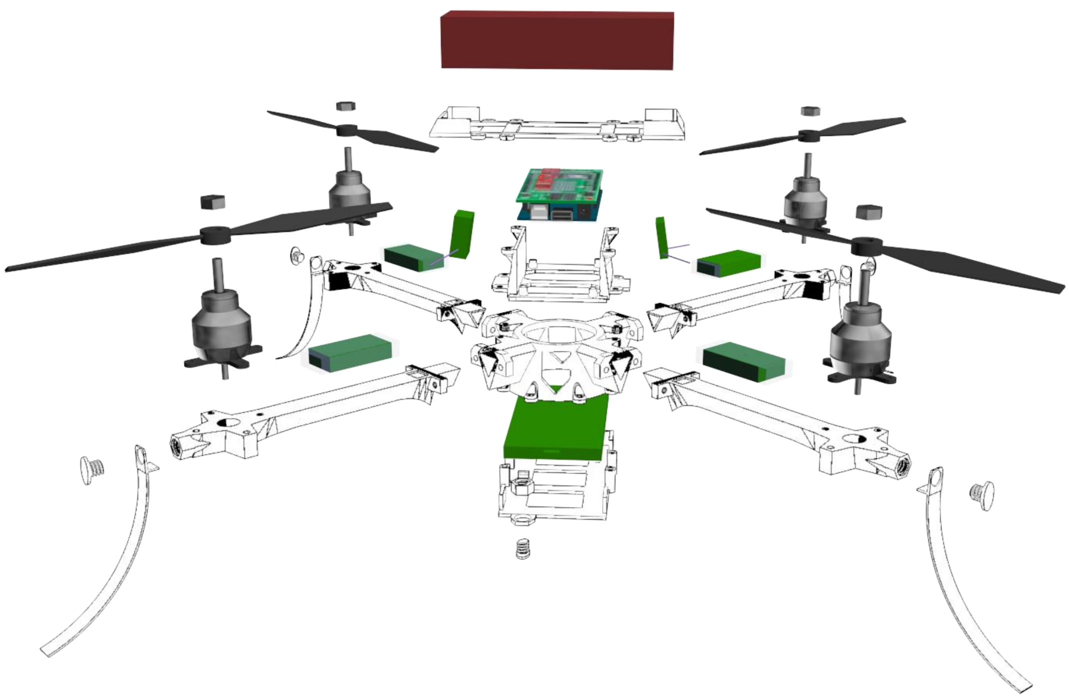
Anatomy of a Drone: A Dissection into Design and Components



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So, you are interested in building a drone, but you have very little or no experience? Fret not, and welcome to this deconstruction of a drone's "anatomy". We're going to be putting a typical quadcopter "under the knife" and discuss each and every component in a beginner friendly manner. Along with this text, there will be supplementary videos and listing to locate these parts. After reading this, hopefully, you will have collected the confidence, and knowledge to assemble your very own drone! Now, let's get started!

Frame

The frame is perhaps the most basic of all of the drone's anatomy, and it helps to give name to what type of drone this document will focus on as well. This document will mostly refer to quadcopters, "quad", meaning "four", just like in the word "quadrilateral". Just as there are four sides like in the polygon, the frame is fitted with four arms. The number of arms will equate to the number of further components such as motors, ESCs, et cetera. The remainder of the hub of the frame is used to house and protect other sensitive and delicate components in the center of the drone. Obviously, in the event of falls and crashes, we want the precious electrical parts to stay safe and avoid breaking, as such, an appropriate frame should be selected. Frames size is determined by the longest motor-to-motor distance, so typically a diagonal distance. While it is true a larger frame will provide more housing to fit more components and perhaps offer more protection, remember, that it will tend to be more cumbersome to reach around and inspect and get to components fitted deeply within the hub. Not to mention, weight is always an issue with drone decisions and design, as the heavier the drone is, the more thrust is required to lift it and achieve flight, so the best size is one you are comfortable with to fit and access components, and not leaning towards too much weight.

