Drones to Go

A Crash Course for Scientists and Makers

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Table of Contents

About the Authors

Julio Alberto Mendoza-Mendoza is a Mechatronic Engineer, with a Masters in Advanced Technologies from UPIITA IPN and a PhD in Computer Sciences from CIC IPN. He is currently a visiting researcher at the National Autonomous University of Mexico (UNAM). His areas of interest and research are robotics (manipulators, aerial vehicles and wheeled robots, humanoids, haptics, exoskeletons, and teleoperation), programming, analytical and intelligent control, electronics, and mechanical design. His most recent line of development is aerial robotic manipulators. He holds five patents. He has written a couple of books for Apress, including this one.

Victor Javier Gonzalez-Villela received a B.Eng. degree in Mechanical and Electrical Engineering and a M.Eng. degree in Electrical Engineering in 1987 and 1993, respectively, from UNAM, Mexico City, Mexico, and a Ph.D. degree in Kinematics, Dynamics, and Nonlinear Systems applied to Mobile Robot Modelling and Control from Loughborough University, Loughborough, UK, in 2006. He is currently a Titular Professor in the Department of Mechatronics Engineering, UNAM.

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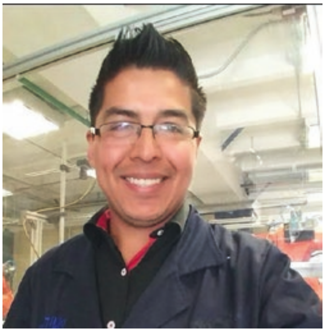
Leonardo Fonseca-Ruiz received a Bachelor's degree in Mechanical and Electrical Engineering from UNAM in 2002 and a M.S. degree from the Department of Electrical Engineering with the Specialty of Bio-Electronics by the Center for Research and Advanced Studies of the National Polytechnic Institute (CINVESTAV-IPN) in 2006. Currently he works as a full-time Research Professor at UPIITA-IPN. He is the author and co-author of 16 works published in magazines and congresses. His areas of interest are PLC, DSP, microcontrollers, automation, design and development of PCBs, and CNC systems.

About the Technical Reviewer



Jesus Vazquez-Nicolas is a mechatronics engineer. He has a Master's of Science in computer engineering from the National Polytechnic Institute, Mexico. He did an academic exchange at the State University of Campinas in Brazil and a research stay at the Institut Polytechnique des Sciences Avancées and the Université d'Évry, both in France.

He is currently pursuing a Ph.D., developing artificial intelligence and control systems for unmanned aerial vehicles (UAV). He is a professor at the Technological University of Mexico, where he was recognized in the circle of academic excellence in 2017, 2018, and 2019. He has had publications in national and international conferences and has indexed scientific journals on robust control and convolutional neural networks applied to UAV. He is very interested in the development of systems that combine mechatronics and artificial intelligence.

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Leonardo Fonseca-Ruiz I dedicate the book to Aidee, Matilde Amelie, and Leonardo, who are the lights of my life. I also thank the National Polytechnic Institute; my students, who keep me updated; Dr. Julio Alberto Mendoza and MSc. Mauricio Méndez, who have been by my side since they were my students and have always done their best, inspiring me to do the same. I am really grateful to the Interdisciplinary Professional Unit of Engineering and Advanced Technologies (UPIITA) of the IPN for giving me the opportunity to teach new mechatronic engineers for over 14 years.

Foreword

This book can be considered as one of the most complete courses on drones and specifically on multicopters with special attention and focus on quadcopters. It is aimed at an audience ranging from makers to scientists. It contains the necessary elements of design, modeling, control, simulation, and programming, explained in a concise but extended way, especially in points that many texts ignore. Additionally, it merges maker knowledge and technical details with scientific knowledge and design details in a single book.

This book is the result of several years of research in the field. It has a staggered pedagogical design, so that the newcomer to the world of drones or the already embedded can obtain strong basis for learning more knowledge.

Detailed step-by-step deductions not available in other works are included, such as the extensive proof of the controllers and their simulations.

It is clearly indicated and with enough references how to extend the knowledge here developed to a wide variety of aircraft or aerial systems.

Finally, an appendix offers a very complete bibliography for those who like to extend their knowledge on the subject.

