

Andrew J. Keane András Sóbester James P. Scanlan

Small Unmanned Fixed-wing Aircraft Design A Practical Approach

Aerospace Series

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SMALL UNMANNED FIXED-WING AIRCRAFT DESIGN

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SMALL UNMANNED FIXED-WING AIRCRAFT DESIGN

A Practical Approach

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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.

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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.



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, multirotorcraft, 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, 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

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Part I Introducing Fixed-Wing UAVs

1

Preliminaries

Fixed-wing aircraft have now been successfully designed and flown for over 100 years. Aero-modelers have been flying quite large aircraft at low subsonic speeds for decades, sometimes at scales as large as one-third the full size. Given the accumulated experience, it is therefore a relatively straightforward task to design, build, and fly a workable fixed-wing unmanned air vehicle (UAV) platform, armed with one of the many textbooks available on aircraft design (perhaps the most famous of these being that by Torenbeek [1], though there are many others). Even a cursory search of the Web will reveal hundreds of UAVs, many of them fixed-wing, and a number being offered for sale commercially. What is much less simple is to quickly make robust and reliable airframes in a repeatable manner at low cost, tailored to specific missions and suitable for commercial-grade operations.

If one has to rely on the craft skills of a highly gifted model-maker to construct an aircraft, costs rapidly rise, timescales lengthen, and repeatability becomes difficult to ensure. The use of bespoke molds and various forms of composites allows a much higher standard of airframe, but the initial production costs become then high and the ability to alter designs becomes very limited. Conversely, by using commodity off-the-shelf components combined with computer-aided design (CAD)-based digital manufacture, craft skills can be eliminated, costs lowered, and repeatability guaranteed. Clearly, if one has always to manually adapt an existing design to come up with a specification for a new aircraft, much design flexibility is lost; if, instead, lightweight decision support tools are linked to sophisticated parametric CAD models, high-quality design concepts can be rapidly developed to specific needs.

This is the fundamental design philosophy adopted by the UAV team at the University of Southampton (Figure 1.1) and forms the guiding approach of this book. The basic idea is to work in a digital, online world, buying parts where possible and manufacturing custom items only where absolutely necessary – essentially the aim is to source a kit of components either from part suppliers or companies offering online CAD-based manufacture, which then simply requires assembly to produce the finished aircraft. This means that the resulting UAVs are of a high and repeatable quality with as much emphasis on smart design as possible. This philosophy has become possible largely because of a revolution in bespoke digital manufacturing capabilities afforded by advanced CAD, Internet-based sourcing, low-cost computer numerical controlled (CNC) machining, and the widespread availability of 3D printing of functional components. In particular, the use of SLS nylon and metal has transformed the way in which main

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Figure 1.1 The University of Southampton UAV team with eight of our aircraft, March 2015. See also https://www.youtube.com/c/SotonUAV and https://www.sotonuav.uk/.

fuselage components and bespoke aircraft fittings can now be made. The core aims throughout our work have been to seek

- 1. low costs with highly repeatable and robust products,
- 2. rapid conversion of design changes into flying aircraft to meet new requirements, and
- 3. flexible payload systems

combined with

- 4. duplication of all flight critical systems,
- 5. sufficiently sophisticated avionics to allow fully autonomous takeoff, flight, and landing,
- 6. large and strong fixtures and joints to provide tolerance of uneven landing sites and day-to-day ground handling, and
- 7. low take-off and landing speeds to minimize risks of damage during operations.

These aims ensure long-lived and robust commercial-grade aircraft, which can survive hundreds of flight cycles and thousands of flight hours – something that model aircraft never see.

1.1 Externally Sourced Components

To test our evolving design environments and build capabilities, a range of aircraft types have been considered. In all cases, these started with the knowledge that some of the major airframe components have to be externally sourced and that one has therefore to work with what is readily available in appropriate sizes. The following list of such components forms a key starting point for what follows. To maintain low costs, some things simply have to be sourced *off the shelf*:

- 1. *Engines*. Either petrol or glow-plug internal combustion engines ranging from 10 up to 200 cc (cm³) in single-, twin-, three-, and four-cylinder configurations;
- 2. *Electric motors*. Usually rare-earth permanent magnet motors with digital speed controllers which are available in a wide range of sizes;
- 3. Starters and generators. External or in-built starters, direct drive or coupled via drive belts;
- 4. *Propellers*. Pusher and tractor propellers available in wood, nylon, and carbon-fiberreinforced plastic (CFRP) with between two and six blades;
- 5. Batteries. NiMH, LiFe, or LiPo aircraft-grade batteries;
- 6. *Receiver/transmitter systems for primary flight control.* High end aero-modeler systems from companies such as Futaba (which now support two-way transmission of data including rpm, temperature, and geographical positioning system (GPS) sensors on the aircraft);
- 7. *Autopilots*. Many are available, but we use Arduino and SkyCircuits¹ systems (including ground stations and software environments);
- 8. Servos and actuators. High-quality, high-torque, metal-geared aero-modeler items;
- 9. Undercarriages and wheels. High-quality aero-modeler items, typically including suspension and sometimes a retract capability.

At larger take-off weights, items such as propellers and undercarriages are more difficult to source, and then it is sometimes necessary to have bespoke items made by specialist suppliers – even so, it is desirable to use companies with sufficient turnover and expertise so that costs can be controlled and quality maintained. Given a ready supply of such items and the intention to build a conventional fixed-wing monoplane, the primary layout choices available to the designer then concern the number and positioning of engines/motors and the choice of fuselage/empennage type.

1.2 Manufacturing Methods

As already noted, a key requirement for the manufacture of the UAVs being considered here is that ideally no craft skills be needed in construction. Thus the focus is on

- advanced parametric CAD-based geometry design;
- logical and CAD-based design of wiring looms including all plug/socket physical details with manufacture by dedicated specialists;
- numerically controlled digital manufacture involving
 - 3D printing selective laser-sintered (SLS) nylon or metal and fused deposition modeling (FDM) ABS,
 - laser-cut wood and plastic,
 - hot-wire-cut foam (foam parts sometimes being covered by outsourcing to specialists);
- use of stock-sized materials such as off-the-shelf CFRP tubular sections.

¹ See http://www.skycircuits.com/.