UAV Components
Part 1

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Erasmus+ Programme
of the European Union

Autonomian

UAV ecosystem components

Hardware components

Frame / body / wing

Propulsions: motors, servos (actuators)

Sensors

Flight Controller and Remote Control

Powering

Additionals

Frame / body / wing

UAV hardware components

Wing: Plane / Soarer

Helicopter

Multirotor

Body / frame

Drone’s frame is a base component to fix any others.

If has to be durable yet lightweight:

Common materials include: carbon fiber, plastic, polystyrene, aluminum / duralumin, balsa

It is great if it can generate lift force itself, because it removes other lift generators (i.e. propellers), i.e. a flying wing.

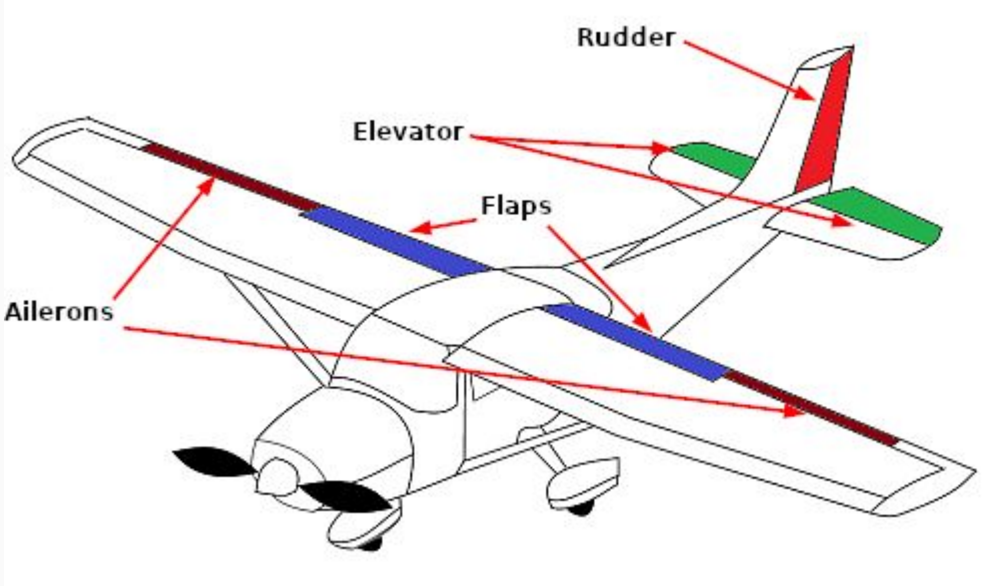
Each construction has set of very individual and specific features.

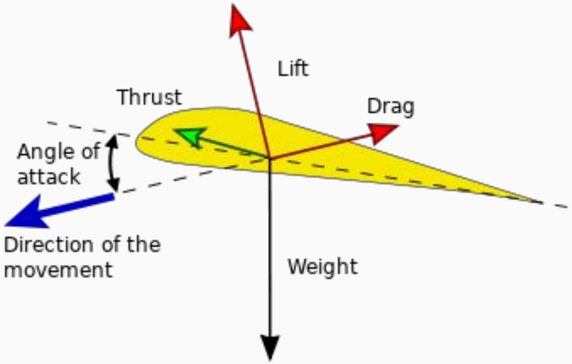
Plane - construction

Historically, the oldest model, based on the birds.