The text assumes that the readers have at least a high school or technical bachelor's degree and understand concepts such as derivatives, integrals, basic ordinary differential equations, and notions of algorithms and programming.

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With This Book, You Will Learn

- An introduction to the five desirable skills to become a multicopter developer: design, modeling, control, simulation, and programming
- An extended model on the mathematics of a multicopter, not present in any previous work and with a visual and pedagogical development, answering many of the doubts that remain in the air at the time of such explanations
- A novel way to visualize the controllers of a multicopter, that is fully compatible with the existing state of the art
- A detailed description of the controllers and their simulation, which is not widely disseminated in articles or other books and is usually reserved for classrooms
- You can use this book as the basis for future learning in a small, highly visual, and easy-to-understand presentation.
- The goal of this book is to unify the maker world with the scientific world through this type of aircraft, including design tips omitted in scientific books and scientific tips omitted in design books.
- You can extend the acquired knowledge to the design and analysis of other types of vehicles with a moderate but systematic effort.

How to Read This Book

This book is divided into five sections that in our opinion are necessary for an acceptable level of knowledge for a drone designer:

- In the design section, the technical characteristics to be considered when preparing a prototype of a multicopter are shown. This section is based on a compilation of maker-style texts and webpages. Note that this knowledge can be easily extended to other types of vehicles.
- In the modeling section, the mathematics related to a quadcopter (and generic aircraft) are shown, emphasizing the three basic sets of equations: the dynamic set (with this, the control is designed), the kinematic set (with this, the tasks to be executed are designed), and the set of allocation (with this, each motor is programmed and works as the link between theory and practice). Also here, the knowledge shown is moderately easy to be extended to other types of vehicles.
- In the control section, four basic types of multicopter controllers are developed, classifying them into two main branches: vehicle mode control, also known as on-board or first-person mode, and robot mode control, also known as external or third-person mode. This categorization was preferred because these aircraft can be seen as a vehicle or as a robot depending on the application they have. The knowledge in this section can be extended to other types of vehicles under certain mobility conditions.

- The simulation section provides a simplified way (a template) to simulate the previous systems and their controllers, allowing you to understand that only two sections of code are required: the one that contains modeling and control equations, and the one that contains the ODE solver. Although in this book we use MATLAB and Simulink for simplicity, with the concepts outlined, you will be able to use any other programming language or graphic simulator for the same purposes.
- And finally the implementation section, which shows the coding considerations and signal processing currently available or required to use most of the unmanned aerial systems. Also this section may be useful for other types of vehicles.

As you can see, this book and its chapters can be used as the basis for the elaboration of a complete plan for teaching and studying the described subject. This book is by itself a complete course in a pocket size.

This book is aimed at makers, designers, scientists, and researchers related to the drone world and specifically to multicopters. However, if you are a pilot or a hobbyist and you are interested in knowing every corner of your vehicle, this text will be a useful and understandable reading.

If you have the printed version of this book, consider to download also the pdf of the same in order to see detailed close-ups of the equations.

CHAPTER 1

Drone Design Concepts

In this chapter, you will find the most relevant information about what a drone is, including historical and social context. This chapter will cover international standards, some etymologies, and certain safety considerations that you should keep in mind while working with these aircraft. We'll go through a description of generic components and their selection and connection. As a result, you will learn the technical details, international standards, and necessary requirements for the design of drones and other vehicles. Remember that this book is a crash course, so this chapter just provides a fast way for you to assimilate the contents. If you want to extend this knowledge, go to the guided reference appendix.

Historical Context

If you look at the Figure 1-1, you will notice that drones, and particularly multicopters, have centuries of history. They started as sketches designed by DaVinci (at least that's how occidental history reports it). Recently these sketches were carried out in a giant quadcopter in a kind of retrotechnology developed by the University of Maryland where the processor and base engine are the human body (the brain and the extremities, respectively). Multicopters came back around in 1907 with the Breguet brothers and later in the 1920s with Oehmichen and Bothezat.

J. A. Mendoza-Mendoza et al., *Drones to Go*, https://doi.org/10.1007/978-1-4842-6788-2_1

In these drones, the processor and base engine were, respectively, a pilot and a mechanical computer (a mechanism) in charge of coordinating the movements of each propeller and internal combustion motors. They were forgotten until the 2010s, when the commercial and research booms in these vehicles/robots occurred. Currently, the processor and engine base are, respectively, an autopilot and electric motors. Now you that you know some history, let's move on to some useful nomenclatures.

