Multicopters and drones

*How the f*ck do these things fly?*

Anthony Gautier http://silica.io

« Multicopter » or « drone » ?

First, let's make things clear :

- A multicopter is some kind of helicopter with multiple propellers for lift (usually 3, 4 or 6)
- A drone is an unmanned, autonomous aircraft

« Multicopter » or « drone » ?

A multicopter is not necessarily a drone,
and a drone is not necessarily a multicopter.

« Multicopter » or « drone » ?

This is not a drone, because it requires a pilot.

Image source : lesnumeriques.com

« Multicopter » or « drone » ?

This is a drone (even though it's a plane), because it can fly fully autonomously.

Image source : kiloohm.com

« Multicopter » or « drone » ?

Here, we'll talk about multicopters which can (sometimes) fly autonomously and therefore be called « drones ».

Alright, let's dive in now.

Approch

This guide will take a practical approch : we'll take every component of my custom-built quadcopter (« quad ») Phasma, mostly from the outmost to the inmost, and see why it's there and how it works.

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- Overview
- Radio transmitter
- Frame
- Propellers
- Motors
- Motor controllers (« ESC »)
- Receiver
- Battery and power distribution
- Flight Controller

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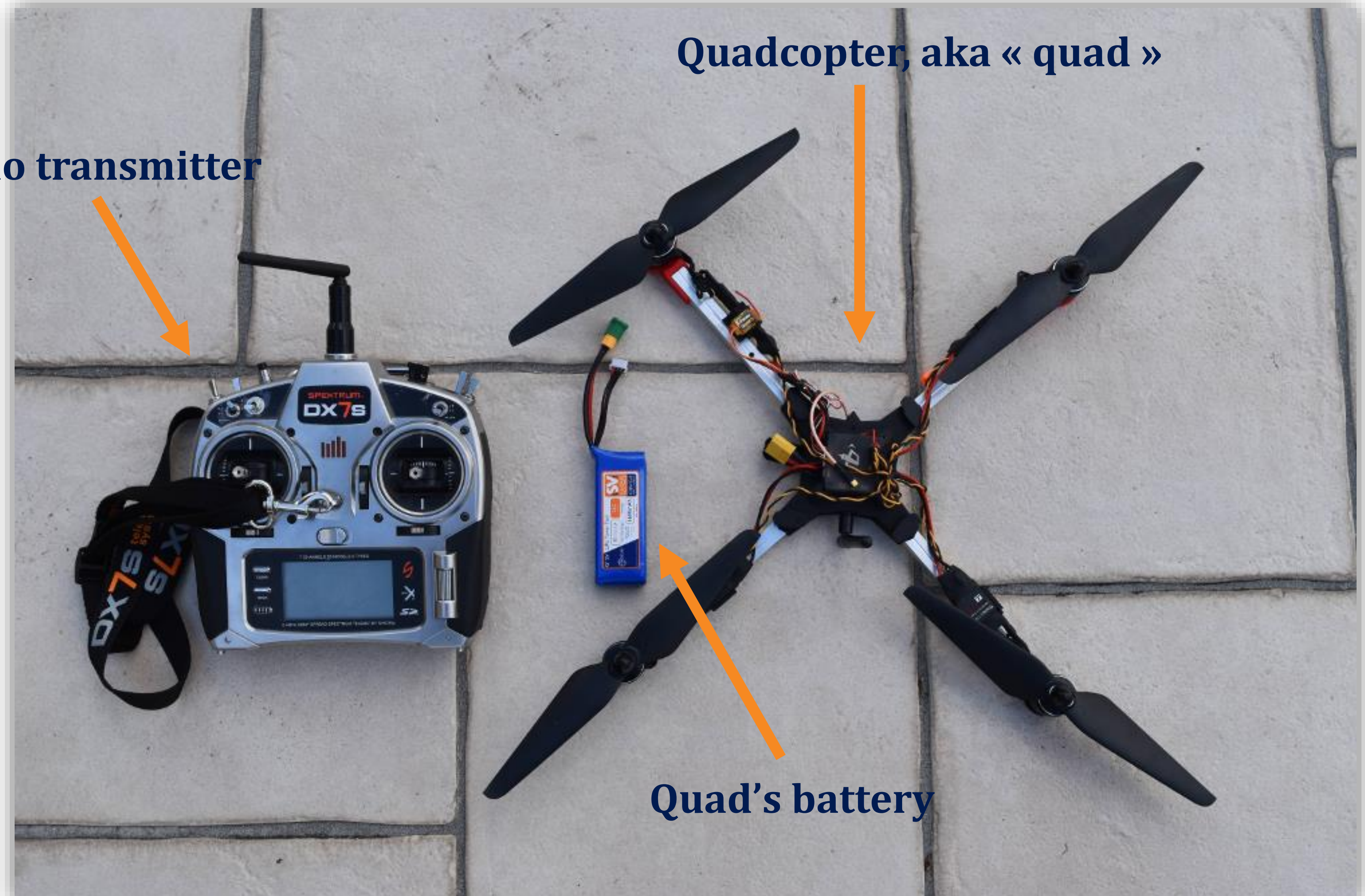
Overview

« What do I need to make this thing fly ? »

Complete setup, ready to fly !

Complete setup, ready to fly !



Radio transmitter

Protip : don't drop it when you fly

Overview

Antenna

Switches

Sticks

Trims

Screen and buttons for the radio menus and configuration

Sticks

There are different standards for « which stick controls what », called *modes*. Here, we use **mode 1** :

Tilt forward / tilt backward (« pitch »)

Up / Down (« gas »)

Rotate left / rotate right (« yaw »)

Tilt left / tilt right (« roll »)

Switches

Switches are general-purpose and can be configured to do (almost) anything you want, such as :

- Altering your radio settings (stick sensitivity, …) mid-flight
- Changing flight modes and settings (when connected properly to the flight controller)
- Controlling something on your aircraft, such as turning on lights and deploying landing gear

Channels

The main parameter of a radio transmitter is its number of channels. It indicates how many *things* you can control on the aircraft at the same time.

This DX7S has 7 channels :

- 4 channels for the sticks
- 3 channels for the switches
  - For example, the 3-position switch is mapped to the « flight mode » setting in the flight controller
  - The rotating button could control another parameter, such as stabilisation gain
  - A switch could control an embedded servomotor for jettisonning something in altitude

Menus

Modern radios have a small embedded computer with a screen and menus which allow you to :

- Save different settings for each aircraft you own
- Configure the stick response curves
- Configure the switches behaviour
- Set up channel mixing* for more complicated aircrafts : V-tails, flying wings, helicopters, …
- Display flight time or a countdown
- Display real-time flight telemetry (for more advanced radios)

* channel mixing is when a movement on a single stick (input) changes the output (the instructions sent to the model) on multiple channels. For example, on a flying wing, the pitch and roll sticks are mixed together to control the flaps. But don't worry if you don't understand : as we'll see shortly, this is not used for multicopters and has to be disabled.

