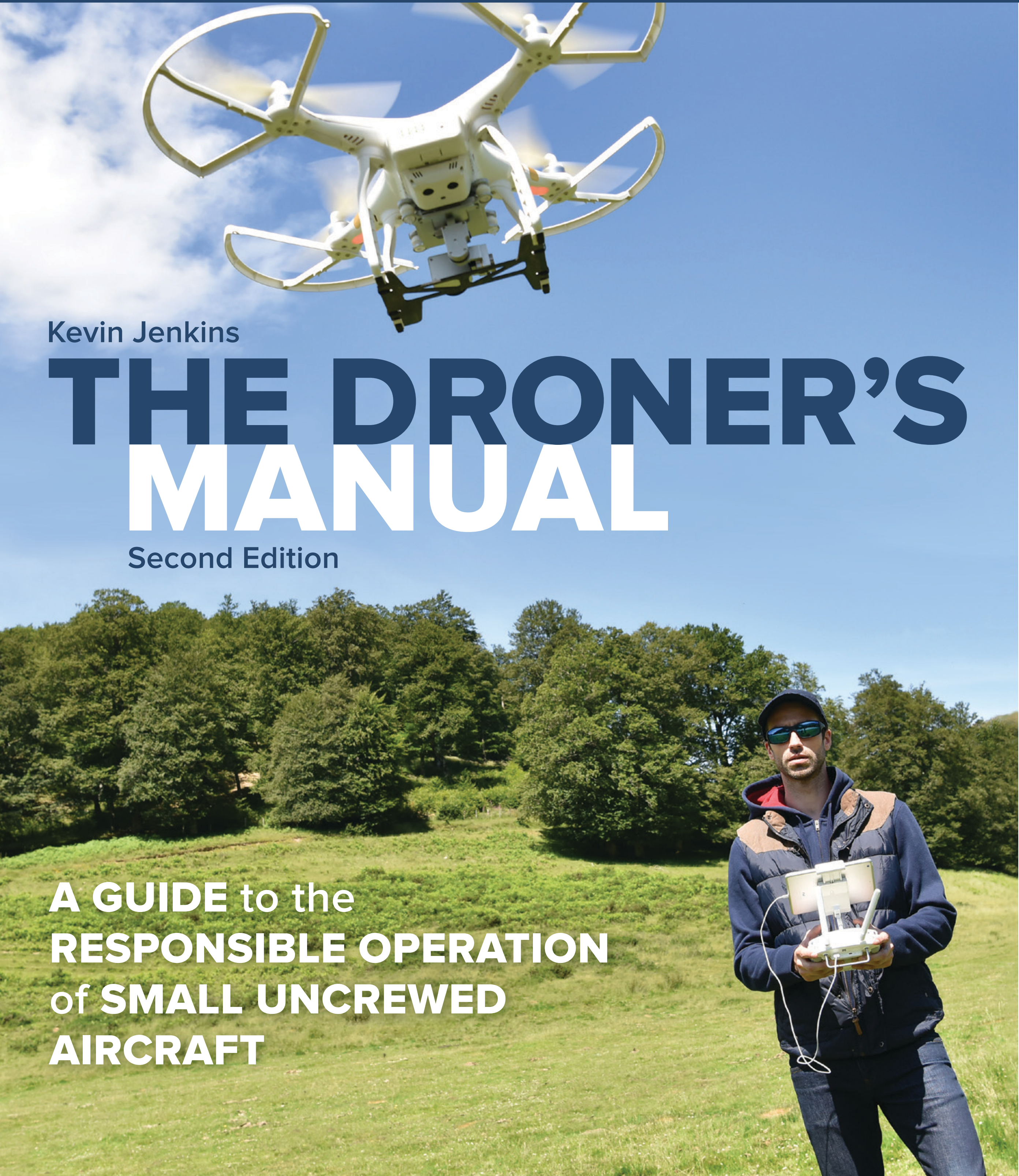

Kevin Jenkins

THE DRONER'S MANUAL

Second Edition

A GUIDE to the **RESPONSIBLE OPERATION** of **SMALL UNCREWED AIRCRAFT**

Kevin **JENKINS**

THE DRONER'S MANUAL

A Guide to the Responsible Operation of Small Uncrewed Aircraft

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The Droner's Manual: A Guide to the Responsible Operation of Uncrewed Aircraft
Second Edition
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 (uncrewed air vehicle) operator, including deployments to Iraq and Afghanistan. After returning to the United States, he was soon drawn back into the field of uncrewed aircraft. What began as a hobby in his garage developed into a full-time career, working with several companies developing small UAVs for civilian applications. Kevin is deeply passionate about the science of uncrewed flight and its potential to shape the world we live in.

Introduction

RC Aircraft, Drones, and UAVs

With the rise of civilian uncrewed 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 uncrewed aircraft and their operation.

The use of uncrewed 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 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 World War II.

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 uncrewed air vehicle (UAV), but in the interest of brevity and demilitarization, we'll refer to them as **uncrewed 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 (e.g., 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 smaller, cheaper, and therefore, generally 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.

Note: The FAA and aviation community are in the process of transitioning from use of the terms *manned* and *unmanned* to *crewed* and *uncrewed*. Many FAA regulations and documents still use the former, but you can expect to see increasing use of *crewed* and *uncrewed* over time. The newer terms will be used throughout this book.