What is the best material for frames? While beginning to garner interest, one should not force themselves to access the most expensive of materials, just enough to gather interest and gain experience, many people choose to 3D print their frames, however, there is a strong caveat behind such. There exists a likely chance that the infill in your print is not a large percentage, yielding gaps within the solid. So, this will cause issues in being stable, and will be weaker. Copious people choose to go with a carbon fiber frame, as it offers strength, durability, while maintaining a small weight. Contrary to what it sounds, these types of frames are quite commonplace on online shopping, and not nearly as steeply priced as one would believe.

While not necessary, on the frame, one could attach leg mountings, akin to that of an airplane landing gear. It can be assistive in breaking falls and having the quadcopter to be at a stable standstill prior to taking off. However, as said, it is not imperative in include this in your drone, take it as merely a suggestion.

ESC

What is an ESC? It is an abbreviation for "Electronic Speed Controller", it controls the speed which the motors run at; for the sake of a mechanical analogy, it is akin to the gearbox of an automobile, which dictates the speed at which the wheels rotate. The ESC is not an aloof component, it is cooperative with the Flight Controller (FC) and the motors. The FC sends out signals into the ESC, which then regulates the voltage evenly across the four motors. Most ESCs are in configurations of 4-in-1, meaning that an individual unit divides the power across the motors rather than a single ESC for each motor.

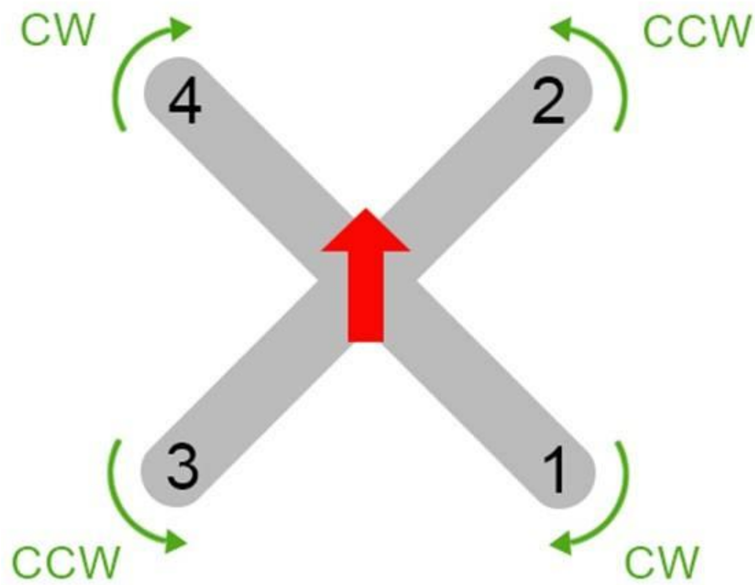
What is imperative before test flying is to calibrate the ESCs so that the minimum and maximum pulse width-modulation to be sent from the FC are expected. Below will be an explanation of manual ESC calibration via Ardupilot. First on the agenda is a safety check, propellers must be removed from the motors, the battery is disconnected, and the drone is not connected to your ground control system (computer with the Ardupilot software).

- Set the transmitter (controller) to full throttle
- Connect the battery, then proceed to disconnect and connect

Motors

The focus is on quadcopters, meaning that there are four motors which propel the device up into the air; motors deliver power in order to perform motion. Most drones have what are known as "brushless motors", which are a simple yet efficiently designed motor. How they operate is that when an electrical current provided by the ESC is sent to them, the current goes into a set of coils in a fixed magnetic field. When electrical current "travels" into a coil or a wire, a magnetic field of its own fashion is induced. In a brushless motor, the coils are wrapped in a circular series, which are aligned with magnets that are attached, this allows that the generated magnetic field to drive the rotation, and in order to keep it going, all the current would need to do is to swap to the sequential coil. Since the motor is capable of regulating itself without needing to input more power like in a brushed motor, this type of motor more easily accomplishes the desired speed established by the pilot. Other additional benefits to using brushless motors is that in comparison, they produce far less noise, are lighter to alleviate the burdens that a heavy load can induce, and are less susceptible to fatigue, meaning that they have a longer usage life. Given their advantages and efficiencies, brushless motors are the standard in drone operations. Fret not being unable to locate these types of motors, as when purchasing supplies, there is almost a guarantee that they are indeed, brushless motors.

