Kevin **JENKINS**

THE DRONER'S MANUAL

A Guide to the Responsible Operation of Small Unmanned Aircraft

The Droner's Manual: A Guide to the Responsible Operation of Small Unmanned Aircraft
by Kevin Jenkins

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About the Author

Kevin Jenkins grew up outside of Portland, Oregon, near the airport where he first learned to fly. In 2009, he earned a degree in Aerospace Engineering from Embry-Riddle Aeronautical University in Prescott, Arizona. Kevin spent several years as a test engineer and UAV operator, including deployments to Iraq and Afghanistan. After returning to the United States, he worked on a composites research and development team but was soon drawn back into the field of unmanned aircraft. What began as a hobby in his garage developed into a full-time career, leading to positions with three small companies developing small UAVs for civilian applications. Kevin is deeply passionate about the science of unmanned flight and its potential to shape the world we live in.

Introduction

RC Aircraft, Drones, and UAVs

With the rise of civilian unmanned aviation, several terms have entered the public vocabulary which are, in many cases, falsely considered synonymous. Therefore, it is important to establish, at least within the framework of this book, what each of the terms mean, beginning with the one that is probably most familiar to the layperson.

*A **remote control** or **radio control (RC) aircraft** is an aircraft, regardless of size, that is piloted solely by a person outside of that aircraft via some means of wireless communication.* While some advanced RC systems are capable of transmitting basic information (such as battery voltage or signal strength) back to the pilot, communication is more commonly entirely one-way, with the pilot sending commands to the aircraft. These aircraft are not capable of autonomous flight, and the act of flying an RC aircraft is a finely honed skill. It is important to understand RC flight as many conventions and components from this hobby are used in small civilian unmanned aircraft and their operation.

The use of unmanned aircraft by the military as targets for aerial gunnery practice and as reconnaissance platforms can be traced back to before the first world war. Initially, these aircraft employed rudimentary mechanical autopilots to maintain a single course and altitude but later RC systems were added in order to be able to control them remotely, albeit at short ranges. Eventually, small aircraft were outfitted with basic forms of memory and gyroscopes allowing them to execute simple commands or even be pre-programmed with flight plans while flying beyond the range of RC transmitters. Once launched, these aircraft would mindlessly "drone" along their predetermined flight path (perhaps snapping photos or impersonating an enemy plane along the way) until meeting their end in one form or another. This is the origin of the military ***drone,*** *an aircraft capable of autonomous flight but which cannot be monitored or controlled for most or all of its flight.* Similar principles of operation were later employed in the Nazi V weapons, the first guided ballistic missiles used to bombard England from Germany during WWII.

Drones continued to be used by the military for decades. However, technological advances—specifically increased computing power within a small space, greater data transmission capability, and the advent of the Global Positioning System (GPS)—allowed a similar but distinctly new type of aircraft to take on increasingly greater mission capabilities. Since their introduction into military service around the time of the first Persian Gulf War in the early 1990s, these aircraft have borne several technical acronyms, most notably unmanned air vehicle (UAV), but in the interest of brevity and demilitarization, we'll refer to them as **unmanned aircraft (UA).** *A UA may be piloted remotely, similar to an RC aircraft, or fly autonomously, like a drone, due to* *its distinguishing feature: an onboard flight controller with a two-way data transmission system. This system facilitates communication between the aircraft and a ground station, allowing an external pilot to both monitor the aircraft's status (i.e., position, altitude, heading) and send commands to the aircraft in flight.* Further technical advancements in the last decade have put these UAs within reach of the average person as their components become more widely available. These are the aircraft that will be discussed at length in this guide.

Recently, the term "drone" has become a catch-all for anything resembling the aircraft described above, regardless of actual configuration. This is especially true for multirotor airframes, the existence of which are due to the same recent advancements in technology that allow autonomous flight on a small scale. Moreover, for multiple reasons, multirotors have been many people's point of introduction into the world of RC and autonomous flight. The popularity of this term is partially due to the fact that "UAV" does not exactly roll off the tongue, and also because the imagery of flying robots roaming the skies of their own volition has been seized upon by some in the interest of sensationalism. Nevertheless, many experts and practitioners within the field, who in the past may have considered the term "drone" derogatory, seem to have yielded in their protests and begun to accept the term, at least in casual conversation.

The purpose of this text is to serve as a guide to the construction, operation, and maintenance of these small, electric UAs for both recreational and commercial use. Beginners in this field will be able to use this book as a point of entry, while more experienced operators will find ways to improve their systems and procedures. With UA technology readily available and huge commercial opportunities on the horizon, the objective of this book is to empower new operators with the knowledge required to use this technology safely, responsibly, and effectively.