Lift force is generated with wings

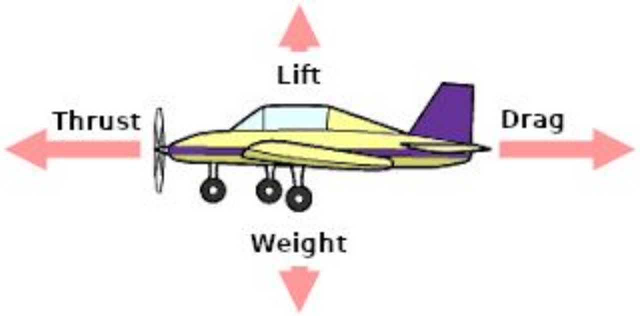
Many control surfaces

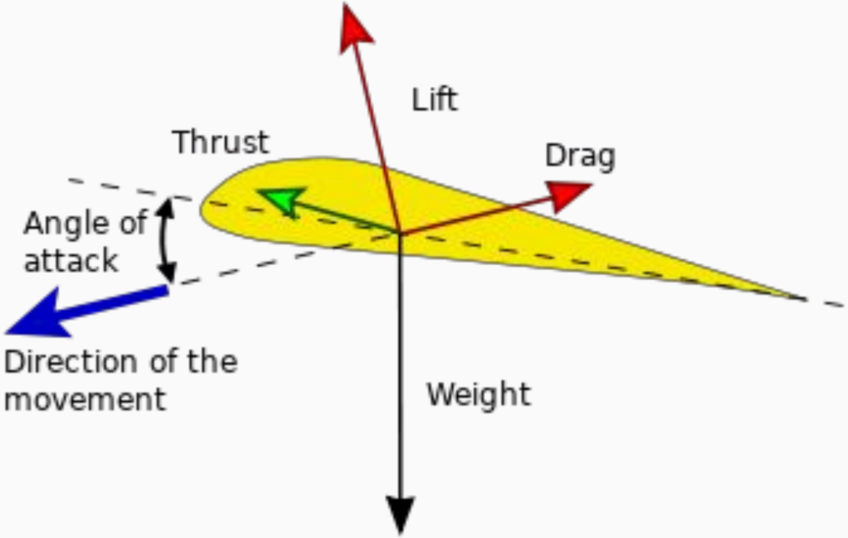




Plane - construction

Why something that is heavier than an air is flying?



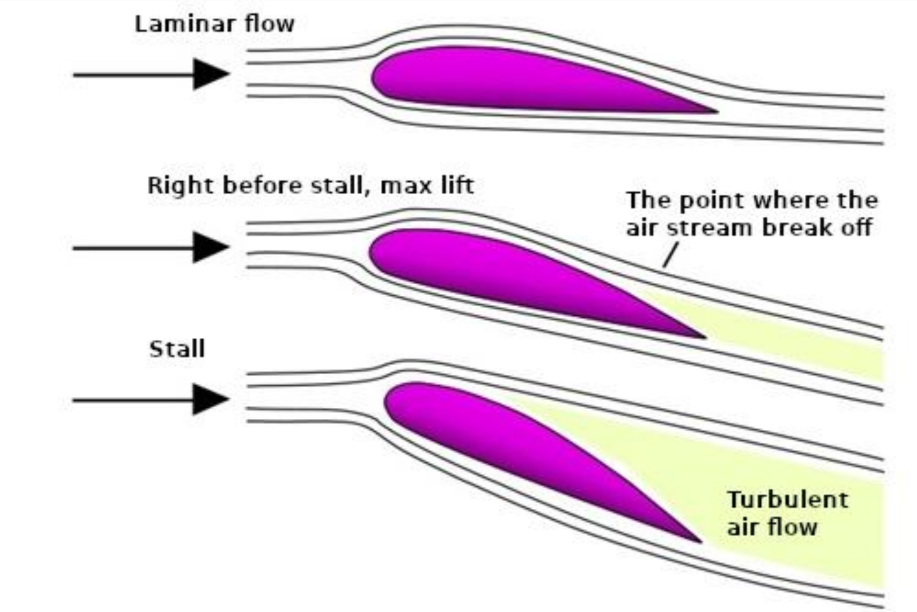


Plane - construction

And why sometimes it falls down?

Lost of a lift force is because of:

- Speed below minimum **airspeed** (stall)
  - Stall speed depends on many factors, including cruise altitude, temperature, humidity, also mass, shape, and so on.
- Too high angle of attack causing laminar flow to become turbulent (breaking the airstream laminar flow over the wing).

