanned Fixed-wing Aircraft Design

## A Practical Approach



**Andrew J. Keane** is a Professor of Computational Engineering in the Faculty of Engineering and the Environment at the University of Southampton. He is the Director of the Rolls-Royce University Technology Center for Computational Engineering at the University and is a fellow of the RINA, IMechE and the Royal Academy of Engineering.

**Andras Sobester** is a Senior Lecturer of Aeronautical Engineering in the Faculty of Engineering and the Environment at the University of Southampton. His main research focus is on developing techniques for the aerodynamic optimization of aircraft.

**James P. Scanlan** is a Professor of Design in the Faculty of Engineering and the Environment at the University of Southampton. He spent more than 10 years working in the aerospace industry and now manages a number of research programmes sponsored by BAE systems, Airbus, Rolls-Royce and the EPSRC. He is a Fellow of the Royal Aeronautical Society.

Small Unmanned Fixed-wing Aircraft Design is the essential guide to designing, building and testing fixed wing UAVs (or drones). It deals with aircraft from two to 150 kg in weight and is based on the first-hand experiences of the world renowned UAV team at the UK's University of Southampton.


The book covers both the practical aspects of designing, manufacturing and flight testing and outlines the essential calculations needed to underpin successful designs. It describes the entire process of UAV design from requirements definition to configuration layout and sizing, through preliminary design and analysis using simple panel codes and spreadsheets to full CFD and FEA models and on to detailed design with parametric CAD tools. Its focus is on modest cost approaches that draw heavily on the latest digital design and manufacturing methods, including a strong emphasis on utilizing off-the-shelf components, low cost analysis, automated geometry modelling and 3D printing.

It deliberately avoids a deep theoretical coverage of aerodynamics or structural mechanics; rather it provides a design team with sufficient insights and guidance to get the essentials undertaken more pragmatically. The book contains many all-colour illustrations of the dozens of aircraft built by the authors and their students over the last ten years giving much detailed information on what works best. It is predominantly aimed at under-graduate and MSc level student design and build projects, but will be of interest to anyone engaged in the practical problems of getting quite complex unmanned aircraft flying. It should also appeal to the more sophisticated aero-modeller and those engaged on research based around fixed wing UAVs.

Cover Design: Wiley  
Cover Image: Courtesy of the authors

[www.wiley.com](http://www.wiley.com)

# WILEY

 Also available  
as an e-book

ISBN 978-1-119-40629-7



9 781119 406297

**Kearne**

**Söbester**

**Scanlan**

**Small Unmanned Fixed-Wing Aircraft Design**

**WILEY**

# **SMALL UNMANNED FIXED-WING AIRCRAFT DESIGN**

**A Practical Approach**

**Andrew J. Keane**

*University of Southampton  
UK*

**András Sóbester**

*University of Southampton  
UK*

**James P. Scanlan**

*University of Southampton  
UK*

**WILEY**

This edition first published 2017  
© 2017 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 Andrew J. Keane, András Sóbester and James P. Scanlan to be identified as the authors 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](http://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*

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: Keane, Andrew J., author. | Sóbester, András, author. | Scanlan, James P., author.  
Title: Small unmanned fixed-wing aircraft design : a practical approach /  
Andrew J. Keane, University of Southampton, UK, András Sóbester,  
University of Southampton, UK, James P. Scanlan, University of  
Southampton, UK.

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

[2017] | Series: Aerospace series | Includes bibliographical references and index. |

Identifiers: LCCN 2017024962 (print) | LCCN 2017027876 (ebook) | ISBN 9781119406327 (pdf) |  
ISBN 9781119406310 (epub) | ISBN 9781119406297 (cloth)

Subjects: LCSH: Drone aircraft—Design and construction. | Airplanes—Design and construction.