Abbreviations

AC	alternating current
AGL	above ground level
ATC	air traffic control
BEC	battery eliminator circuit
CG	center of gravity
COA	certificate of waiver or authorization
DC	direct current
EDF	electric ducted fan
ESC	electronic speed controller
FAA	Federal Aviation Administration
FPV	first-person view
GCS	ground control station
GCU	gimbal control unit
GSD	ground sample distance
GPS	Global Positioning System
HUD	heads-up display
IMU	intertial measurement unit
IR	infrared
LiPo	lithium polymer (battery)
LOS	line of sight
MUX	multiplexer
OSD	on-screen display
PDB	power distribution board
PID	proportional-integral-derivative
PMU	power management unit
PPM	pulse-position modulation
PWM	pulse-width modulation
RC	remote control
ROI	region of interest
RPC	remote pilot certificate
RSSI	received signal strength indication
RTH	return to home
RX	receiver
TX	transmitter
UA	unmanned aircraft
UAS	unmanned aircraft system
UAV	unmanned air vehicle
UPS	uninterruptible power supply
VFR	visual flight rules
VLOS	visual line-of-sight
VTOL	vertical takeoff and landing

CHAPTER ONE

Unmanned System Components

Ground Systems

UNMANNED AIRCRAFT SYSTEMS require a collection of ground-based components, which although not as glamorous as airborne components, are just as essential in order to operate safely and effectively. These components are commonly referred to together as a **ground control station (GCS)**. The elements of a GCS include an interface device, telemetry transceiver (combination transmitter/receiver), remote control (RC) transmitter, payload interface, and power sources.

Interface Device

The interface device is a means of displaying data received from the aircraft for monitoring flight status as well as command options for controlling the aircraft. In most cases, the interface device is a laptop, tablet, or mobile device running appropriate mission control software.

This software will usually be accompanied by the software drivers required to utilize the telemetry transceiver unit. The primary function of this software is twofold: to present telemetry data coming from the aircraft to the user and to allow the user to transmit commands to the aircraft. This mission control software may have a secondary purpose of configuring and maintaining the aircraft (for example, accessing system errors, troubleshooting vibration issues, or analyzing power consumption).

/ SELECTING A SYSTEM

When selecting an interface device, the first important consideration is ensuring it will support the mission control software, as not all of these software packages are agnostic to operating on all systems. Furthermore, it is essential to select a system suitable for the mission profile and operating environment in which it will be used. These considerations may lead to selecting a tablet over a traditional laptop. It can also be beneficial to select a device that is suitably ruggedized to meet the operating environment; otherwise, the device may require aftermarket ruggedization, including cases and screen protectors. As it may be necessary to input commands as quickly as possible, a touchscreen can be advantageous but may not completely replace a keyboard, and it may also lead to inadvertent inputs. Finally, in most cases it is preferable to choose an interface device with multiple USB ports, an HDMI port (or other means of externally displaying or expanding the screen imagery), and an SD card port for readily downloading camera images as required.

Telemetry Transceiver (TX/RX)

A transceiver, a combination of a telemetry transmitter and receiver, is a hardware module connected to a standard interface device allowing two-way wireless data transmission between the aircraft and the ground station.

Normally, telemetry transceiver units are specific to or dictated by the mission control software and/or flight controller system being used. The ground unit is typically identical to the air unit on the vehicle, although the external housing or casing of the air unit may be removed in order to reduce weight where prudent and possible.

In order to achieve the best possible signal between the GCS and the aircraft, it is important to provide the ground telemetry unit with the best possible "view" of the aircraft during flight. This is commonly done by elevating the unit (or its antenna), which may also serve to distance the unit from sources of interference. This may be accomplished simply by fixing the unit atop a telescoping pole mount. It is important to note that the practical maximum length of a low-speed USB cable is approximately 9 feet; therefore, it may be necessary to use Ethernet cabling and converters for certain applications.

Remote Control Transmitter (RC TX)

A **remote control transmitter (RC TX)** is the handheld ground component of the RC system and serves as the primary means of controlling the aircraft when it is not in an autonomous flight mode.

Certain mission control software packages have been developed and vetted to such a degree that RC systems are not necessarily required for normal operations. After all, the main benefit of unmanned systems is that they do not normally require the highly technical skill of RC flying. However, an RC transmitter in the hands of a competent pilot and assisted by the stabilization of the flight controller is a highly recommended insurance policy for professional operations and will likely be required by regulatory agencies in the near future. While RC transmitters initially can be intimidating, they provide a more direct means of interfacing with the aircraft and commanding flight and payload functions.

The RC transmitter system will be described in more detail in the "Remote Control Systems" section later in this chapter.

Payload Interface

The payload interface includes any additional equipment required to operate the aircraft's payload. For example, in a first-person view (FPV) video system, this would consist of a monitor and video receiver.

An example payload setup for such an FPV system is covered in detail in the Imaging Sensor Payloads section later in this chapter.