Ground Systems

UNCREWED AIRCRAFT SYSTEMS require a collection of ground-based components, which although not as glamorous as airborne components, are just as essential 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 designed to interface with the aircraft or, more specifically, the flight controller.

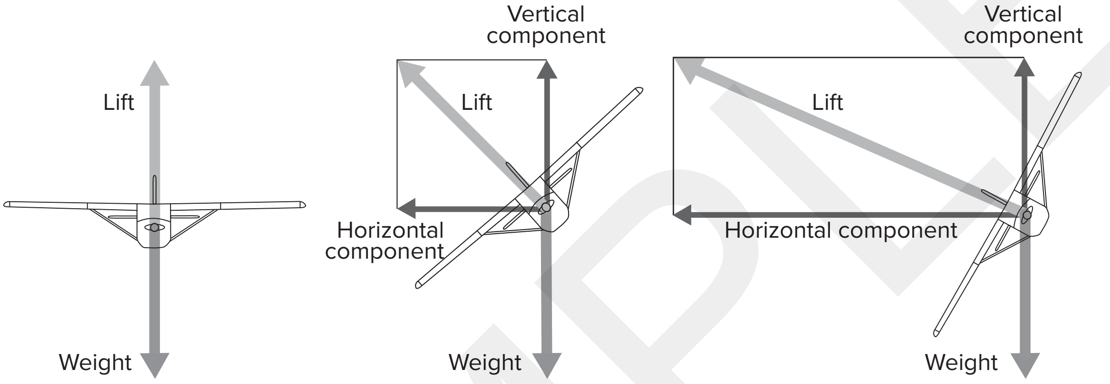
This software will usually be accompanied by the software drivers required to utilize the telemetry transceiver unit. The primary function of this software is twofold: to present telemetry data coming from the aircraft to the user and to allow the user to transmit commands to the aircraft. This mission 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.

Coordination of Turns

A fixed-wing aircraft turns by banking, meaning it rolls its wing tip down in the direction of the turn. This redirects the lift vector, which is always perpendicular to the wingspan, in the direction of the intended turn and pulls the aircraft into a circular turn. However, because the magnitude of the lift vector is constant for a given airspeed, banking the aircraft reduces the vertical (opposing gravity) component of the lift. Thus, an aircraft in a banking turn and at a constant throttle setting will require the generation of more lift, achieved by increasing pitch, to maintain a constant altitude *(Figure 1-17)*.



(a) Straight-and-level flight **(b) Shallow bank** **(c) Steep bank**

Figure 1-17. Lift vector in a banking turn: To maintain a constant altitude as the bank angle increases, the total lift vector must increase to keep the vertical component of lift equal to the weight.