Classification: LCC TL685.35 (ebook) | LCC TL685.35 .K43 2017 (print) | DDC 629.133/39—dc23  
LC record available at <https://lccn.loc.gov/2017024962>

Cover image: Courtesy of the authors

Cover design by Wiley

Set in 10/12pt, TimesLTStd by SPi Global, Chennai, India

10 9 8 7 6 5 4 3 2 1

Printed and bound by CPI Group (UK) Ltd, Croydon, CR0 4YY

# **SMALL UNMANNED FIXED-WING AIRCRAFT DESIGN**

## Related titles

### Aerospace Series

Small Unmanned Fixed-wing Aircraft Design: A Practical Approach	Keane	October 2017
Performance of the Jet Transport Airplane: Analysis Methods, Flight Operations, and Regulations	Young	August 2017
Differential Game Theory with Applications to Missiles and Autonomous Systems Guidance	Faruqi	May 2017
Advanced UAV Aerodynamics, Flight Stability and Control: Novel Concepts, Theory and Applications	Marques and Da Ronch	April 2017
Introduction to Nonlinear Aeroelasticity	Dimitriadis	April 2017
Introduction to Aerospace Engineering with a Flight Test Perspective	Corda	March 2017
Aircraft Control Allocation	Durham, Bordignon and Beck	January 2017
Remotely Piloted Aircraft Systems: A Human Systems Integration Perspective	Cooke, Rowe, Bennett. Jr. and Joralmon	October 2016
Adaptive Aeroservoelastic Control	Tewari	March 2016
Theory and Practice of Aircraft Performance	Kundu, Price and Riordan	November 2015
The Global Airline Industry, Second Edition	Belobaba, Odoni and Barnhart	July 2015
Modeling the Effect of Damage in Composite Structures: Simplified Approaches	Kassapoglou	March 2015
Introduction to Aircraft Aeroelasticity and Loads, 2nd Edition	Wright and Cooper	December 2014
Aircraft Aerodynamic Design: Geometry and Optimization	Sóbester and Forrester	October 2014
Theoretical and Computational Aerodynamics	Sengupta	September 2014
Aerospace Propulsion	Lee	October 2013
Aircraft Flight Dynamics and Control	Durham	August 2013
Civil Avionics Systems, 2nd Edition	Moir, Seabridge and Jukes	August 2013
Modelling and Managing Airport Performance	Zografos, Andreatta and Odoni	July 2013
Advanced Aircraft Design: Conceptual Design, Analysis and Optimization of Subsonic Civil Airplanes	Torenbeek	June 2013
Design and Analysis of Composite Structures: With Applications to Aerospace Structures, 2nd Edition	Kassapoglou	April 2013
Aircraft Systems Integration of Air-Launched Weapons	Rigby	April 2013
Design and Development of Aircraft Systems, 2nd Edition	Moir and Seabridge	November 2012
Understanding Aerodynamics: Arguing from the Real Physics	McLean	November 2012
Aircraft Design: A Systems Engineering Approach	Sadraey	October 2012
Introduction to UAV Systems 4e	Fahlstrom and Gleason	August 2012
Theory of Lift: Introductory Computational Aerodynamics with MATLAB and Octave	McBain	August 2012
Sense and Avoid in UAS: Research and Applications	Angelov	April 2012
Morphing Aerospace Vehicles and Structures	Valasek	April 2012
Gas Turbine Propulsion Systems	MacIsaac and Langton	July 2011
Basic Helicopter Aerodynamics, 3rd Edition	Seddon and Newman	July 2011
Advanced Control of Aircraft, Spacecraft and Rockets	Tewari	July 2011
Cooperative Path Planning of Unmanned Aerial Vehicles	Tsourdos et al	November 2010
Principles of Flight for Pilots	Swatton	October 2010
Air Travel and Health: A Systems Perspective	Seabridge et al	September 2010
Design and Analysis of Composite Structures: With applications to aerospace Structures	Kassapoglou	September 2010
Unmanned Aircraft Systems: UAVS Design, Development and Deployment	Austin	April 2010
Introduction to Antenna Placement & Installations	Macnamara	April 2010