Power Sources

The GCS must have a system for providing reliable power to the electronic systems described above while operating in the field. This may consist of a combination of generators, auto battery and inverter, and spare system batteries.

Due to the dependence on power to continue safe flight operations, the following considerations and options are important in order to allow for redundant power supplies:

- All power supply options require an appropriate length of extension cord(s). One or two heavy-duty reels of 100 feet or more in length is advisable for most circumstances.
- It is recommended to have a LiPo battery charger available in the field.
- Use outlet power whenever possible. This requires appropriate circuit breakers or fuses in order to support the load.
- Small gas generators can provide several hours of power under normal circumstances. However, these generators can struggle under a heavy load, such as when powering multiple devices and/or charging batteries. They can also be dirty and noisy.
- DC-to-AC inverters running off automobile batteries may be used to power short-term, small-scale operations. However, special care should be taken not to fully discharge the battery.
- Ensure that you have spare batteries for ground components. It is often prudent to have at least two fully-charged batteries for each component, including the interface device, RC transmitter, and FPV monitors.
- An uninterruptible power supply (UPS) is a highly recommended backup power system that is capable of immediately providing power for several minutes in the event of main power system failure. This can facilitate a safe landing and shutdown in the event of a generator failure or blown fuse, for example. UPS systems are available in several forms, one of the most useful resembling a bulky surge protector providing multiple outlets. UPS systems will commonly emit a loud audible tone in the event that power input is no longer being received, signaling that flight operations should be safely ended.

Remote Control (RC) Systems

MANY SMALL UNMANNED SYSTEMS rely on components from the hobby world of **remote control (RC) aircraft**, including servos, speed controllers, and the RC system itself. The airborne component of the RC system receives the pilot's command via signals from the RC transmitter and outputs corresponding commands to the flight controller.

Theory of Operation

RC systems consist of a **receiver** (RC RX) installed on board the aircraft and a handheld **transmitter** (RC TX) on the ground, and these systems are the basis for RC flying. Current systems operate at a frequency of approximately 2.4 gigahertz (GHz) and advertise a range of approximately 1 statute mile along line-of-sight (LOS), but this range can be extended using external modules.

The signal from the RC transmitter to the RC receiver contains the RC transmitter's unique binding code (described later in this section) as well as command inputs for a given number of "channels." Each channel corresponds to an attribute of the aircraft, the position or degree of which can be controlled by the pilot. The most common signal protocol for an individual channel is referred to as pulse-width modulation (PWM), which usually ranges from a low value of about 1000 to a high value of approximately 2000 microseconds (μs). These values correspond to the duration of time that the pulse waves are held high (width of the pulse).

Almost all RC transmitters include two control sticks (tiny joysticks) which are arranged side by side and can each be moved in two directions (up and down, and left and right) to control the four main flight control channels (pitch, roll, yaw, and thrust) *(Figure 1-1)*. The remaining channels, if any, can be assigned to switches or knobs on the RC transmitter by the operator based on their needs. In RC flying, these extra channels would usually be assigned to control accessories like flaps or retractable landing gear, but on unmanned aircraft (UA), they can be used to control flight modes, emergency modes, or payload functions.

Each channel usually corresponds to an individual three-wire servo output port on the RC receiver module *(Figure 1-2)*. Each wire in the standard three-wire servo connector is color coded, usually in a series of yellow, red and black; orange, red, and brown; or white, red and black. The yellow, orange, or white wire carries the control signal for the connection, the red wire supplies power, and the black or brown wire provides the ground for the other two wires. In RC flying, the 5 volts (V) of power that the RC receiver requires to operate is usually supplied from an external battery or a **battery eliminator circuit (BEC)** incorporated into an **electronic speed controller**

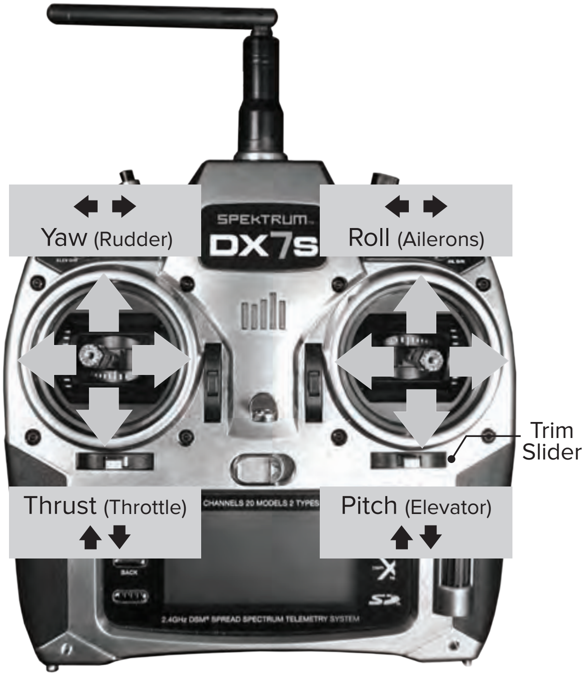

Figure 1-1. RC transmitter, mode 2 configuration.