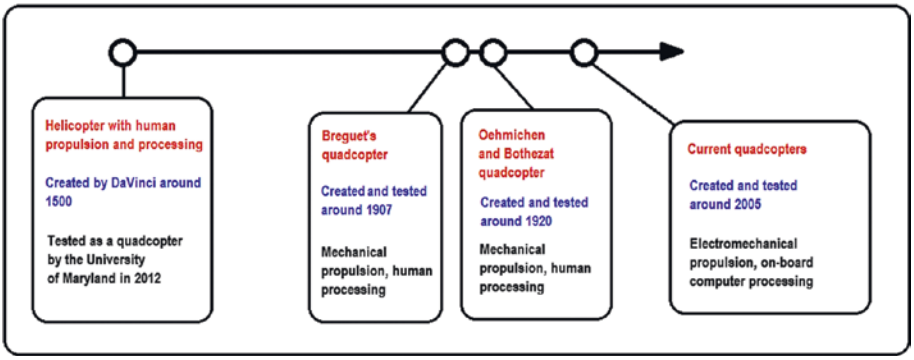

Figure 1-1. *Quadcopter history*

Etymologies and Names in Use

Although the term "drone" is correctly used for any unmanned vehicle, commercial popularization associates it with aerial vehicles, and more specifically, with multicopters. This term comes from insects, very specifically from those whose function in the hive or nest is simply to perpetuate the species.

More professional words to refer to an aerial drone are

- UAV or unmanned aerial vehicle
- UAS or unmanned aerial system
- RPAS or remotely piloted aircraft system

You should also familiarize yourself with the terms “multirotor” and “multicopter,” which roughly mean multiple rotating motors. The term “multiple copters” was adapted from the French “hélicoptère,” a word invented by Gustave d’Amécourt in 1861 that means spiral wing. The word is based on the Greek “helix,” which means helix or spiral, and “pteron,” which means wing.

Why is this useful to know? Perhaps it seems trivial, but for those who want to research the classic concepts of drones, the archaic nomenclature is important to know. Of course, if you only need current research and new trends, you only need to know the modern terms. For the vehicles presented in this book, the evolution from classic to current terminologies is

- Multicopter (22,400 results in Google Scholar on May 5, 2020) -> multirotor (10,600 results in Google Scholar on May 5, 2020)
- Quadcopter (37,400 results in Google Scholar on May 5, 2020) -> Quadrotor (35,500 results in Google Scholar on May 5, 2020)
- And, in an unusual way, the word quadricopter (674 results in Google Scholar on May 5, 2020)

Figure 1-2 is based on Google Trends, indicating when the boom of the term “quadcopter” began. In early 2011 approximately, the words “quadrotor” and “quadcopter” were almost equally employed. In fact, it was very frequent to read “quadrotor” in the scientific field, but the use of the “quadcopter” grew as time evolved (including in scientific and technological research). Currently, both terms are more or less equal in use due to a reduction in their use, and the domination and popularization of the term “drone” (Figure 1-3). Curiously, the terms “quadcopter” and “quadrotor” have been relegated to the research field where the growing term now is “UAV.”