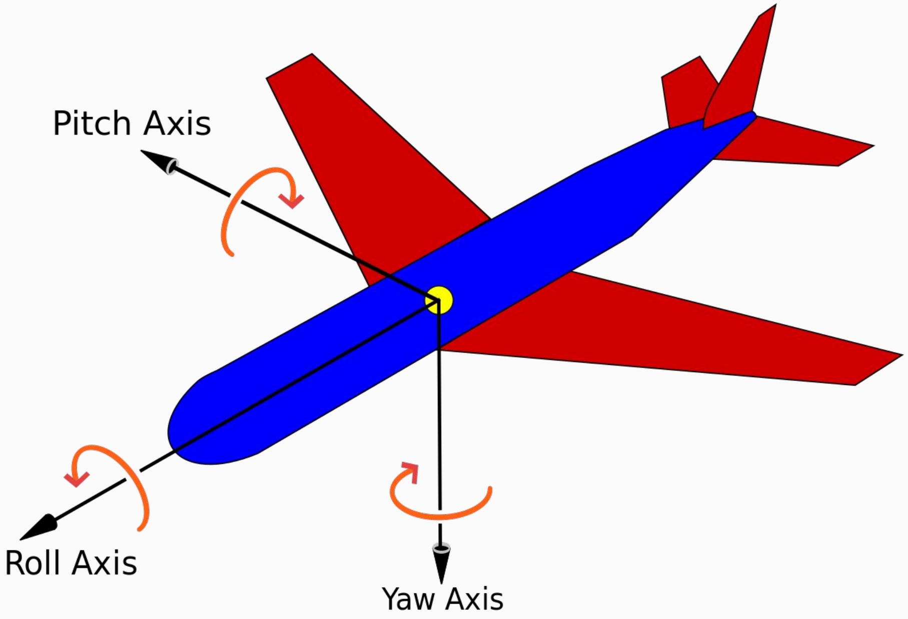


Plane - construction and control

Rotation axes

Classical, using Euler’s angles:

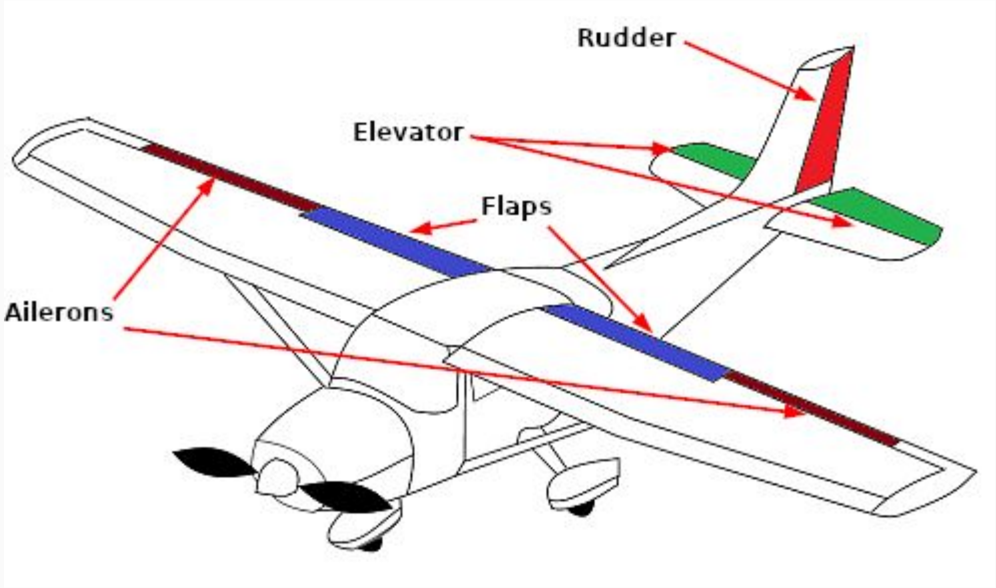
- Pitch - controlled with elevator*
- Roll - controlled with ailerons (the work contercurrently)
- Yaw - controlled with rudder



Plane - construction and control

How the plane slows down?