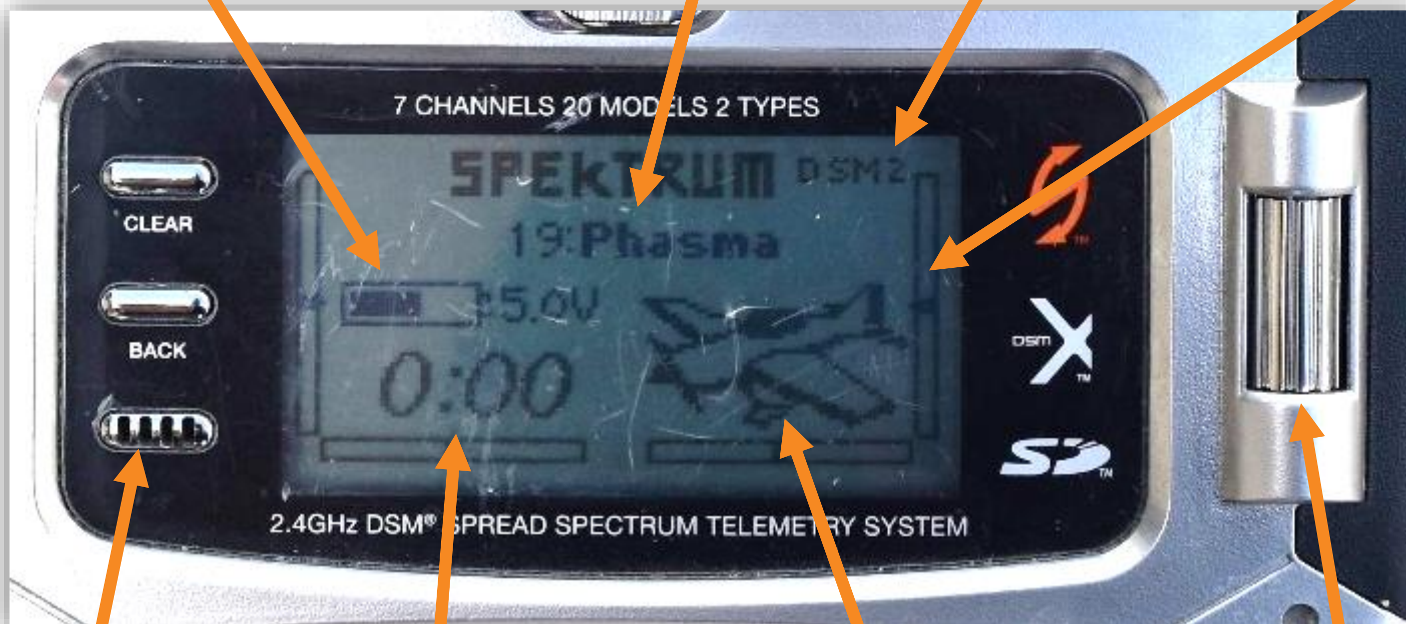
Menus

Radio's battery level
(⚠ not model's battery)

Model name and id

Link transmission type

Trims



Buzzer and vibration
for alerts

Timer/Countdown

Model type

« wheel and click »
button

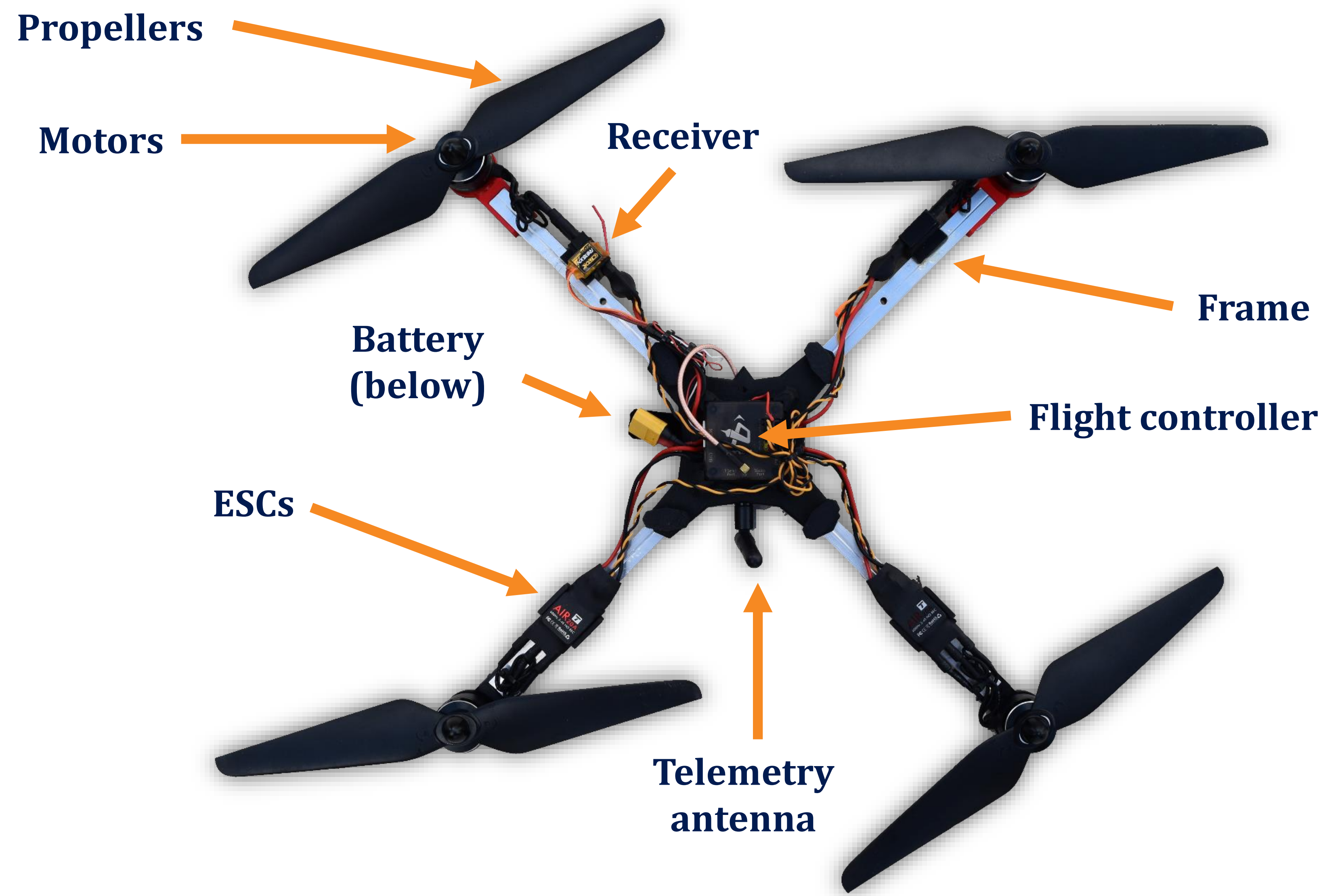
Which model type ?

The model type selected on the radio is used to set up default channel mixing for more complicated aircrafts (such as an helicopter). A multicopter uses mixing extensively, but it is handled on-board in the flight controller. This is why, surprisingly, you must select on the radio a basic plane model, without mixing.

Multicopter

« Was it supposed to get *that* near from the tree ? »

Overview

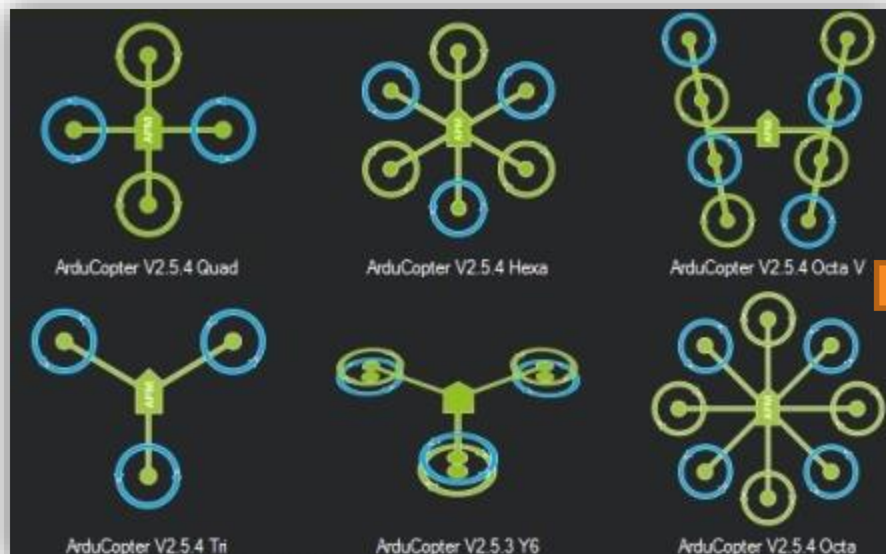

Propellers
Motors
Receiver
Frame
Battery (below)
Flight controller
ESCs
Telemetry antenna