Wing and Tail Variations

Fixed-wing aircraft come in a wide range of configurations, mainly distinguished by variations in the wings *(Figure 1-18)* and tail *(Figure 1-19)*.

- *Straight Wing*—The simplest, most traditional wing variation is a straight wing with a generally rectangular profile *(Figure 1-18A–D)*. Straight wings, especially with greater wingspans (the distance between wing tips), provide greater lift, even at lower speeds, and are best used on vehicles carrying greater payloads or intended for high endurance. Straight wings with a consistent airfoil profile across their span are sometimes referred to as “Hershey Bar wings” in the RC world.
- *Sweptback Wings*—Wings with the swept leading edge wing profile generally have reduced wingspans when compared to straight wings *(Figure 1-18E)*. This reduces drag and favors high-speed flight but will reduce low-speed performance.
- *Delta Wing*—Delta wings also have a swept leading edge while combining the surface of the wing and the fuselage, making the entire

aircraft a single lifting body *(Figure 1-18F)*. These aircraft usually forgo vertical and horizontal tails in favor of two control surfaces on the wings acting as both ailerons and elevators (commonly referred to as elevons). This configuration does require the two-servo aileron configuration and elevon mixing but generally makes the aircraft mechanically simpler, with fewer points of failure. Delta-wing aircraft are usually fairly robust, having a single continuous body, and they can provide ample internal space depending on the model. However, in most cases these aircraft have rear-mounted or pusher propellers (instead of the conventional idea of an airplane with a front-mounted or tractor propeller), which can make them difficult or even dangerous to hand launch. If these aircraft do not incorporate a vertical tail, as many do not, they may also suffer from diminished yaw control.

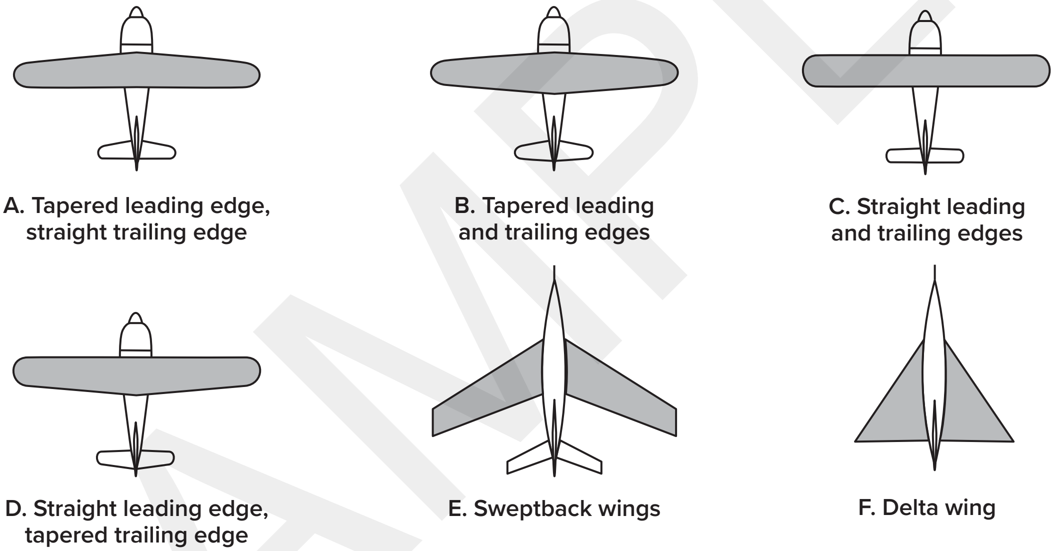


Figure 1-18. Airplane wing configurations.

- *Standard Tail*—The standard and most common tail configuration is the fuselage-mounted tail, with the horizontal tail below the vertical tail and intersecting at the fuselage *(Figure 1-19A)*. This type of empennage configuration is common among RC airplanes, as it tends to provide simple and strong construction along with straightforward control.
- *T-Tail*—A T-tail can be described as a horizontal tail mounted on top of a vertical tail *(Figure 1-19B)*. While this configuration can remove the horizontal tail from the turbulent prop wash created by a propeller, T-tails can be fragile and difficult to integrate mechanically.