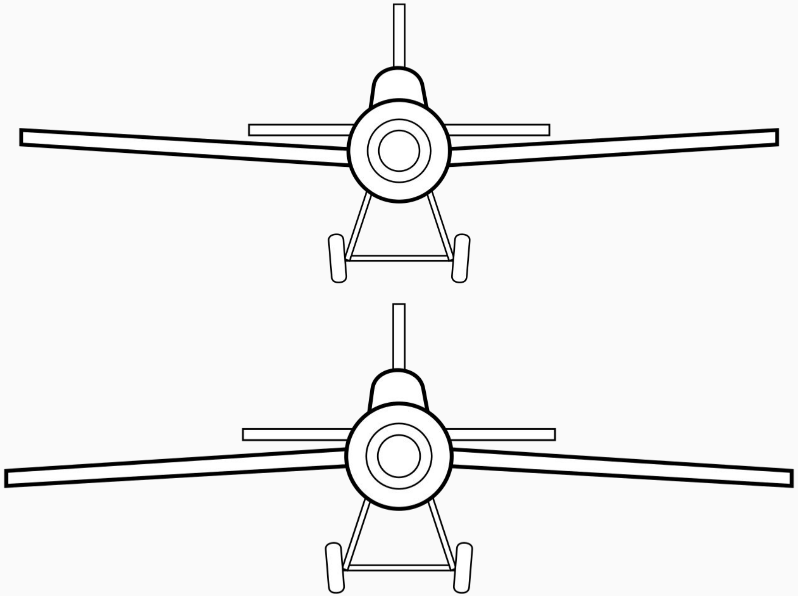
- Via ascend with constant or lowering thrust
- Using spoilers (aerodynamic brakes)
- Also using flaps but those cause increase of the lift force that equals ascend when used with constant thrust



Plane - construction - hints

Wing construction variants:

- Dihedral
- Anhedral
- Other



Mind lift vectors generated with each of the wings!

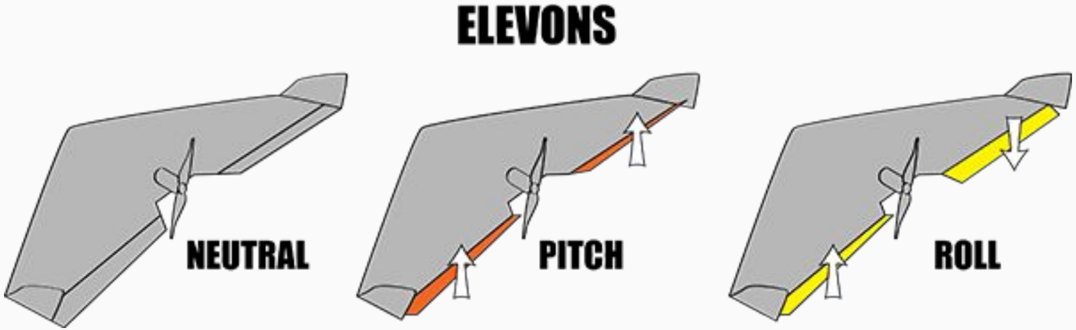
Flying wing

Best surface (volume) to lift ratio - it brings highest payload and MTOM.

There is a problem to stabilise in the yaw axis, no vertical wing/surface. May require thrust control, including thrust vectoring, to yaw properly.

In many models, there are just 2 control surfaces, so that requires mixing of the ailerons and elevators in the control unit (FC).

Its construction is simple



Plane - construction and control

V-tail (butterfly tail) construction using only 2 control surfaces for pitch and yaw.

Also requires mixing.

Invented in 1930 by Polish engineer, Jerzy Rudlicki

Plane - construction and control

RC plane drones frequently use flaps.

They increase lift force (but also increase drag). Changing of the wing shape lowers the stall speed and increase stability when flaps deployed. Used in particular on take-off and landing.