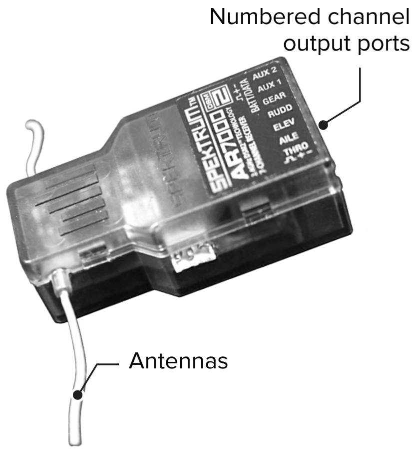

Figure 1-2. RC receiver.

(**ESC**), which is connected to one of the output servo ports of the RC receiver. The RC receiver in turn shares this power with any other component connected to it (servos in most cases). In UA construction, however, the output ports of the RC receiver are connected to corresponding input ports on the flight controller and, in turn, most flight controllers will provide the RC receiver with power over this connection.

Some RC receivers, rather than having individual ports for each channel, have the ability to communicate multiple channels over a single three-wire connector. These systems, such as the Futaba S.BUS system, can reduce wiring clutter considerably by carrying all commands from the RC receiver to the flight controller on a single, three-wire connection.

Configuration

Most programmable RC transmitters will support multiple aircraft models or profiles, allowing a single RC transmitter to be used to control multiple aircraft, a key selling point for hobbyists with a garage full of RC projects. Since these aircraft will obviously have very different configurations, a model or a profile will include the following basic selections.

/ BINDING

A 2.4 GHz RC system allows an operator to "bind" or pair a receiver with a specific RC transmitter. This process usually involves pushing a button on the RC transmitter and/or RC receiver, or inserting a special plug into the receiver while powering on both systems within close proximity. When binding is performed properly, a RC receiver will only respond to command signals that include the unique binding code of the RC transmitter with which it is paired. A similar system is used in automobile keyless entry remotes: most of these remotes operate within the same frequency band but each car responds only to a unique code broadcast on that frequency by its corresponding remote. This binding protocol allows multiple RC aircraft to operate nearby without interfering with each other, unlike older RC systems. It also allows the installation of multiple RC receivers on a single aircraft to create a multiple operator system, which is the recommended configuration for large professional video aircraft with 3D gimbals (described in detail under Imaging Sensor Payloads later in this chapter). Under normal circumstances, the binding procedure only needs to be performed once, but it can be a good idea to install the RC receiver so it is easily accessible within the aircraft in the event that binding must be repeated.

/ REVERSE

Reverse simply changes the output of a given stick, switch, or knob position from high to low PWM, or vice versa. If a control surface is not deflecting in the correct direction, the applicable RC channel may be reversed in order to correct this, making control surface deflections an important part of aircraft setup, which will be discussed later.

/ TRIM

Trim is a means of adjusting the current PWM value output by a certain channel. For example, if the nose of an airplane is constantly dipping down and the pilot must keep pressure on the pitch control stick to keep the aircraft level, then trim could be used to adjust the PWM value output when the pitch stick is in the center or neutral position to one that would maintain level flight. A well-trimmed aircraft flying on a calm day will usually not require any input from the pilot to continue flying straight and level (in the case of a fixed-wing aircraft) or maintain a stable hover (in the case of a rotor-wing aircraft). Most RC transmitters will include trim sliders next to the two main control sticks to adjust trim in flight. However, if a flight controller is being used, then trimming is best performed through that system rather than through the RC transmitter.

/ SUBTRIM

Subtrim performs the same function as trim, but is considered a deeper layer of programming. Whereas trims are usually controlled by knobs on the RC transmitter, subtrims are usually edited within the aircraft transmitter model or profile. Once proper trims are determined through flight testing, these values may be applied to the subtrims. This will allow the trims to be set to zero so that they are less likely to be inadvertently changed or forgotten. From this point, the pilot may still use the trim slider knobs to make small adjustments based on payload and flying conditions. Subtrims may also be used to set control surfaces to the proper neutral positions when it is not possible to achieve this mechanically (which is preferable).

/ END POINT

The end point adjustment allows the operator to change the range of PWM values that are allowed on a given channel. For example, this may be used to limit the range of gimbal tilt. Some servos may be capable of providing more range of motion than the attached linkage or control surface, putting undue stress on the servo. In this case, limiting the end point of the servo can be used to prevent the servo from exceeding its safe range of motion.