An important detail is on the position and orientation which the motors are arranged. Despite the freeform nature of drone building and design, there is indeed a correct method which to place the four motors. Not every motor rotates in the same direction, they either operate in a clockwise or counterclockwise direction, and it is of absolute importance to place them correctly. From going left to right, from the front the rear of the drone, the orientation is as follows: clockwise, counterclockwise, counterclockwise, clockwise. In order to prevent confusion, a helpful pictorial will be placed below. The diagram abbreviates clockwise as “CW” and counterclockwise as “CCW”.

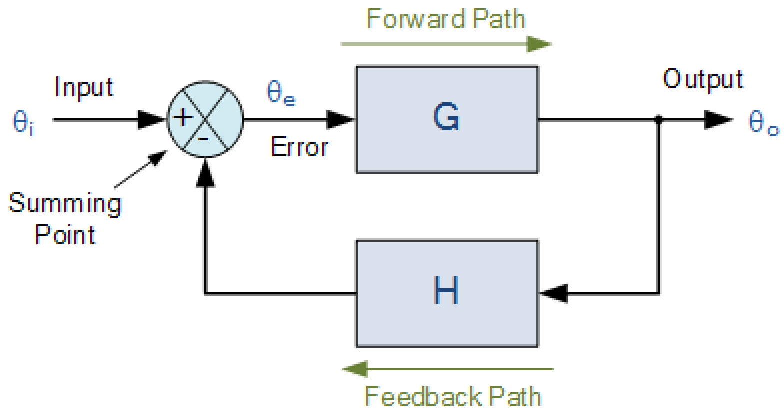


As previously mentioned, it is imperative that they are implemented as pictured, as this directly affects the flight dynamics of the drone. Notice how the same motor directions are at a diagonal from each other; this is because this allows for the angular momentum to zero out. To briefly explain, angular momentum is the rotational analogue of linear momentum, which is the product of a mass and the velocity. When “translating” into an angular mindset, it is the moment of inertia times its angular velocity. The angular velocity is quite simple to explain, it is the speed at which something rotates. The moment of inertia can easily become convoluted, however to simplify, let us use an example and define inertia first. Inertia is an object’s tendency to resist a change in motion. This concept is derived from Newton’s first law of motion, you may be familiar with the phrase, “an object at rest will stay at rest and an object in motion will stay in motion”. To exemplify, imagine that you are driving, and you have a box on your floorboard. When making a right turn, you are attempting to change the box’s state of motion, as such, to resist change, the box will actually shift to the left!