Frame

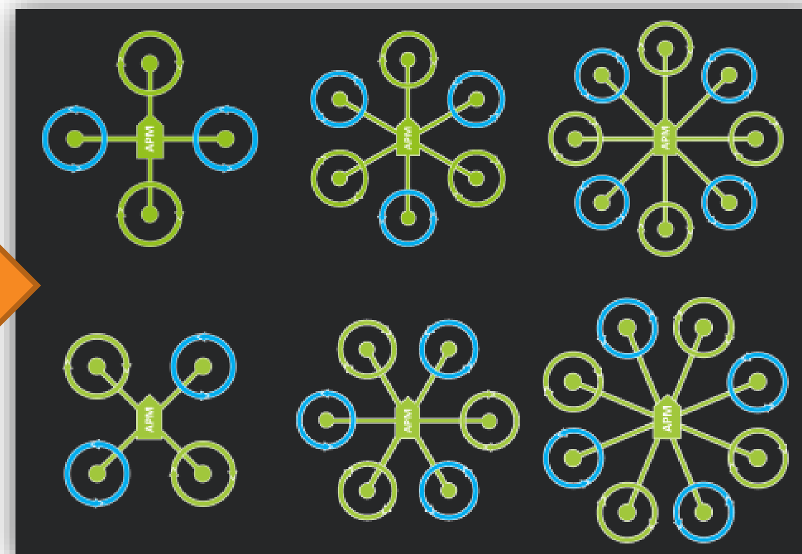
Frame

- Defines the number and position of motors
  - Tricopter, quadcopter, hexacopter, octocopter…
- Must be strong, light and rigid
  - Tough plastic, aluminium, carbon fiber…
- Size expressed as the diameter of the circle joining the motors' axes, in millimeters

Frame configurations



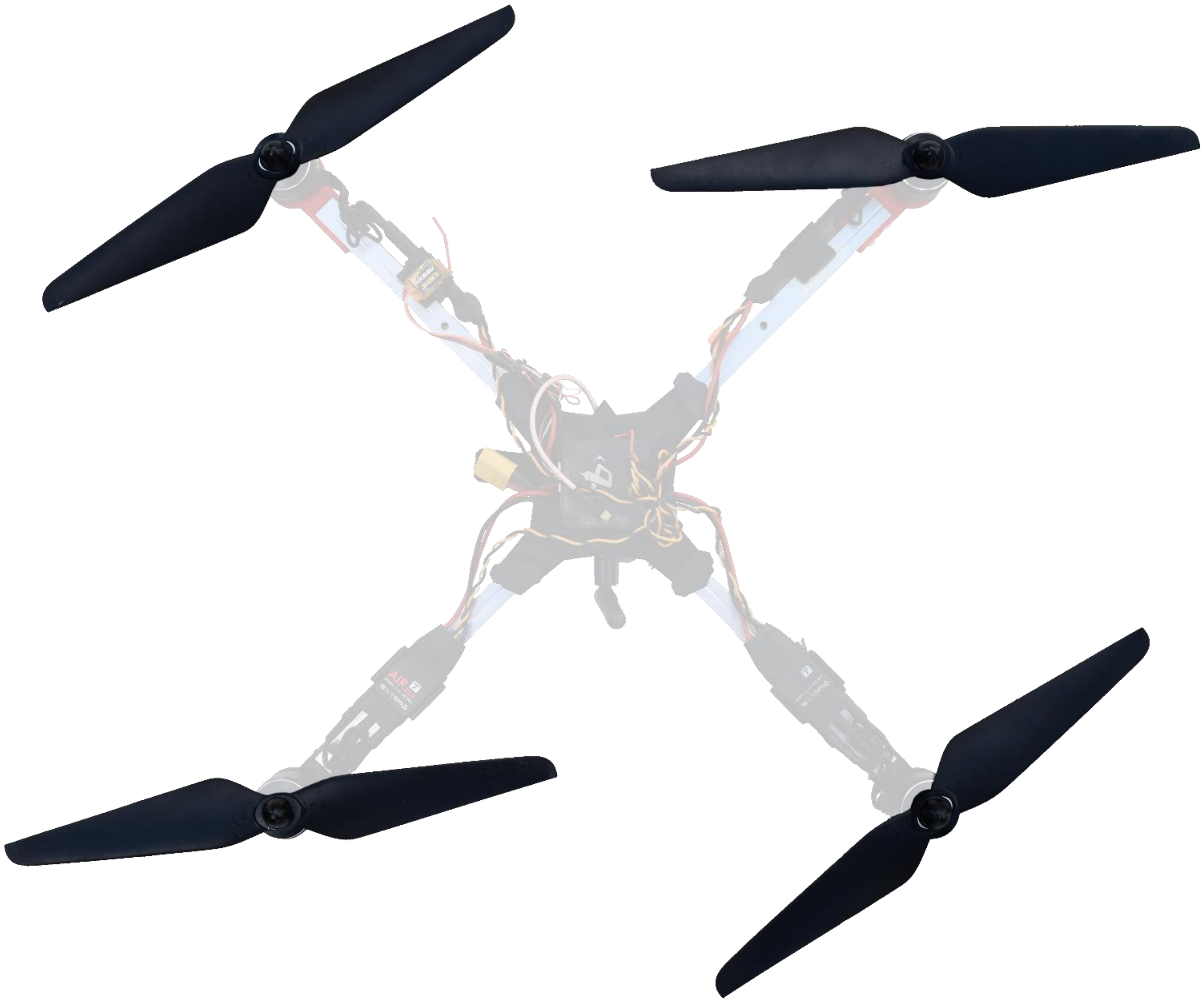
Configuration



Orientation

Images source : APM Planner

Propellers



Propellers

- Three main parameters :
  - Diameter (X, inch)
  - Pitch (Y, inch)
  - Direction (CW, CCW)
- Examples :
  - **9x3** : 9in wide, low pitch, normal direction
  - **10x5R** : 10in wide, high pitch, reverse direction