INERTIAL MEASUREMENT UNIT (IMU)

The **inertial measurement unit (IMU)** is used to measure the aircraft's orientation with regard to the three axes as well as the aircraft's translational and rotational movement about these axes (*Figure 1-38*). This data is used by the flight controller to stabilize the aircraft and maintain coordination during maneuvers. The IMU information can also be directly conveyed to the user through telemetry and displayed as the artificial horizon or attitude indicator on the ground control station and in the video signal with on-screen display (OSD) overlay. IMUs are some sometimes referred to as accelerometers or gyros, while, in reality, an IMU is made up of a series of accelerometers and gyroscopes, one each devoted to the three axes of motion. If small, relatively cheap flight controllers have a weak point, it is the internal IMU. These sensors can be negatively impacted by extreme temperatures and vibrations, which, in turn, can have disastrous impacts on flight. While internal IMUs have improved over the years due to environmental calibrations and internal isolation, supplemental, multiple, or replacement (read more expensive) IMU use is not uncommon to improve reliability where it is critical. Whether the IMU is incorporated internally into the flight controller or is a separate external unit, it is important that it is securely mounted in the proper orientation relative to the front of the aircraft, while also being isolated against vibrations. IMUs can be adversely affected by crashes or rough landings, and thus regular checks of IMU fidelity, and calibrations, if necessary, are a prudent part of preflight (covered in detail in Chapter 6).

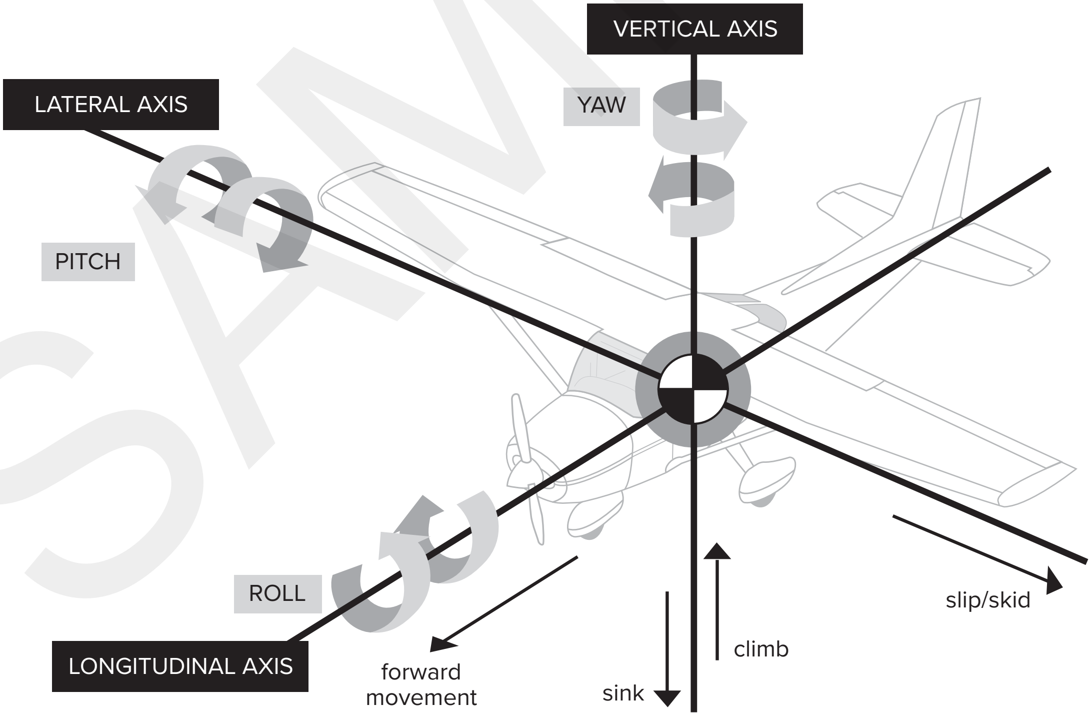


Figure 1-38. Aircraft translation and rotation measured by the IMU.