/ MIXING

Mixing allows the positions of two sticks, switches, or knobs to control the output of a single channel. Traditionally, this was important in RC fixed-wing flight with flaps and in helicopter flight. In UA flight, mixing, along with end point configuration, will prove important in controlling the aircraft while in manual flight modes, as will be described further in Chapter 2 and Chapter 5.

/ FAILSAFE

Some high-end RC systems will include a **failsafe system**, which, in general, is *a means of protecting or attempting to save the aircraft in the event of an emergency or adverse event.* In the case of an RC system, a failsafe will cause the RC receiver to output preprogrammed channel values in the event that the signal from the RC transmitter is lost for a specific period of time. This may be due to the aircraft flying out of range or the RC transmitter losing power. Ideally, the failsafe channel settings would be those providing the greatest likelihood of a safe termination of the flight assuming that the pilot cannot regain control. For example, the best failsafe outputs for a fixed-wing aircraft would most likely involve cutting the throttle to idle and pitching for a gentle glide with wings level. These failsafe outputs must be predetermined by the operator and are usually saved when the RC receiver and RC transmitter bind to each other. While this can be a very useful feature for RC flying, it is important to configure an RC failsafe system so as not to interfere with the signal provided by the flight controller, which is usually much more advanced.

Selecting a System

The first feature to take note of when selecting an RC system is the number of channels. The practical minimum number of channels required for UA operations is six, four of which are reserved for the main flight controls, leaving at least two channels to control the flight mode and an accessory such as a camera trigger or gimbal tilt. Three-position switches are another important feature to look for as they offer more convenient control of UA flight modes.

The two main control sticks on RC transmitters are usually spring-loaded in the pitch, roll, and yaw axes so the sticks will return to center when released. The channel intended to control the throttle, usually one of the “up and down” axes, is often left without this feature, especially for fixed-wing aircraft, so the throttle can be set and maintained. RC transmitters with the throttle on the right are referred to as Mode 1 or Mode 3, and those with the throttle on the left are referred to as Mode 2 or Mode 4 *(Figure 1-3)*.

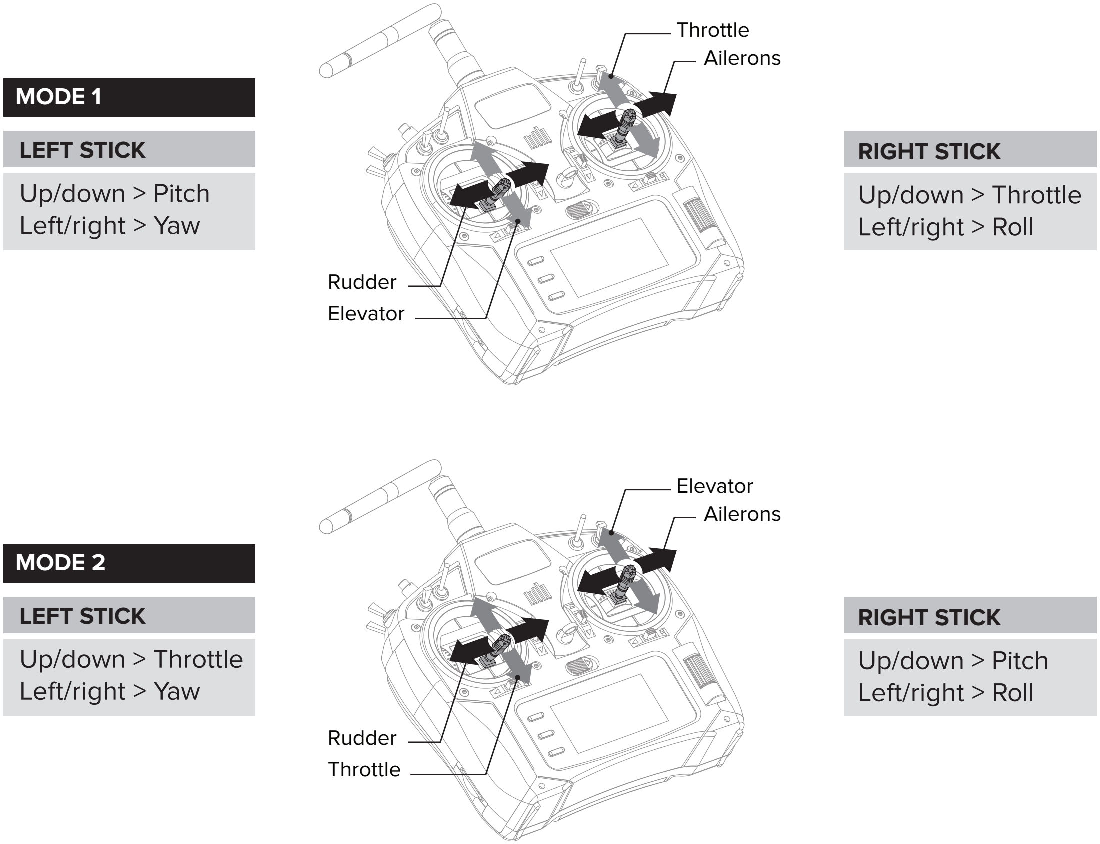

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Figure 1-3. RC transmitter modes and channel assignments.