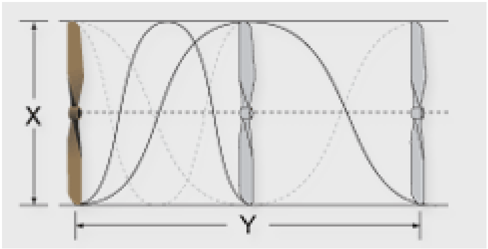
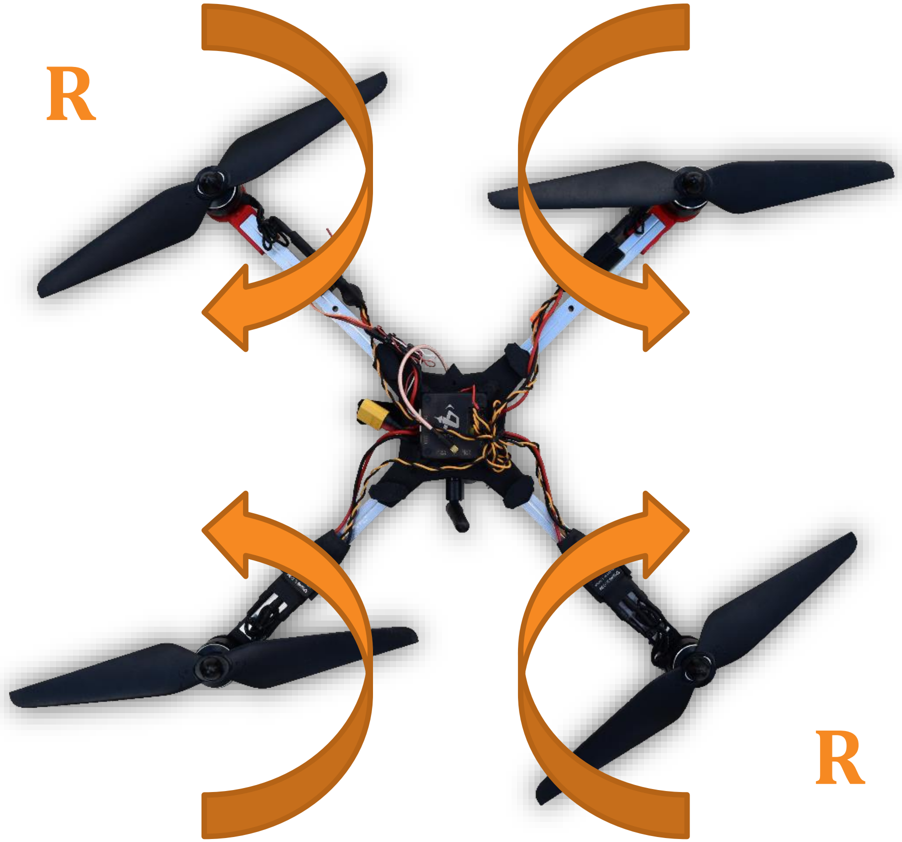


Image source : HobbyKing

Low pitch (~3) **High pitch (~5)**

Propellers

In order to avoid counter-rotation, half the propellers turn in reversed direction, hence « R ».



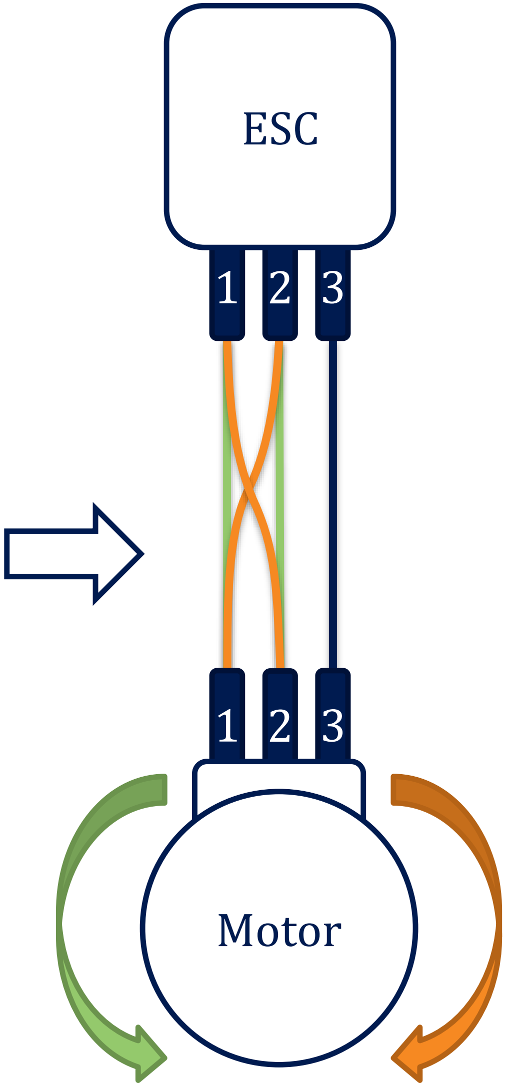
Motors

Motors

- **Brushless** :
  - Powerful and reliable motors
  - 3 wires
  - Need a dedicated controller (ESC)
- Two main parameters :
  - Size
  - Speed
- Example :
  - **2213/920KV** : diameter 22mm, height 18mm, 920 RPM/V

Motors

- Brushless motors have no particular wiring order :
  - Inverting the three wires (1,2,3 → 2,3,1) doesn't change anything
  - Inverting only two wires (1,2,3 → 2,1,3) only changes the direction of rotation
- Simply plug the wires, make the motor spin, and if it's reversed, invert two wires



Motors

- The speed constant (**Kv**), in RPM/V, indicates the motor's full speed (no load) at a given voltage :
  - 920Kv with a 11V battery → 10120 RPM at full speed
- The torque constant is the inverse of the speed constant : Kp = 1/Kv

→ High Kv (> 2000) = high speed, low torque

→ Low Kv (< 700) = low speed, high torque

Motor/propeller matching

- A larger propeller with higher pitch will have more drag, therefore need more torque to spin.
- A smaller propeller with lower pitch will generate less lift, therefore need higher RPM to fly.

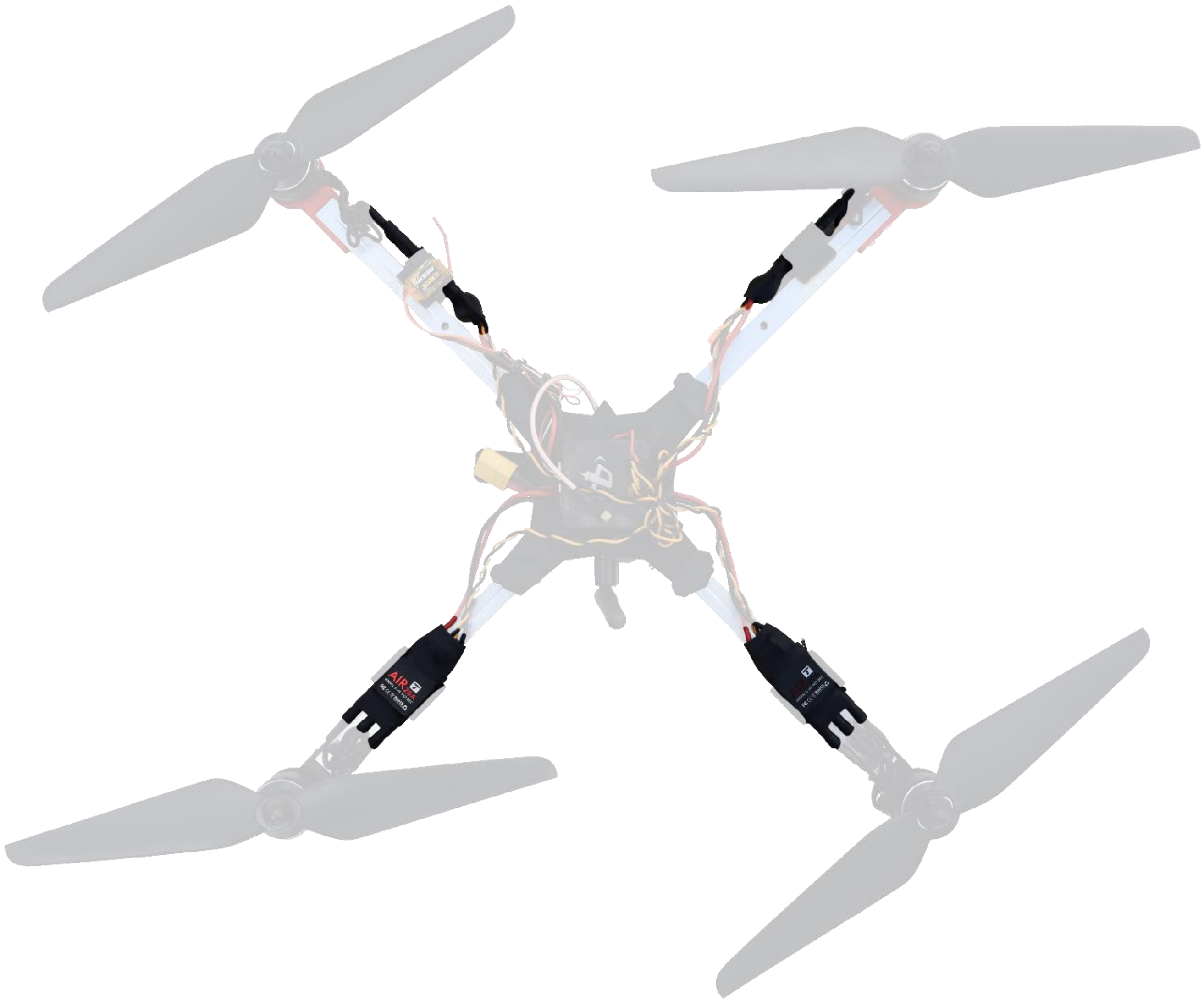
→ Large propellers = low-Kv motors (= high Kp)

→ Small propellers = high-Kv motors

It's a compromise. In most cases, a larger propeller spinning slower (low Kv) is better : less vibration, better efficiency, better carrying capacity and/or autonomy.