POWER MANAGEMENT UNIT (PMU)

The power management unit (PMU) performs a basic function as part of the electrical system by providing regulated power to the flight controller. Some PMUs can also be considered sensors in that they provide battery voltage and current draw information to the flight controller. This information can in turn be transmitted to the ground control station via the telemetry link to be monitored by the operator as well as used by the flight controller to trigger failsafe contingencies at a predetermined low battery voltage. *It is important to understand the voltage limits of the PMU, which is usually expressed in terms of LiPo battery cell count, before connecting to power.*

PITOT TUBE/AIRSPEED SENSOR

For multicopters and helicopters, the GPS can be used to determine the aircraft speed over the ground (ground speed). However, flight controllers on airplanes are heavily dependent on accurate measurements of the aircraft's speed through the air (airspeed) to avoid stall, especially during landing. This is accomplished through the use of a pitot tube, which uses differences in total and static air pressure to determine airspeed *(Figure 1-39)*. A pitot tube should be mounted so that the tube is pointed directly forward relative to the front of the aircraft, commonly mounted to the leading edge of the wing or the side of the fuselage but removed from the turbulent air created behind propellers *(Figure 1-40)*. The pitot tube can be susceptible to blockage from debris and should be checked prior to each flight. Airspeed sensors can also be drastically affected by temperature variations and usually require frequent calibration to maintain accuracy.

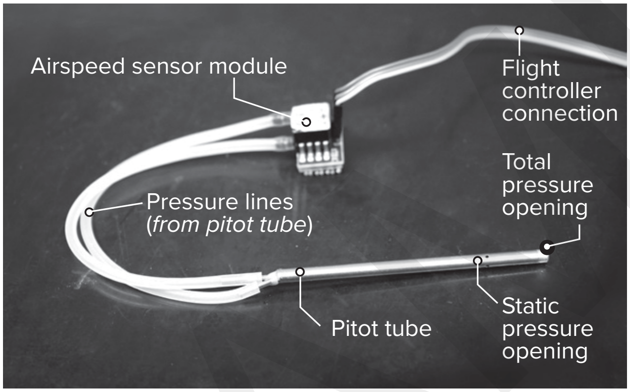


Figure 1-39. Airspeed sensor and pitot tube.

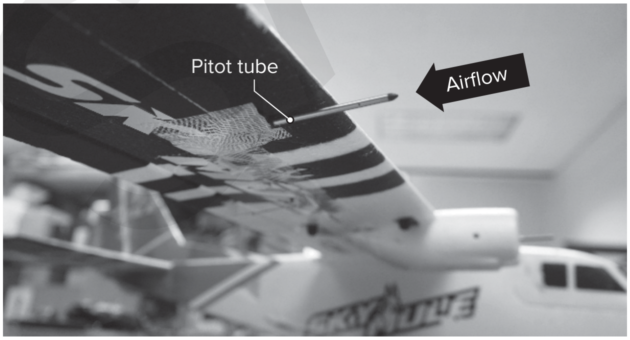


Figure 1-40. Pitot tube mounting.

RANGE SENSOR

A range sensor, such as a sonar or laser module, can be used on rotor-wing aircraft to accurately determine the aircraft's height above the ground or a structure. This information may also be used to control the descent rate during landing or kill the engines when on the ground. In a fixed-wing aircraft, data from such a sensor can be used during landing to adjust the determined by the throttle input coming from the pilot via the flight controller, which will in turn rotate the motor bell to which the propeller is mounted.

Because brushless motors really have only one moving part, and very little contact occurs between parts, brushless motors tend to be less likely to wear out than their predecessors. The most likely point of failure is usually the bearing, which is the only interface between moving parts and is held in place with a small C-clip on the underside of the motor.