Models tend to “bubble” on flap deploy. Special, slow servos are used to deploy flaps.

Plane - construction and control

In scale models, body and frames are usually built using:

- Styrofoam
- Elapor
- EPS (Expanded PolyStyrene)
- EPO (Expanded PolyOlefin)
- EPP (Expanded PolyPropylene)
- Light wood
- Reinforcements are made of carbon fiber rods
- Sheathing - modeling foil or fabric

Plane - construction and control

Propeller materials:

- Wood
- Plastic
- Carbon fiber

Fixed propellers and propellers with variable blade pitch.

Folding propellers i.e. motorised soarers

Helis (Helicopters)

A construction that is known for a long time (vide Leonardo DaVinci's drawings).

There is no passive lift generation (only active)

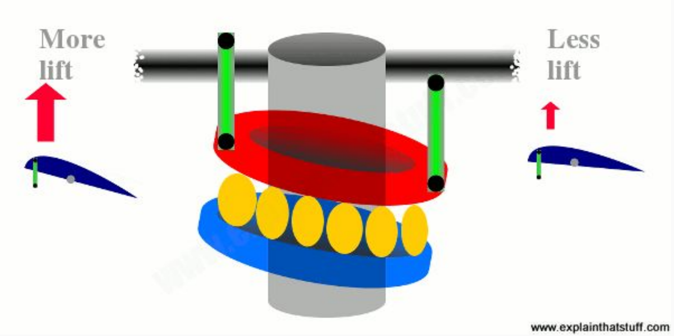
There is variety of approaches to the helicopter construction, but the most common is the one with main rotor and tail rotor, eventually with two tandem or coaxial main rotors.

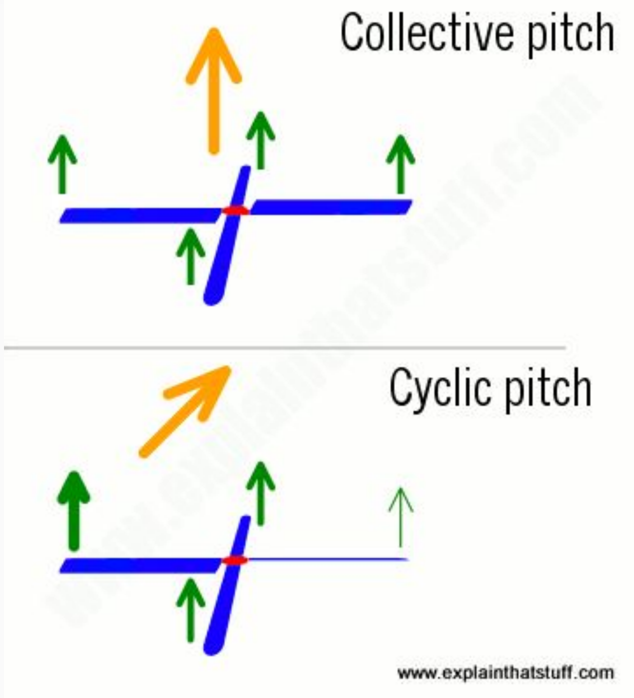
Helicopter's construction and principles of operation

The blade of the main rotor in its intersection looks (and operates) like a rotating wing.

The hub is able to change blades' angle of attack thus change both thrust and its vector!

Hub controls Pitch & Roll





Helicopter’s construction and principles of operation

Tail rotor acts opposite to the rotation force, thus causing the helicopter not to “rotate” itself under the wing.

Tail rotors are variable pitch (eventually with variable rotation speed as in micro UAV) so changing the force generated by the tail rotor, causes the helicopter to yaw.

This UAV model requires flight controller to stabilise its operation.