But it takes more space and requires a bigger frame.

ESC



ESC

→ Electronic Speed Controller

Command input (from receiver or FC)

Battery input

Motor output

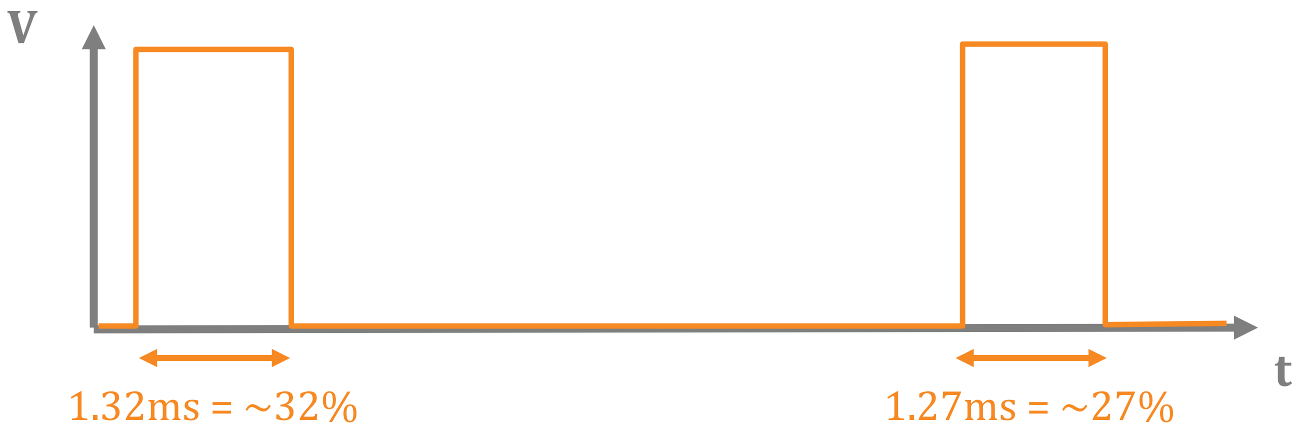
ESC

- Main parameters :
  - Max power, in Amps (must be greater than the max power consumption of the motor, otherwise... Magic blue smoke! and crash.)
  - Max voltage : depends on the battery, usually not a problem
  - BEC or NO-BEC/OPTO :

    A BEC is a 5V regulator which can power the receiver or the flight controller (FC) from the battery. Some models of ESC embed a BEC, because it's the easiest way to set up a model airplane. However, a multicopter has multiple ESCs but you shouldn't have multiple BECs at the same time, therefore NO-BEC ESCs (also called « OPTO ») and an external BEC are preferred.

ESC : PWM signal

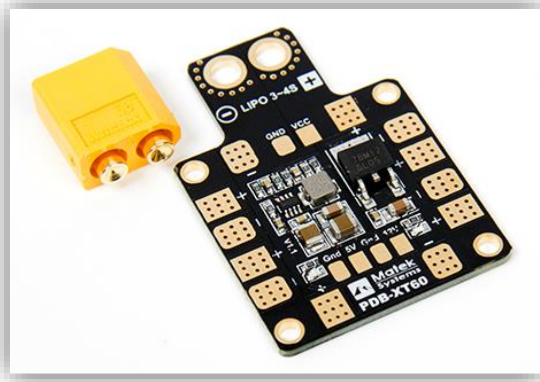
- The command signal the ESC needs is PWM :
  - Square wave of ~10ms period
  - Command set by adjusting the time at level HIGH
  - 1ms = 0%, 1.5ms = 50%, 2ms = 100%
  - These values are approximate : e.g. sometimes between 0.7 and 2.3ms (depends on the manufacturer, must be calibrated)



External BEC

- When the ESCs don't have embedded BECs (prefered case for multicopters), you need a dedicated 5V power supply for the flight controller and the receiver.
- You can use a simple external BEC, or go with a board dedicated to multicopters which distributes battery power and embeds a BEC. This allows cleaner wiring.

External BEC



Power distribution board with BEC

Images source : HobbyKing

Receiver

Receiver

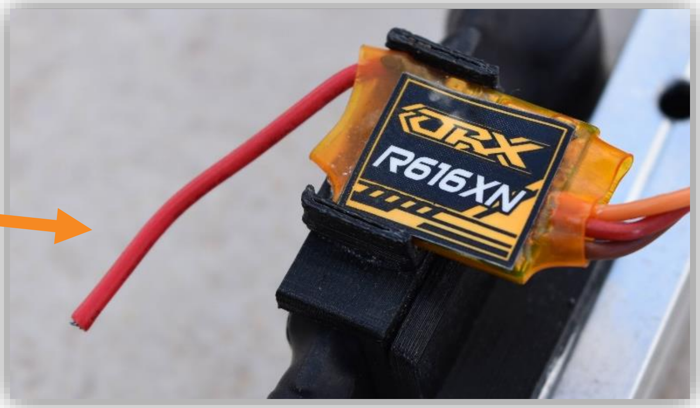
- Modern receivers use a 2.4GHz digital radio link
    - No need to mess around with quartz and frequency boards
    - You just need to « bind » the radio and the receiver
- It's made to control servos and ESCs, therefore it outputs PWM signals
- On a model airplane, you connect each servo to its corresponding channel
- On a multicopter, you connect all channels to the flight controller, which will take care of controlling the ESCs

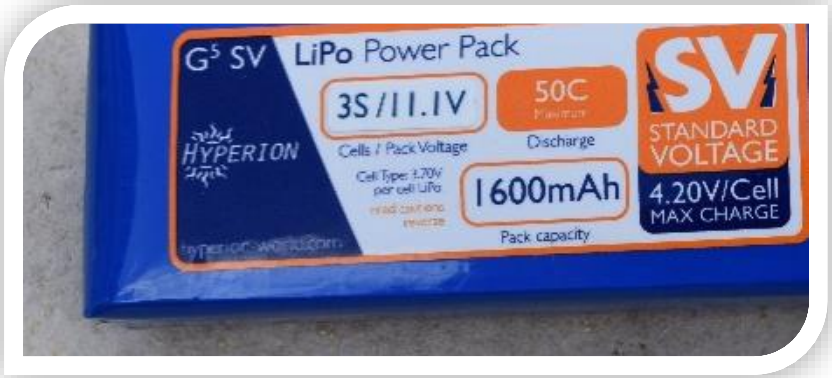
Receiver : PPM

- Some receivers are « PPM-compatible » :
  - PPM is basically a way to transmit multiple PWM channels on a single wire
  - If the flight controller is compatible as well, this allows to connect only a single cable (3 wires) between the receiver and the flight controller, instead of one for each channel (6 channels = 6 cables = 18 wires…)
  - This is lighter and cleaner, therefore should be preferred

Receiver satellite

- Sometimes, a 2.4GHz can have a « satellite » : a small auxiliary antenna to improve link quality and avoid data loss
  - A satellite actually is a full-featured receiver, just smaller, with less connectors and only a serial communication interface
- And sometimes, a flight controller can talk to a satellite directly, and avoid having a dedicated receiver completely!