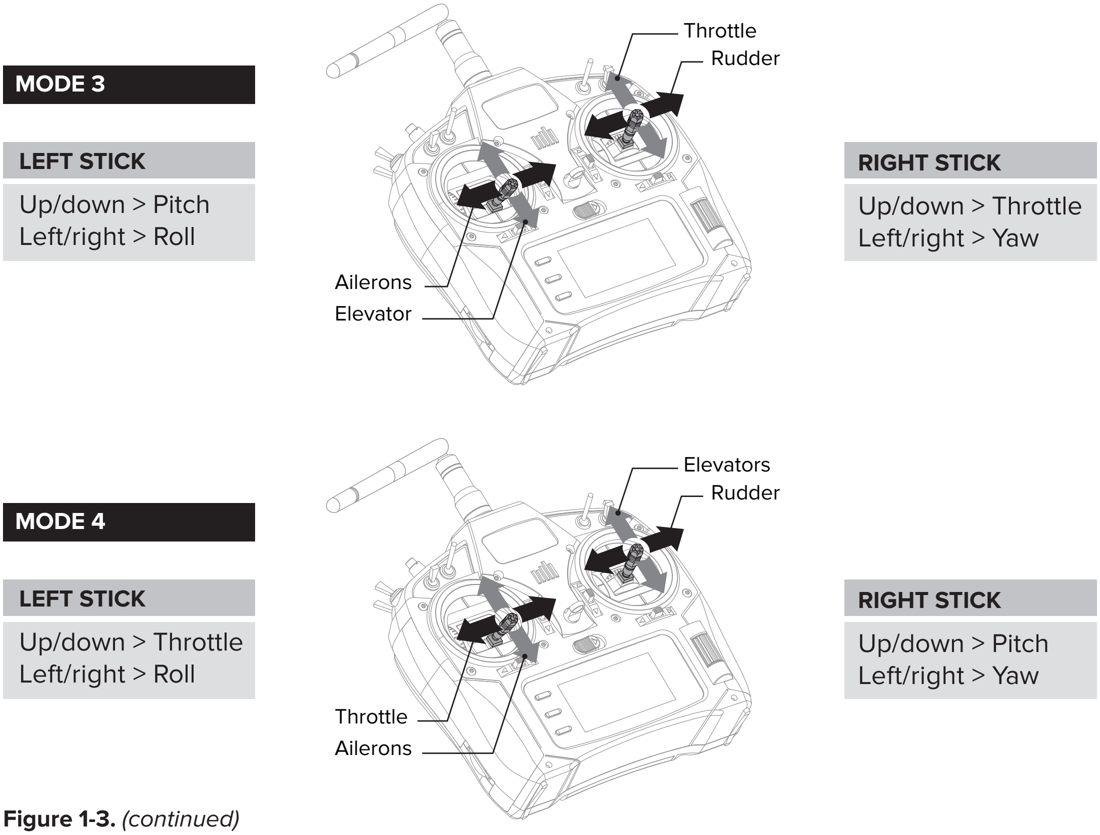

Figure 1-3. *(continued)*

Some RC transmitters include digital displays and inputs for configuring the system directly, which is much more convenient than having to connect the system to a laptop. Many of these RC transmitters also allow multiple aircraft profiles or models to be saved, allowing a single RC transmitter to be used to control multiple aircraft (but not at the same time). Some advanced RC systems will include failsafe and basic telemetry features; however, these are both usually disabled in favor of the systems offered by the flight controller.

An RC system with all of these features may turn out to be one of the more costly components within the overall UA system. However, the fact that it contributes directly to the safe flight of the aircraft, as well as the fact that the RC transmitter will remain intact even if the aircraft is completely lost, makes the RC system a good investment.

Some flight controllers allow video game controllers connected to a laptop to control the aircraft over the telemetry link in a similar fashion. While this can be a good idea in some cases, a better option may be an RC transmitter with a mounted video monitor and/or mobile device, which makes a great, self-contained, mobile means of controlling and monitoring the aircraft in the field.

most quadcopters will be uncontrollable if a motor fails, while an octocopter may be capable of flying stably. But regardless of the multicopter configuration, in the case of a motor failure the aircraft should still land as soon as possible to avoid overstressing the flight controller and the remaining motors.