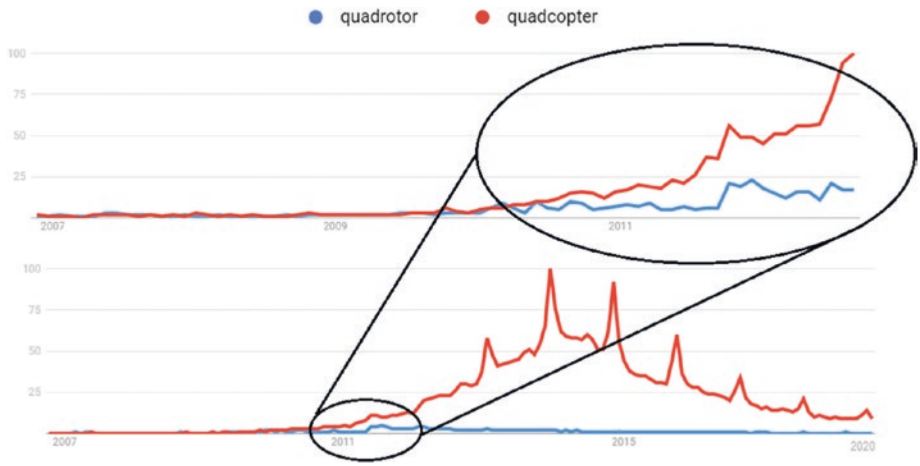

Figure 1-2. *Quadrotor vs. quadcopter search results on Google Trends*

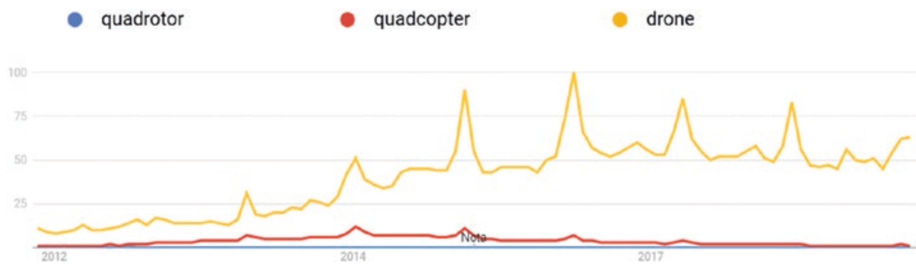

Figure 1-3. *Quadrotor vs. quadcopter vs. drone search results on Google Trends*

In summary, the value of this section is to indicate the trend of certain terms to facilitate any necessary research, and also the way to provide background on how each term should be used in context. Now that you know about etymologies as a tool for searching, let's consider what kind of drone you need.

What Kind of Drone Do You Need?

There are four types of drone users: the specialist researcher, the researcher (who uses a drone as a tool), the designer, and the pilot. Table 1-1 shows some of the characteristics and recommended equipment for each type of user.

Table 1-1. *Types of Drone Users and Characteristics*

User	Most common vehicle	Kind of software (see Chapter 5 regarding ways to program a drone)	What do they need to know?	Examples
Pilot	Closed architectures (prebuilt drones)	Closed architecture GUI	Maker-style technical knowledge, regulations, and unmanned flight courses. The vehicle is a work tool.	Racing pilot or photographer
Researcher who uses a drone as a tool	Mostly closed or limited open architectures	GUI or SDK type 1	Maker-style technical knowledge. The vehicle is still a work tool but with a specialized task unrelated to the drone. The aircraft is a test platform.	Research in artificial vision or artificial intelligence algorithms, including SLAM

(*continued*)

Table 1-1. (*continued*)

User	Most common vehicle	Kind of software (see Chapter 5 regarding ways to program a drone)	What do they need to know?	Examples
Specialist researcher	Kit-like open architectures	SDK type 2 or 3	Scientific knowledge about control and robotic vehicles, and maker-style technical knowledge are desired. Here, the vehicle's flight mode is designed.	Research in automatic control algorithms for aircraft flight
Designer	Open architectures which are selected component by component	SDK type 3 In general, a design component by component is related to open software architectures and conversely, almost all the commercial drones have software with limited capabilities.	Scientific knowledge specialized in aircraft control and design, and advanced technical knowledge are required. Here, the whole vehicle is designed.	Aircraft designer

Now you have an idea about the vehicle that is useful for your purposes, but what about safety and standards? Let's answer this now.

Generic Safety Issues and International Standards

In general, nobody will persecute you for carrying out prototype tests in your home, garden, or in a laboratory with the appropriate equipment and security measures, as long as people, animals, buildings, or property other than your own are not injured. However, in order to reduce risks and accidents, we include a small section with generic recommendations. Note that the impact of these recommendations for each person may vary based on local laws.

Communications

A drone can affect and infringe on local telecommunications in two ways and in both cases you could be penalized.

1. **Telemetry system and remote control system**: Telemetry and remote control transmitters must be compatible with the range of transmission frequencies allowed in your locality. A typical example is that telemetry radios usually come in two presentations: 433 MHz, which is used in Europe and countries with the same standard, and 915 MHz, which is used in the US and countries compatible with the same standard.
2. **Electrical power consumption**: People who design and use quadcopters with high power consumption, especially in high current applications, know that this affects the performance of the vehicle's sensors, and it's necessary to shield the cables, twist them, cover them, or even separate the connections.