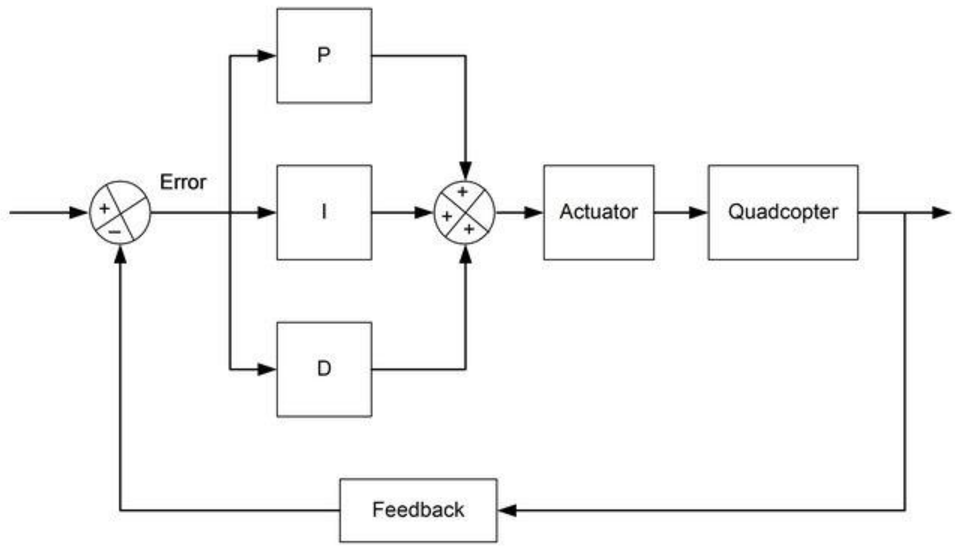
Let’s translate this into the rotational analog, in the example, the box translated, so in our case of the quadcopter, it will rotate. In physics, it is convention to state that CCW is the positive direction, and that CW is the negative direction, ideally, each motor will operate at the same (RPM), since there are two positive directions and two negative directions, all four of which of equal size, which excludes direction, then the total angular momentum is zero, meaning the system is stable, and so more easily controllable. If one of the motors operates in a different angular velocity, then this balance will not occur and the drone will be unstable; torque induces a rotational force, and as such will rotate the drone. Such will be an unstable system, and nigh impossible.

Flight Controller

The flight controller is perhaps one of the most essential components of a drone's construction, it is a small circuit board that is responsible for interpreting input signals delivered from the receiver and outputs system responses. Keep in mind, that the term, "controller", is used in the sense of a control system, which will be elaborated on later; the controller is not the physical device that is held to activate and dictate flight, that is known as the transmitter, which is paired with its corresponding receiver. The flight controller, which will be shortened to FC for the sake of brevity, can accomplish a number of tasks depending on its complexity. Some of the tasks which are carried out by the FC include but are not limited to autonomous actions, failsafe, autopilot if programmed, programmed flight patterns, interpreting signals outputted from the GPS module and the receiver, of course, along with determining the motor speeds via utilization of the ESCs as previously discussed. Flight controllers also hold control over PID tuning; PID, abbreviated for Proportional-Integral-Derivative, and is commonplace in the world of automatic controls. Fret not; first, let us establish what each of those terms in the abbreviation mean in the first place, as well as some basic control theory. What is a controls system? Well, they are ubiquitous and you have used them every single day, however, a proper definition is provided by Norman Nise's, "Controls Systems Engineering": a control system is a series of process and subsystems composed in order to achieve a certain output. In almost all cases, this output is not achieved, so most control systems are "closed loop" systems, meaning that the response of the actual out is detectable via a sensor, this signal is then returned into a summing junction and measure this as error, the error being between the desired output and the actual output. This error is transmitted as a signal back into in the control system, this error signal will serve as feedback and is utilized to further attempt to reach the desired output. Underneath, a figure has been supplemented in order to aid in the visual understanding.



The ratio of the input and the output magnitude is known as the gain, and the ultimate goal is to have it so that the gain reaches a certain value, such that the desired output of the control system has been satisfied. In a drone, the PID within the FC's software calculates the angular velocity which the motors should spin at such the flight is capable of being performed. This signal is later sent off to the ESC to determine the amount of power that the battery should deliver such that the motors spin at an equal and opposite rate in order to maintain angular momentum as discussed earlier. As such, there is a desired rotation speed, but an actual rotation speed is the output of the system. The PID is similar to that of the control system described previously, however, each component, the proportional, integrator, and deriving factors play as a subsystem which feeds to the actuator, then the drone, before yielding an output to be feedback into a beginning summing junction.