Selecting a Multicopter

When selecting a multicopter airframe, it is important to consider the following:

- *Number of Arms/Motors*—As a general rule, carrying any payload larger than a small camera like a GoPro demands at least six motors, both for lifting capacity and for greater redundancy in the event of a motor failure. However, these airframes tend to be less compact and portable. This makes coaxial motor arrangements especially appealing, with the added benefit of the reduced weight of fewer arms. One option to consider, especially if entertaining the possibility of expanding to larger payloads, is an airframe that allows for either single or coaxial mounting of motors. Such an airframe would allow, for example, a multicopter to begin flying as a quadcopter and then be upgraded to an octocopter at a later point, if necessary.
- *Motor and Propeller Compatibility*—It is important to verify that the motors selected can be mounted to the airframe and that the propeller size is appropriate (refer to the "Propulsion Systems" section later in this chapter).
- *Flight Controller, Battery, and Payload Mounting*—It is best to start planning the mounting of critical components before purchasing an airframe. Some airframes incorporate vibration-isolated payload rails and battery trays, which make the mounting of certain but not all types of payloads and batteries especially convenient. There is also the question of where to mount the flight controller, which would ideally be mounted where it is easily accessible. However, suitable locations for mounting the flight controller are often limited, especially on small aircraft, which usually require that the battery be mounted to the upper plate.
- *Retractable Landing Gear*—This feature might be important depending on the intended use for the multicopter. For example, when selecting an airframe for a professional cinematic video platform, retractable landing gear, or the ability to add them, can be essential for panning shots that might be blocked by fixed landing gear.

/ AIRPLANE THEORY

Although commonly known as airplanes, these are also referred to in technical parlance as **fixed-wing aircraft** because they generally are built around a single, non-rotating main wing. There are many variations, but a fixed-wing aircraft's most

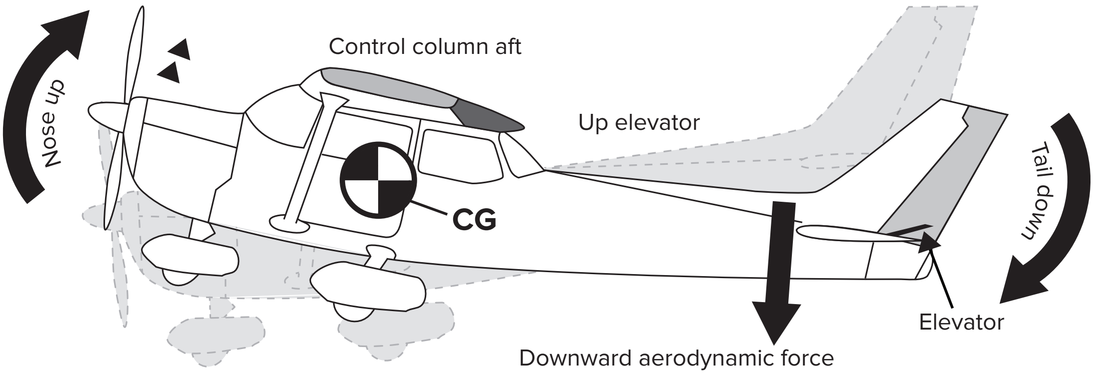

Figure 1-12. The location and operation of the elevator.

Elevators—These control surfaces on the horizontal stabilizer may be deflected downward in order to produce more lift on that aerodynamic surface, rotating the tail upward and the nose downward. Deflecting the elevators upward will result in negative lift or a downforce on the horizontal tail, pointing the nose upward *(Figure 1-12)*. This control surface is responsible for changes in pitch, rotating the aircraft about the lateral axis.

Rudder—Similarly, the control surface referred to as the rudder on the vertical stabilizer may be deflected either left or right in order to generate a side force in the opposite direction, thus yawing the aircraft *(Figure 1-13)*. This force generated by the rudder rotates the aircraft about the vertical axis. The rudder is primarily used to coordinate the aircraft when banking or turning.