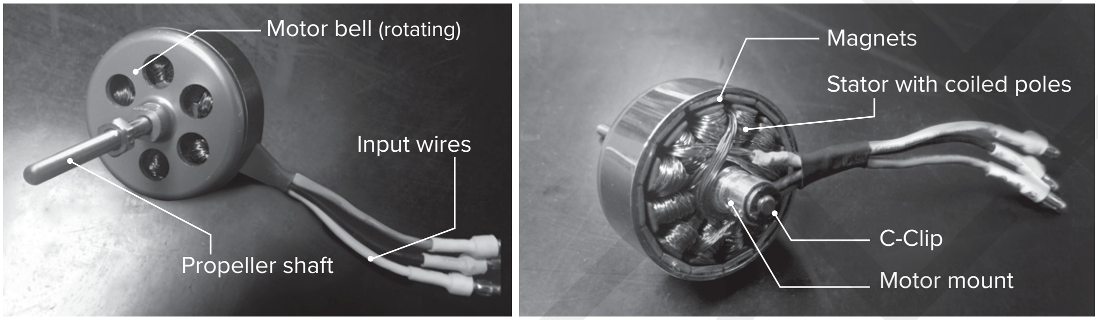


Figure 1-47. Components of an outrunner brushless motor.

Brushless Motor Designations

Unfortunately, no standard currently exists among brushless motor manufacturers for assigning numerical designations to motors. Therefore, different companies will number their motor models using very different conventions. The most common information found in motor numbers denotes the physical size of the motor. Usually, a four-digit number sequence will contain the circumference of the motor (first two digits) and the length or height of the motor (last two digits), both given in millimeters. However, some motor manufacturers may include the diameter of the stator rather than the outer diameter of the motor. Motor designations may also include the number of poles or the number of wire windings within each stator coil. Refer to the manufacturer's documentation or specifications to determine what motor designation numbering system is used for a specific motor.

Important Motor Information

The most important motor information to consider is usually not contained within manufacturer designations but is commonly advertised. The first important consideration describes the maximum speed at which a motor will spin, which is a function of the voltage of the battery. Therefore, brushless motors will be assigned a kilovolt (kV) term, which is a measure of RPM × 1000 per volt. In general, higher kV motors will spin a propeller faster but rarely provide much torque. Therefore, they are not capable of spinning larger, heavier propellers and are better suited for smaller aircraft. Lower kV motors, on the other hand, are capable of spinning larger propellers but at lower speeds and tend to be more efficient. These low-kV motors are sometimes referred to

Components

Camera—This configuration frequently uses so-called **board cameras**, essentially tiny spy cameras that are usually mounted on small circuit boards. Usually having no internal recording capability, these cameras are typically light and compact, allowing them to be easily mounted onto the aircraft. While generally inexpensive, the quality of these cameras is usually directly proportional to their price.

Video Transmitter—Some board cameras are now available with integrated video transmitters and permanently mounted antennas. This may greatly simplify the integration of FPV pilot cams. However, separate video transmitters should be considered in cases where collocating the camera and the video transmitter would be prevented by the structure of the aircraft or due to signal interference. External video transmitters can also provide more options as far as channels and output power.

On-Screen Display (OSD)—This payload configuration is greatly improved by the use of an **on-screen display (OSD)** module, a component installed on board the aircraft that visually overlays data taken from the flight controller telemetry onto the video feed (*Figure 1-50*). When viewed on the monitor, this data appears similar to a heads-up display (HUD) system used on military aircraft, providing the pilot with greater awareness of the aircraft's status.