P, for the proportional factor is by far the most comprehensive of the terms, relates to increasing or decreasing the gains and/or errors of a system by magnitude factors. For the sake of being analogous, imagine the proportional influence to be akin to a sensitivity knob, like on a guitar amplifier. When adjusted and cranked to the maximum, the largest possible sound emits from the amplifier. As such, the P factor is symptomatic of overshoots and oscillations when at high settings due to an attempt of the drone to self-correct. At low settings, the controls are "slippery" and sloppy, a balance must be found, as the quality of control is dependent on the P factor.

I, for integral factor stores and summates the errors measured in the feedback. In the sense of a drone, this dictates how the drone responds and external forces; this could mean being off balanced, inducing a torque offsetting the system into a rotation, or perhaps a strong wind, interfering with flight. This factor is the "stiffness" of the drone.

D, the deriving factor is the more abstruse of the tuners, this factor finds the rate of change of the errors in the system and attempts to dampen their effects. Think of a shock absorber in a vehicle's suspension system, as it absorbs the energy of a car's bounciness, so that not many oscillations occur when driving, and adapts to different qualities of road.

It is usually suggested that when operating a newly built drone, to function at the default PID gains, and to slowly adjust the gains to achieve the performance you would like to achieve.

Some also recommend that when beginning to tune, to begin at smaller gain values, then increase until your drone starts to inappropriately behave in its flight, as such, you would know the threshold of the gains to maintain performance. It should be denoted that PID gains are unique to any and all drones – asking someone else what their gains will not provide a helpful reference.

Although PID tuning is quite handy and takes a relatively short amount of time to accomplish, it is imperative to remember that it is very well possible that not all irregularities and poor flight performance can be the gains play the role of the scapegoat. Prior to beginning to arbitrarily adjust gains, one should attempt to investigate any and all potential reasons as to why your drone is behaving the way it is. For instance, not all vibrations are the fault of high proportional gains, it could very well be due to poor damping the frame or an imbalance of motors. Ensure that the motors are functioning properly and that they are securely attached to the arm mounts and are going at the same speed; in the event of poor damping, check your frame. Inspect the housing of your components, see if they are secured and try strapping them down with Velcro or tape. The root of oscillations can also be the result of an offset of the center of gravity, the point where all of the weight of a rigid body acts about. Usually this is caused by poor positioning of the battery, as it is the bulkiest of the components and supplies a good quantity of weight into the system. Ideally, the center of gravity would be in about the very center of the drone, the intersection of the imaginary lines presented in the arms. In this instance, the battery offsets the center of gravity, as such, the inertia tensors are not symmetric, and in order to compensate, some motors might be overperforming to make up for the lack of the other two motors. These are just some suggestions to inspect prior to adjusting the PID gains, and in the event of such be sure to perform it in a methodological manner. Start at the nominal gain values provided by the FC software and slowly but surely make adjustments.

Transmitter and Receiver

As discussed during the elucidation of the FC, the transmitter is the physical remote which you hold to fly the drone. Such is also easy to explain, it uses radio-wave technology, when pushing up against the stick inputs, a radio signal is sent to the receiver in the drone, which is then processed by the FC to achieve the necessary motor speeds required to meet the flight specifications dictated by your input into the transmitter. Typically, a transmitter will have four channels, one for each of the directions the stick inputs can achieve. Transmitters tend to function at 2.4 GHZ band of frequency for the receiver to pick up and detect a solid connection. Usually, this permits the telemetry to be vital at about 1 kilometer, however, in the event of connection issues, ensure that your antenna is positioned in a way so that the signal can be easily detected. You can also test the sensitivity of your sensor, in the circumstance that it does not meet the requirements desired, you should be in the market for a new telemetry kit. Of course, remember that while this is a long distance, and reaching those heights are exciting! – You must comply with the FAA rules and regulations, and not fly higher than 400 feet.

Hopefully this brief crash course in inspecting the various components helps to ease you into the drone building process, remember, this document is not the "end-all-be-all", seek outside help! Whether it be an expert or the copious sources on the internet; happy flying!

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