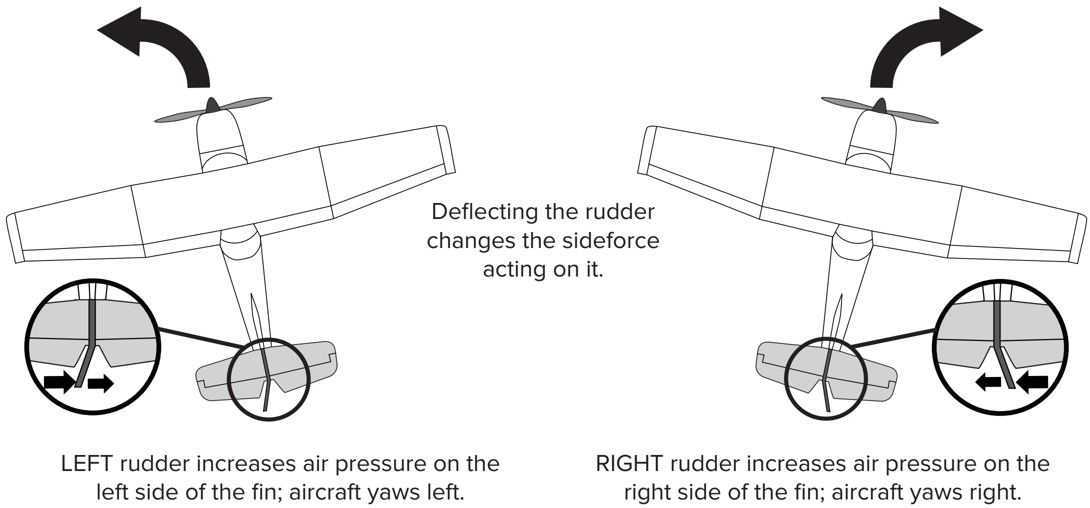

Figure 1-13. The location and operation of the rudder.

Ailerons—A pair of control surfaces called ailerons located near the wing tips deflect oppositely from one another to produce changes in roll (rotation of the aircraft about the longitudinal axis). For example, if a right roll is commanded, the right aileron will deflect upward, decreasing lift or creating a downward force on that wing tip, forcing it to lower. At the same time, the left aileron will lower, producing more lift on that wing tip and raising it up to produce the desired right roll *(Figure 1-14)*.

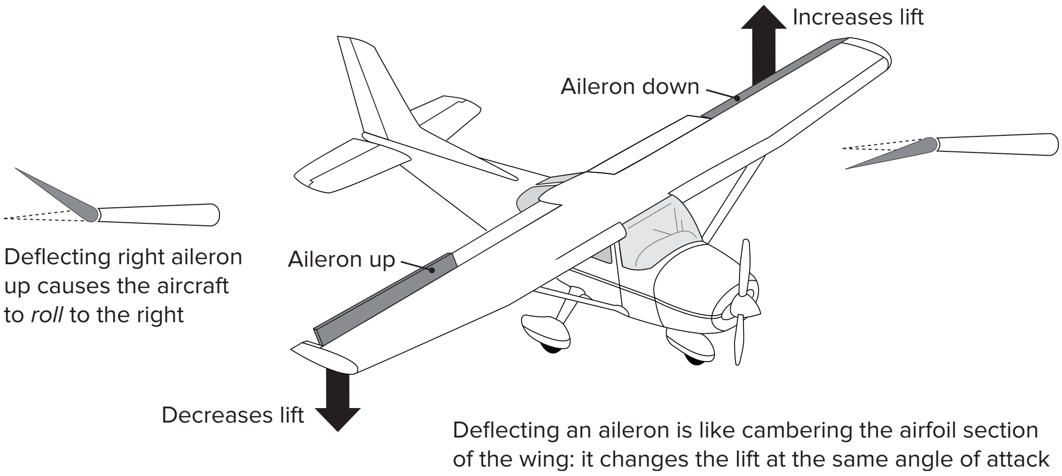

Figure 1-14. The location and operation of the ailerons.

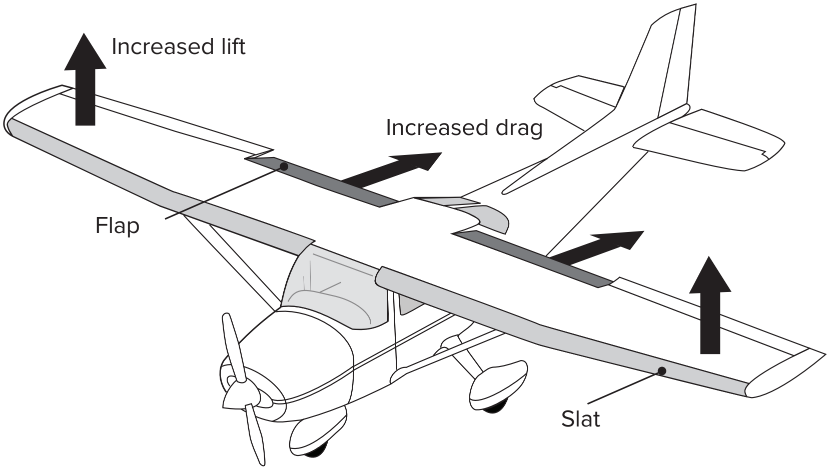

Figure 1-15. The location and function of flaps.

Kevin **JENKINS**

THE DRONER'S MANUAL

A Guide to the Responsible Operation of Small Unmanned Aircraft

The incredible advancements in the field of unmanned aircraft within the last decade have made it possible for almost anyone to build their own UAV, opening up exciting business opportunities in numerous fields ranging from video production to agriculture. However, many beginners and even more experienced hobbyists find this daunting, as reliable information for construction and programming of unmanned aircraft is often scattered across various sources, and the industry lacks established standards for the safe and efficient operation of small unmanned aircraft.

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