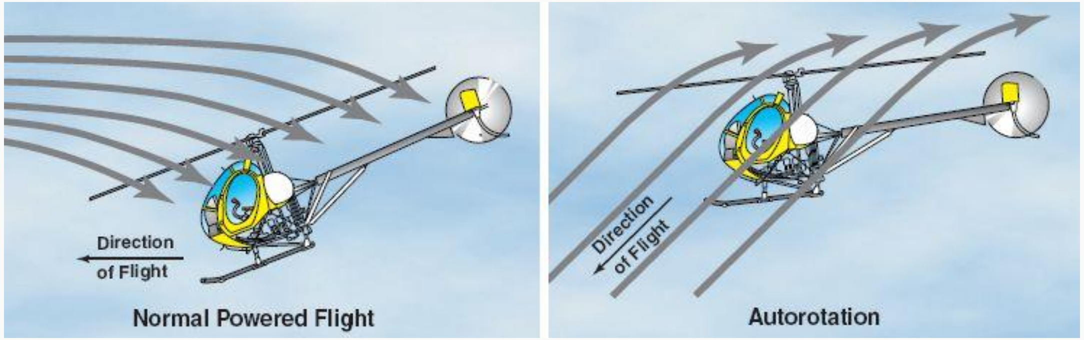
Helicopter’s construction and principles of operation - hint

What happens if helicopter’s engine is down?

Will it fall and break? Well, not necessarily...

<u>Autorotation…</u>

You can try it with large helicopter models
But it is really hard even in real helis and requires skilled operator.



A research possibility: a system that automatically introduces autorotation on engine failure

Helicopter’s construction and principles of operation

UAV heli body frames are made of UAV są wykonywane z carbon fiber, sometimes aluminum and partially steel.

The external body (case) is made of the thin plastic.

Blades and rotors:

- Small models use plastic blades/fans
- Large constructions use carbon fiber

Multirotors

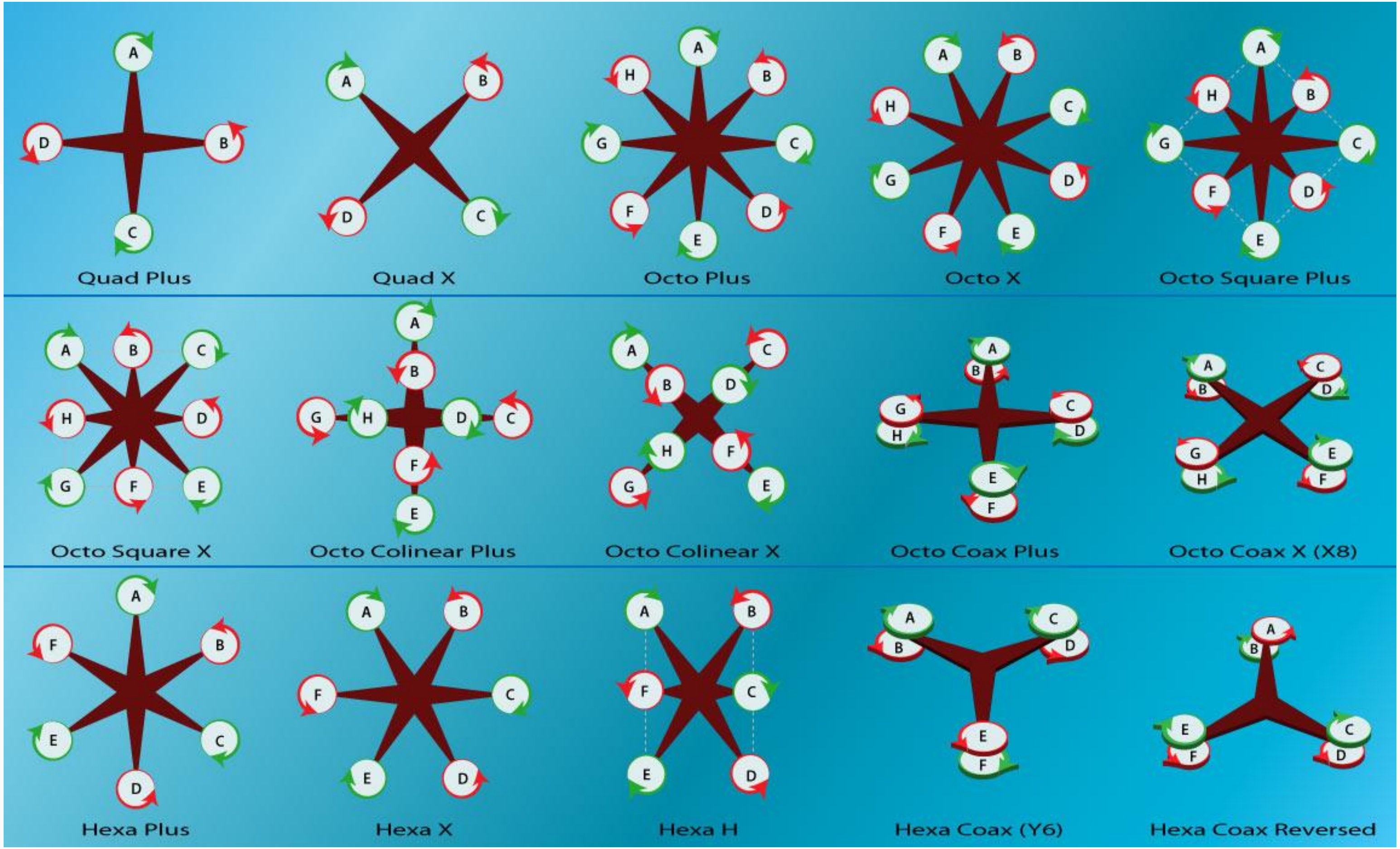
Most popular UAV constructions so far :-)