Battery

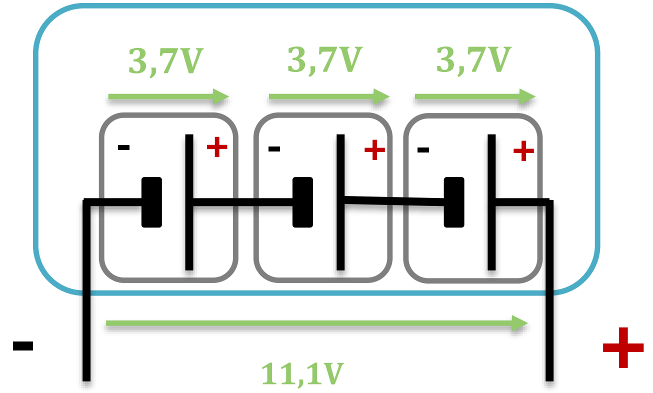
Take care of it, you don’t want it to get angry

Battery

- Three main parameters :
  - Number of elements/cells (→ voltage)
  - Capacity (quantity of energy the battery can store)
  - Maximum discharge current

Battery : number of cells

- Each Lithium-Polymer (LiPo) cell is :
  - 3.3V when discharged
  - 3.7V nominal
  - 4.2V when charged
- For example : a 3S battery is :
  - 9.9V when discharged
  - 11.1V nominal
  - 12.6V when charged



Battery : capacity

- The capacity is the theoretical quantity of energy stored in the battery, expressed in mAh
- For example : a 2000mAh battery can (theoretically) provide :
  - 2A for 1 hour
  - Or 8A for 15 minutes
  - Or 500mA for 4 hours
- ⚠ However, **never discharge a LiPo below 30% !**
- In practice, don't expect more than 60% of the theoretical capacity

Battery : (dis)charge current

- A « C » is a unit of current (charging or discharging current) relative to the battery capacity :
  - For a 1600mAh battery, 1C = 1600mA = 1.6A
- The maximum discharge current accepted by the battery is specified on the sticker in units of C
  - 1600mAh battery with 50C max discharge current = 80A max in total (for all motors, the receiver, flight controller, …)
  - In practice, take a ~20% security margin
  - Some cheaper batteries have smaller discharge ratings, for use in radio transmitters (« Tx battery pack »)
- **The standard charge current is 1C**
  - That means charging a battery from empty to full theoretically takes 1 hour
  - If you charge faster, you reduce the lifespan of the battery

Battery : security notice

- Do **NOT** discharge below 30%
- Do **NOT** short-circuit
- Do **NOT** cut, open, or otherwise damage the battery wrapper
- Do **NOT** leave charging or discharging unattended
- **DO** store in a dedicated *LiPo safe bag*
- Do **NOT** let plugged in for an extended period of time

It's quite simple : if you brutalise the battery, the battery will brutalise you in return. You, your house, your family and your dog. You don't want that.

Battery

Battery chemistry

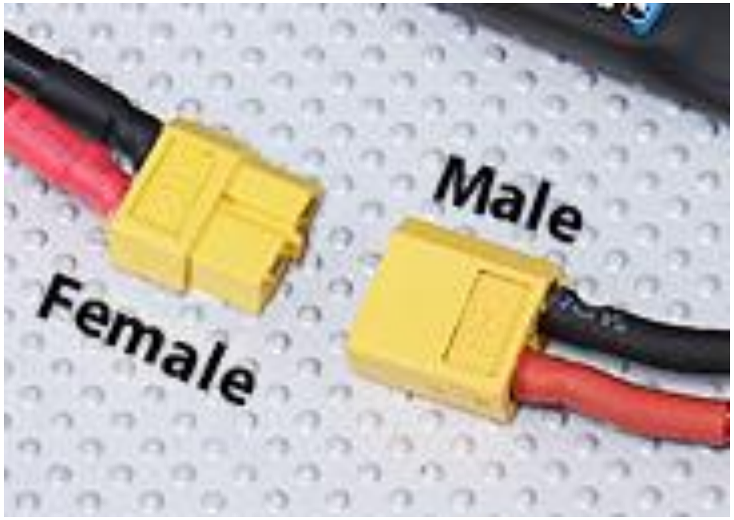
Discharge current

Cells/Voltage

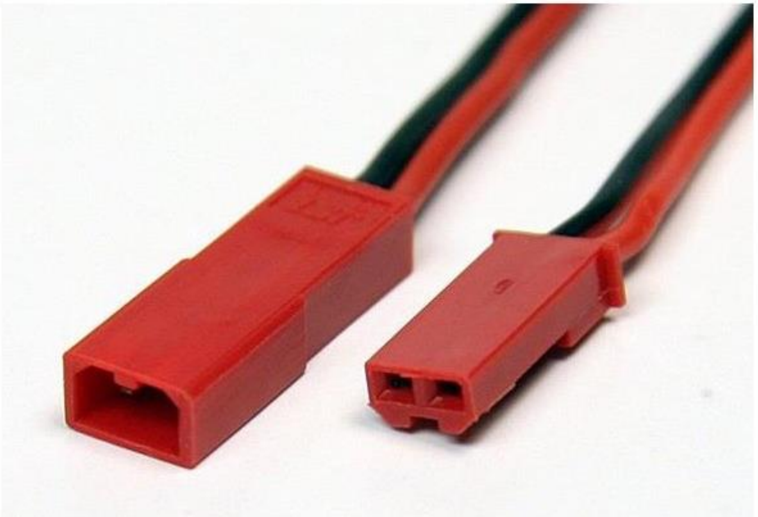
Capacity

Battery connector

- There are a few standards :
  - **XT60** : max 60A (most widely used)
  - XT90 : max 90A (same form but bigger)
  - JST : small and red, for smaller batteries

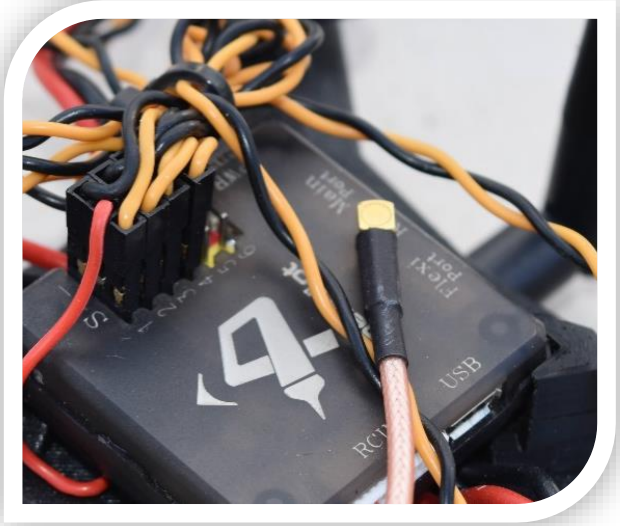


XT60



JST

Images source : HobbyKing



Flight controller

aka, « the brain »