Principles of Flight Simulation	Allerton	October 2009
Aircraft Fuel Systems	Langton et al	May 2009
The Global Airline Industry	Belobaba	April 2009
Computational Modelling and Simulation of Aircraft and the Environment: Volume 1 - Platform Kinematics and Synthetic Environment	Diston	April 2009
Handbook of Space Technology	Ley, Wittmann Hallmann	April 2009
Aircraft Performance Theory and Practice for Pilots	Swatton	August 2008
Aircraft Systems, 3 <sup>rd</sup> Edition	Moir & Seabridge	March 2008
Introduction to Aircraft Aeroelasticity And Loads	Wright & Cooper	December 2007
Stability and Control of Aircraft Systems	Langton	September 2006
Military Avionics Systems	Moir & Seabridge	February 2006
Design and Development of Aircraft Systems	Moir & Seabridge	June 2004
Aircraft Loading and Structural Layout	Howe	May 2004
Aircraft Display Systems	Jukes	December 2003
Civil Avionics Systems	Moir & Seabridge	December 2002



*This book is dedicated to the students of the University of Southampton  
who have designed, built and flown many UAVs over the last decade  
and who have been great fun to work with.*

# Foreword

As a proud University of Southampton alumnus, I am delighted to have the privilege of writing a few introductory words. My own journey through the ranks of the Royal Navy, and especially in naval aviation, leadership, and the exploitation of technology, has taught me the advantage and fun to be had in challenging convention.

Meanwhile, it is the sheer scale of the emerging new technologies that makes today such an exciting time. And the Internet has unlocked access to diverse technical knowledge. So, now no one has an excuse for inhabiting a warm and comfortable technology stovepipe! The true strength in technical creativity now involves the willingness to mix knowledge, without fear or favor.

The design of drones explores this genuinely new frontier. Why? Because, as this guide book makes clear, the approach is a subtle mix of skills, based of course on aerodynamics and airplane design. But also law, regulation, autonomy, disposability, low cost, unorthodoxy, as well as novel construction, automation, integration, and artificial intelligence. In other words, the chance to think very differently, across numerous domains. For example, mix biology and 3D printing, and you have drone biodegradability options.

Conventional aviation industries and aircraft manufacturers are not best suited to this exploratory approach, because they do not have the freedoms of behavior built into their leadership and management, or their business plans. Nor are their shareholders interested, until the firm is going bust.

So, exciting ideas and courage will come from “left field,” and this is your chance to think differently and be part of that.



*George Zambellas*

Source: Courtesy of Sir George Zambellas.

Admiral Sir George Zambellas GCB DSC DL FRAeS

# Series Preface

Unmanned air vehicles can now be seen in many applications from domestic, industrial, government/official to military. The range of configurations includes fixed wing, multi-rotorcraft, adaptive wing, and space re-entry vehicles, in both remotely piloted and autonomous modes of operation. As a result there are many classes of unmanned air vehicles in existence, and many types within each class, developed by many manufacturers. They are all capable of carrying some form of payload, including sensors, and of relaying sensor information to the ground – their primary use. They should all be designed and tested to meet the accepted airworthiness requirements for certification, although perhaps not all are.

This book is a welcome addition to the literature of unmanned air vehicles concentrating as it does on a particular class, that of small, fixed wing subsonic vehicles capable of carrying significant payloads – a class with little associated literature and a class that is likely to expand in the future. There are configurations in this class that are readily available to members of the public and small businesses who use them as observation or surveillance platforms to complement their business activities. The book has been written by authors with long experience of the development of this class from concept through design, build and test and operation in a teaching environment. This experience shows in the clear explanations assisted by many relevant diagrams. The book stresses the need for a robust design process for the airframe, the systems and the software tool set used to support designers. The completeness of the text results in a handbook on how to design, build and fly small fixed wing Unmanned Air Vehicles.

The *Aerospace Series* has continued to provide practical, topical and relevant information for people working in the field of aerospace design and development, including engineering professionals and operators, allied professions such as commercial and legal executives, and also engineers in academia. In this instance the book is especially suitable for final year graduates and those entering the industry and intending to start a career in the field of unmanned vehicles.