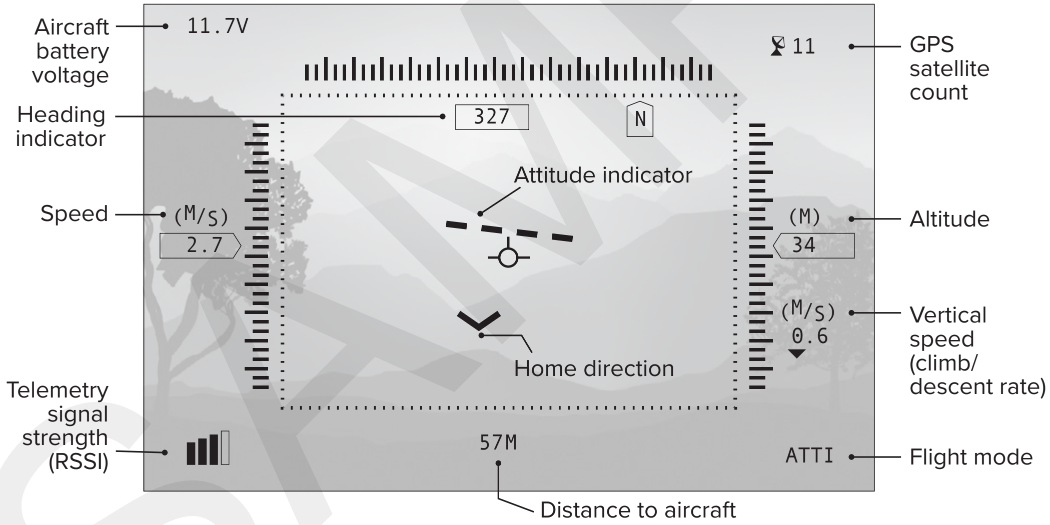


Figure 1-50. Common on-screen display symbology.

Flight testing is essential if you are building your own custom aircraft, but it can also be a great way to familiarize yourself with and validate an off-the-shelf aircraft. Flight testing is also necessary after significantly changing the configuration of an aircraft—for example, after adding a new payload. This flight testing process should include but not be limited to the following considerations and steps.

Multicopter Flight Testing

Selecting a Suitable Test Site

Dry soccer fields, especially with artificial turf, may be ideal for use as test sites. For safety reasons, avoid flying near people and obstacles during the flight testing process. Also attempt to conduct flight testing in still air. Early mornings can be suitable for both.

Safety

Begin by conducting a thorough preflight check with special emphasis on construction, GPS/compass performance, and RC response. Then move to and maintain a safe distance; 10 meters from the aircraft is usually acceptable. Also remember to place the aircraft with its front or nose pointed away from you for takeoffs during flight testing. This will make the aircraft easier to control if you must intervene quickly. It is also a good idea to configure a kill switch on the RC transmitter to allow the aircraft's motors to be stopped in an emergency. This will cause the aircraft to fall and will likely result in significant damage, but may prevent a fly-away or personal injury.

Arming and Tip Over/Control Checks

By this point, motor set up, calibration, and bench testing should be completed, verifying that the flight controller, ESCs, and motors have been correctly configured and reducing the likelihood that the aircraft will become uncontrollable. The ultimate test, however, is an arming and tip over check.

Begin by arming the aircraft in a stabilized flight mode and observe that all propellers spin up to idle without any indication that the aircraft is becoming unstable on the ground. If the aircraft has been configured incorrectly, it will likely begin to tip over at this point. If the aircraft appears stable, it may be possible to check pitch and roll controls without fully lifting off the ground. If these channels have been incorrectly assigned or reversed, the consequences will be much more severe after the aircraft is in the air. Apply small to medium pitch and roll changes and observe the airframe tilt slightly in the expected direction. If you observe an unexpected result, then disarm

LANDING

A landing waypoint normally defines the intended **touchdown point** of the aircraft. The **landing direction** may be defined either as an option within the waypoint or by the direction of the last leg before the landing waypoint. This vector should be aligned with the direction of the runway or landing area and also directed into the wind if possible. The user will usually need to define a **final approach glide slope**, which is the angle of the aircraft's descent path relative to the ground. Some flight controllers will allow a glide slope to be defined directly, whereas others will derive it from the distance between the landing waypoint and the previous waypoint (i.e., approach waypoint) as well as the altitude of that waypoint.