Flight controller

Flight controller's jobs

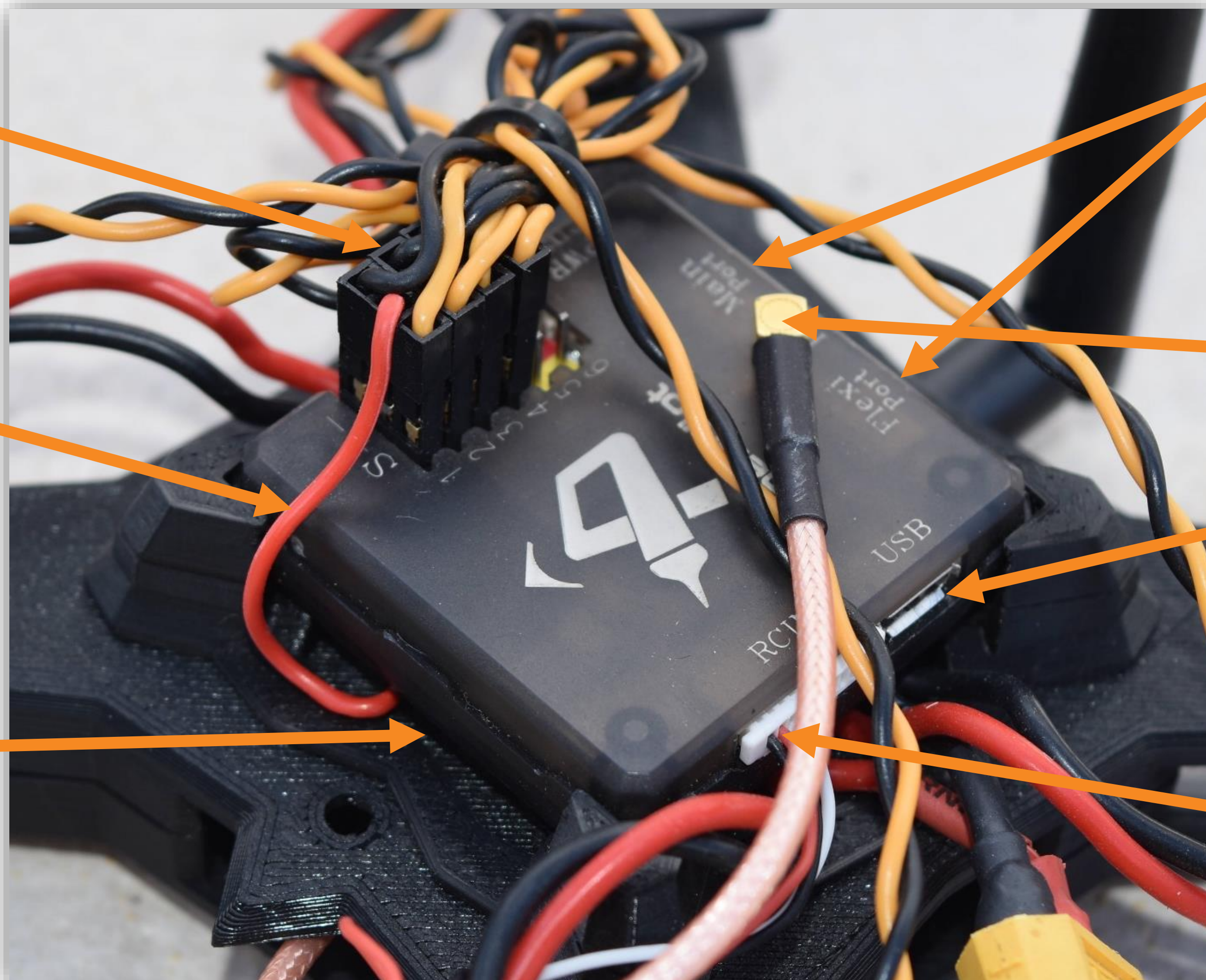
- The flight controller is the central component of the multicopter. Its main jobs are :
  - Getting the pilot instructions from the receiver/satellite
  - Computing the aircraft's dynamic parameters (orientation, speed, altitude…) in real time, with high frequency and accuracy, using an IMU
    - Accelerometers, gyroscopes, barometers, GPS, and lots of maths
  - Computing stabilisation algorithms using PIDs
    - And lots of maths again
  - Compiling all this data to compute the motor commands (for the ESCs)

Flight controller

Outputs to the ESCs

BEC input

Power distribution board with BEC (hidden below)



Extension ports (for sensors, GPS...)

Telemetry antenna output

USB port

Receiver input

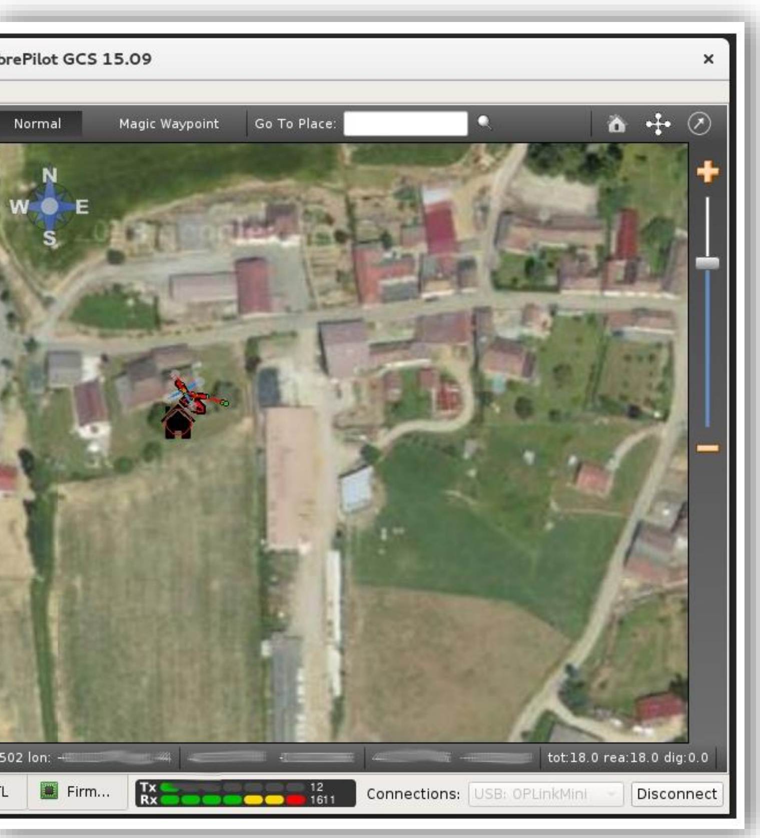
PC software

Configuration of the flight controller is usually done on a computer via an USB cable. Some FC models have a dedicated software which is also able to display real-time flight information when a telemetry receiver is connected.

LibrePilot Ground Control Station software

Images source : LibrePilot documentation

Autonomous flight

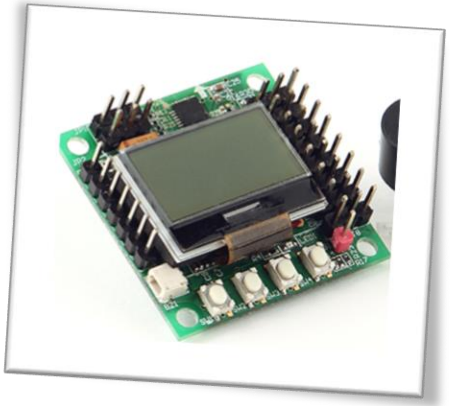


A good FC with a good IMU, a good GPS and a telemetry transmitter is able to fly the multicopter autonomously. The software on the ground computer allows you to define checkpoints and behaviour for the aircraft, store this path in the FC's memory, and observe real-time flight status.