Peter Belobaba, Jonathan Cooper and Allan Seabridge

# Preface

Unmanned air vehicles (sometimes uninhabited air vehicles or even systems, UAVs or UASs) are becoming an increasingly common sight across the globe. Originally the preserve of very secretive military organizations, they are now in routine use by film crews, farmers, search and rescue teams, hobbyists, and so on. Most of the technological difficulties in building a system that can start, take off, fly a mission, and return without human intervention have been overcome, and the wider adoption of these technologies is now mostly a matter of cost, public acceptance, and regulatory approval. The only remaining technological challenges essentially concern the degree of on-board autonomy and decision making such vehicles can provide. If secure and robust communications to a ground-based pilot can be maintained to provide decision-making capabilities, very ambitious missions can be quite readily accomplished. On-board decision making is less well advanced but developments continue apace.

The origins of our interest in UAVs stem from the many years we have spent in the business of design, both practical and academic, teaching, and research. This has exposed us to a great deal of related activity in the aerospace and marine sectors, whose processes have changed considerably over the time we have been involved. A reoccurring theme throughout has been rapid evolution in the software toolset used to support designers, and it is in this area we have been principally engaged. Central to our views is a way of looking at engineering design that distinguishes between synthesis (the business of generating new or changed descriptions of artifacts) and analysis (where one uses the laws of physics, experiments, and past experience to assess the likely or actual performance of the designed artifact). It is by the use of formal analysis and experimentation to ascribe value to an artifact that engineering design distinguishes itself from other forms of design. Thus, to be useful in the world of engineering design, tools must either help describe the product or process being designed, analyze it, or support the delivery and integration of these processes – all else is just bureaucracy: design should always be seen as a decision-making process.

In this book we focus on one particular aspect of the rapidly growing area of UAV technology: the design, construction, and operation of low-cost, fixed-wing UAVs in the 2–150 kg maximum take-off weight (MTOW) class flying at low subsonic speeds. Such vehicles can offer long-endurance, robust platforms capable of operating for 10 h or more on budgets well below \$100 000, often less than \$10 000. They can carry significant payloads and operate from relatively simple ground facilities. In what follows, an approach to designing and building such UAVs, developed over many years at the University of Southampton, is set out. While there are, no doubt, many other valid ways of producing UAVs, the one described here

works for us, providing effective low-cost platforms for teaching, research, and commercial exploitation.

Andrew J. Keane, András Sóbester and James P. Scanlan  
Southampton, UK, 2017

# Acknowledgments

The support and commitment of colleagues in the Computational Engineering and Design Group at the University of Southampton are gratefully acknowledged. The University is a great place to work and a continued source of ideas and renewal. In particular, our thanks are due to a number of academic, post-doctoral, and post-graduate researchers, engineers, and pilots who have contributed to our understanding in this area, including Marc Bolinches, Mantas Brazinskas, Bob Entwistle, Mehmet Erbil, Mario Ferraro, Dirk Gorissen, Paul Heckles, Andrew Lock, Stephen Prior, Erika Quaranta, Jeroen van Schaik, Ben Schumann, Kenji Takeda, David Toal, and Keith Towell.

# Contents

<b>List of Figures</b>	<b>xvii</b>
<b>List of Tables</b>	<b>xxxiii</b>
<b>Foreword</b>	<b>xxxv</b>
<b>Series Preface</b>	<b>xxxvii</b>
<b>Preface</b>	<b>xxxix</b>
<b>Acknowledgments</b>	<b>xli</b>

## **PART I INTRODUCING FIXED-WING UAVS**

<b>1 Preliminaries</b>	<b>3</b>
1.1 Externally Sourced Components	4
1.2 Manufacturing Methods	5
1.3 Project DECODE	6
1.4 The Stages of Design	6
1.4.1 <i>Concept Design</i>	8
1.4.2 <i>Preliminary Design</i>	10
1.4.3 <i>Detail Design</i>	11
1.4.4 <i>Manufacturing Design</i>	12
1.4.5 <i>In-service Design and Decommissioning</i>	13
1.5 Summary	13
<b>2 Unmanned Air Vehicles</b>	<b>15</b>
2.1 A Brief Taxonomy of UAVs	15
2.2 The Morphology of a UAV	19
2.2.1 <i>Lifting Surfaces</i>	21
2.2.2 <i>Control Surfaces</i>	22
2.2.3 <i>Fuselage and Internal Structure</i>	23
2.2.4 <i>Propulsion Systems</i>	24