This can influence the behavior of a public antenna or civil communication equipment. So, as a designer or user, you should be aware that you could be penalized.

Electrical Safety

Drone operation with wired electrical connections, called tethered, involves sending medium voltages of around 400V to the vehicle, which in certain countries (for example, Japan) go beyond what is legally permitted.

Transport and Storage

The tricky topic here is about batteries and fuel tanks, so be sure you know how to properly store and transport such supplies.

Safety of Use

Any person or property that you damage with your vehicle involves legal problems. You must be aware that a drone is an object that, even in small sizes, due to the speeds that it reaches by itself or by its propellers, represents a risk.

Buying and Selling Problems

You may be interested in a vehicle or perhaps you want to commercialize a prototype. If so, you need to verify that its components, features, and materials are permitted in your region. It is possible that something that represents a small expense to you, once you sell it or buy it in a specific country or commercial area, will increase considerably in price or taxes or may even be retained or rejected for the use of illegal components.

Regulations and Standardizations

When you get to Chapter 2, you will notice a non-arbitrary selection of coordinates and angles of rotation, as displayed in Figure 1-4. This selection obeys the ISO 1151-2: 1985 standard and facilitates the link between the described theory and the use of sensors and components already manufactured. However, to simplify equations, we will use the upward Z axis.

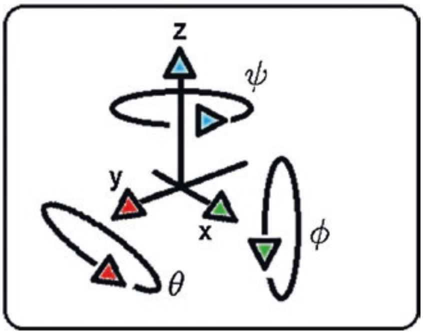

Figure 1-4. *Drone motions as indicated by the ISO 1151-2: 1985 standard*

Notice that in the case of a drone, as you will see later, although the pitch (theta) and roll (phi) angles are measured respectively with the Y and X axes, the motion in X axis depends on controlled tilt rotations in theta, and the motion in the Y axis depends on controlled tilt rotations in phi, as illustrated in Figure 1-5.

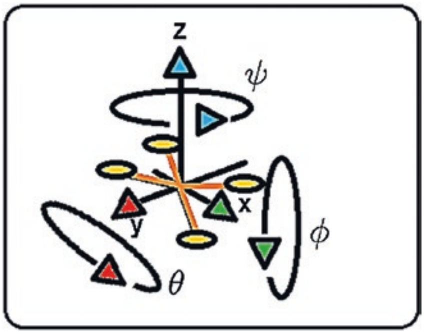

Figure 1-5. *Link between angular and planar motions*

Recommendations

Here are some standard recommendations in order to work with drones:

- Read your local legislation regarding the topics listed here or even additional considerations.
- Verify that your hardware complies with the requirements of said legislations.
- You and your team must use standard protective equipment such as googles or gloves.
- When other people are present during a test, keep in mind that a prototype can cause injuries and it is recommended that you or the person in charge of your laboratory have a license to operate unmanned aerial vehicles.
- Avoid public or private spaces, whether indoors or outdoors, that are not designed for your tests.
- Remember that you are a designer and not necessarily a pilot.

- If you have the necessary permissions, you must prepare the place with walls, protection meshes, or plastic surfaces in case any pieces break or detach from the drone. You should also post warning advisories/ signs to restrict access of non-authorized personnel.
- Perform exhaustive tests without propellers or with the drone anchored before the free flying tests. In order to avoid damaging your motors by testing them without any load, you can replace your propellers with pieces of paper.
- When you have a prototype available, verify that all its components are legal in your specific location and determine if there are functional replacements for the components that are not allowed.

Now it is time to specify the type of drones that we will analyze in the rest of the book.

Types of Drones

According to their displacement, drones can be classified in this way (Figure 1-6):

- **Rotary wings**: They only require propellers to move. In this case, they have vertical takeoff and landing, and are designed for load transport and short- and medium-range applications.
- **Fixed wings**: They require long surfaces in order to move, like most airplanes. In this case, they have applications for horizontal takeoff and landing, and are designed for higher speeds as well as longer flight ranges than rotating wing aircrafts.