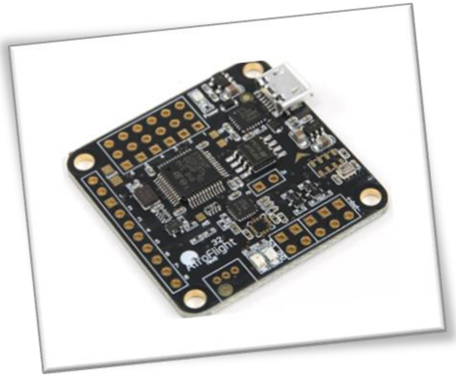
Some common FC models

- HobbyKing KK2
  - Small, cheap, simple to use, embedded screen for configuration
  - Very basic stabilisation algorithms, no GPS, no autonomous flight
- Naze32
  - Similar to the KK2, but more recent, powerful, and overall better
- DJI Naza M-Lite
  - No autonomous flight but good stabilisation algorithms
  - Good for simple, easy-to-fly multicopters
- APM : « ArduPilot Mega »
  - Architecture based on the Arduino Mega platform
  - Open-source Arduino code, customisable, lots of variants and clones
  - Advanced features : GPS, telemetry, sensors, autonomous flight
  - Very popular
- PixHawk, an improved APM
- LibrePilot (formerly OpenPilot)
  - Similar to the APM

Most common FC models



KK-mini



Naze32

OpenPilot

Naza M-Lite

APM

HKPilot32, HobbyKing's Pixhawk clone

Images source : HobbyKing

PID stabilisation

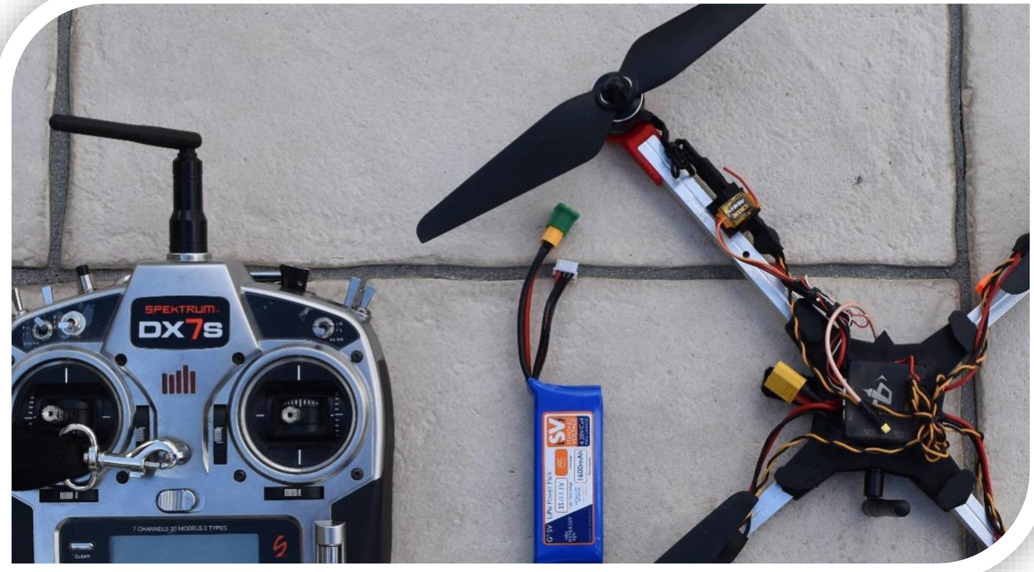
- Tries to achieve a specific orientation (by default, level) according to the current measurement (via the IMU) and the error between the two
- Proportional correction
  - Corrects more if the error is large
- Integral correction
  - Corrects more if there has been an error (even small) for a long time

  → Tries to avoid drift
- Derivative correction
  - Corrects more if the error is rising abruptly

  → Tries to compensate perturbations quickly

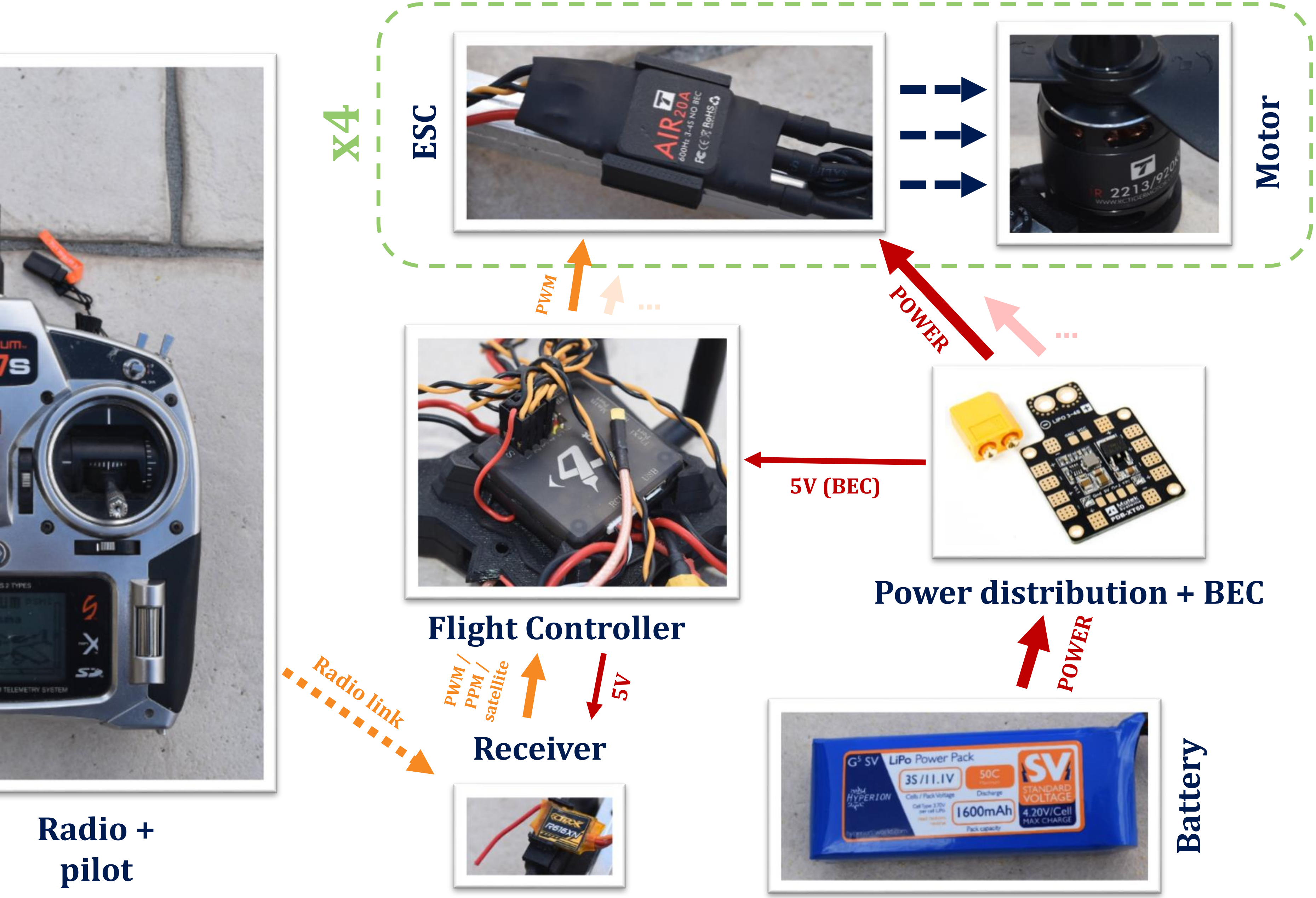
PID stabilisation

- Gain value can be configured independently for each channel and each correction
- Gains too low lead to a dull, slow behaviour, up to no stabilisation at all
- Gains too high lead to oscillations, up to a complete instability and a crash
- Gains depend on the motor power, propellers size, frame size, ESC response curves, …
- They are one of the most important parameters to configure before the first flight



Summary

Let’s put all of that together and make it fly!



x4
ESC
Motor
PWM
...
POWER
...
Flight Controller
5V (BEC)
Power distribution + BEC
POWER
Radio link
PWM / PPM / satellite
5V
Receiver
Battery
Radio + pilot