2.2.5	<i>Fuel Tanks</i>	24
2.2.6	<i>Control Systems</i>	24
2.2.7	<i>Payloads</i>	27
2.2.8	<i>Take-off and Landing Gear</i>	27
2.3	Main Design Drivers	29

## PART II THE AIRCRAFT IN MORE DETAIL

<b>3</b>	<b>Wings</b>	<b>33</b>
3.1	Simple Wing Theory and Aerodynamic Shape	33
3.2	Spars	37
3.3	Covers	37
3.4	Ribs	38
3.5	Fuselage Attachments	38
3.6	Ailerons/Roll Control	40
3.7	Flaps	41
3.8	Wing Tips	42
3.9	Wing-housed Retractable Undercarriage	42
3.10	Integral Fuel Tanks	44
<b>4</b>	<b>Fuselages and Tails (Empennage)</b>	<b>45</b>
4.1	Main Fuselage/Nacelle Structure	45
4.2	Wing Attachment	47
4.3	Engine and Motor Mountings	48
4.4	Avionics Trays	50
4.5	Payloads – Camera Mountings	51
4.6	Integral Fuel Tanks	52
4.7	Assembly Mechanisms and Access Hatches	54
4.8	Undercarriage Attachment	55
4.9	Tails (Empennage)	57
<b>5</b>	<b>Propulsion</b>	<b>59</b>
5.1	Liquid-Fueled IC Engines	59
5.1.1	<i>Glow-plug IC Engines</i>	62
5.1.2	<i>Spark Ignition Gasoline IC Engines</i>	62
5.1.3	<i>IC Engine Testing</i>	65
5.2	Rare-earth Brushless Electric Motors	66
5.3	Propellers	68
5.4	Engine/Motor Control	70
5.5	Fuel Systems	70
5.6	Batteries and Generators	71
<b>6</b>	<b>Airframe Avionics and Systems</b>	<b>73</b>
6.1	Primary Control Transmitter and Receivers	73
6.2	Avionics Power Supplies	76



6.3	Servos	78
6.4	Wiring, Buses, and Boards	82
6.5	Autopilots	86
6.6	Payload Communications Systems	87
6.7	Ancillaries	88
6.8	Resilience and Redundancy	90
<b>7</b>	<b>Undercarriages</b>	<b>93</b>
7.1	Wheels	93
7.2	Suspension	95
7.3	Steering	95
7.4	Retractable Systems	97
<b>PART III DESIGNING UAVS</b>		
<b>8</b>	<b>The Process of Design</b>	<b>101</b>
8.1	Goals and Constraints	101
8.2	Airworthiness	103
8.3	Likely Failure Modes	104
	8.3.1 <i>Aerodynamic and Stability Failure</i>	105
	8.3.2 <i>Structural Failure</i>	106
	8.3.3 <i>Engine/Motor Failure</i>	107
	8.3.4 <i>Control System Failure</i>	107
8.4	Systems Engineering	110
	8.4.1 <i>Work-breakdown Structure</i>	110
	8.4.2 <i>Interface Definitions</i>	112
	8.4.3 <i>Allocation of Responsibility</i>	112
	8.4.4 <i>Requirements Flowdown</i>	112
	8.4.5 <i>Compliance Testing</i>	113
	8.4.6 <i>Cost and Weight Management</i>	114
	8.4.7 <i>Design "Checklist"</i>	117
<b>9</b>	<b>Tool Selection</b>	<b>119</b>
9.1	Geometry/CAD Codes	120
9.2	Concept Design	123
9.3	Operational Simulation and Mission Planning	125
9.4	Aerodynamic and Structural Analysis Codes	125
9.5	Design and Decision Viewing	125
9.6	Supporting Databases	126
<b>10</b>	<b>Concept Design: Initial Constraint Analysis</b>	<b>127</b>
10.1	The Design Brief	127
	10.1.1 <i>Drawing up a Good Design Brief</i>	127
	10.1.2 <i>Environment and Mission</i>	128
	10.1.3 <i>Constraints</i>	129