For example, if the two waypoints are 200 meters apart, and the altitude of the approach waypoint is 20 meters, glide slope and glideslope angle can be calculated as follows (*Figure 6-1*):

1. Determine glide slope as a percentage—rise over run:

$$\frac{\text{20 meters}}{\text{200 meters}} = \text{0.1 or 10\% glide slope}$$

or

2. Determine glideslope angle using inverse tangent:

$$\tan^{-1}\frac{\text{20 meters}}{\text{200 meters}} = \text{5.7 degrees}$$

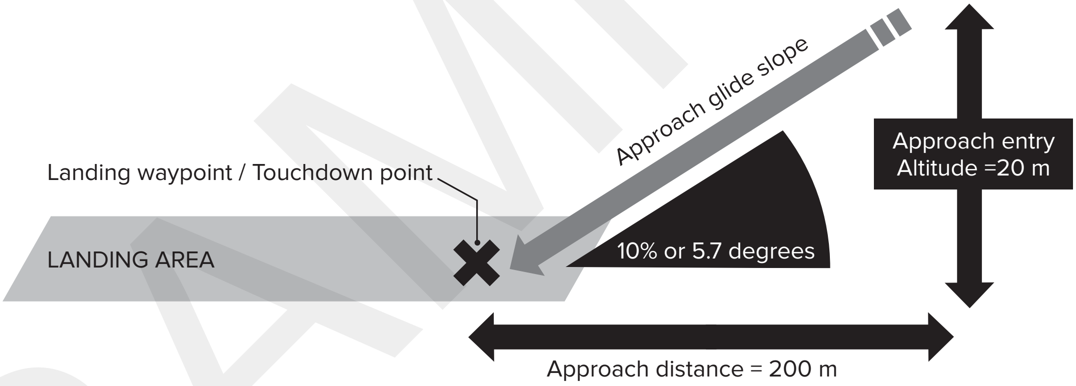


Figure 6-1. Glide slope calculation example.

Most RC airplanes will have no problem achieving a 3–5 degree glide slope angle, or approximately 5–9% glide slope. A steeper glide slope will shorten the total landing distance but will incur more stress on the airframe, because more airspeed is translated to the vertical direction and the airplane will hit the ground harder. Airplanes with higher aspect ratios (long, skinny wings, not surprisingly like a glider) tend to "float," even with power off and especially in **ground effect**, and they may require flaps to make a steeper glide slope without risking stall. One of the best practices for setting up an autonomous landing is to add a descending loiter to the end of the mission, which can be especially useful when operating in areas where terrain restricts flight at lower altitudes. This process will be described further at the end of this section.

THE DRONER'S MANUAL

Kevin Jenkins | Second Edition

A Guide to the Responsible Operation of Small Uncrewed Aircraft

The incredible advancements in the field of uncrewed aircraft over the last decade have made it possible for almost anyone to build and operate their own drone, creating exciting business opportunities in numerous fields ranging from video production to agriculture. However, many beginners and even more experienced hobbyists find these ventures daunting because reliable information for construction and programming of uncrewed aircraft is often scattered across various sources, and the industry is still establishing standards for safe and efficient operation of UAVs.

The Droner's Manual compiles the most important and relevant knowledge into a guide for both beginner and experienced operators. With his expertise as a UAV operator for government, industry, and hobby uses, author Kevin Jenkins offers step-by-step guidance to build, program, test, and fly multicopter, fixed-wing, and hybrid airframe aircraft for a variety of purposes. This comprehensive manual covers uncrewed system components, aircraft set up, flight controller fundamentals and failsafe features, the flight-testing process, and flight operations.

The second edition incorporates regulation exceptions for recreational flying and introduces The Recreational UAS Safety Test (TRUST), as well as offering new and updated information on smart batteries, solving GPS complications, drone photography, remote identification requirements, and the concepts of PID tuning. More than 70 illustrations provide detailed schematics and diagrams for the construction of complex systems such as first-person view (FPV) and imaging payloads.

You will fly with confidence applying this book's direction on mission planning, checklists, and safe flight operations. Whether you use it to build your first unmanned aircraft or as a handy reference in the field, *The Droner's Manual* is essential for drone builders, pilots, and operators.

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