UAV, drone is substituted with multirotor (usually 4 to 8 rotors).

High maneuverability

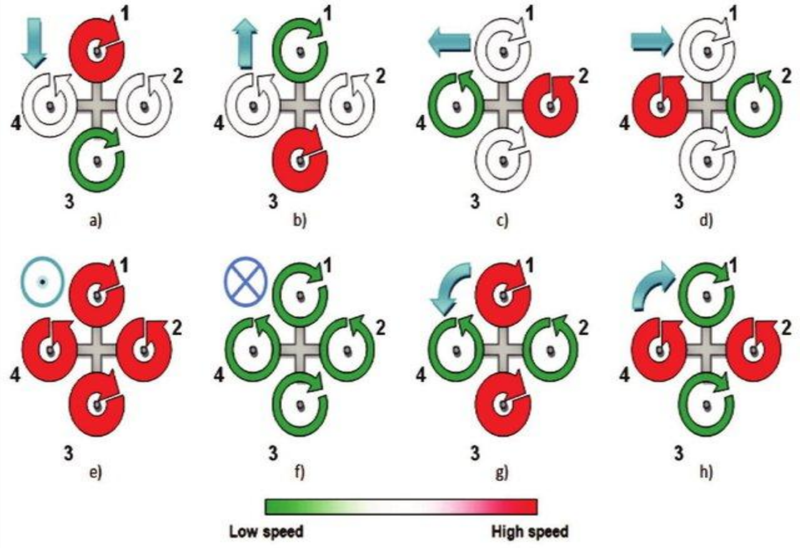
Multirotors require advanced FC

Dynamic generation of the lift force



Types of multirotors

Multirotors - principles of operation



Dr.E.N.Ganesh (Researchgate.net) - based on Quad+

Multirotors - principles of operation

- Multirotors perform worse when rotating in yaw.
- Because they can hoover and fly in any direction, it is common not to rotate multirotor to let it head towards movement direction. You can fly side, backwards, easily.
    - Obviously it depends on the accessories and the mission, i.e. if you have a drone with front mount camera that cannot yaw, then you need to yaw the drone towards observed object.

Multirotor construction - frame

- Majority of the multirotor frames is made of plastic, it is not rare they're 3D printed, 3D), carbon fiber and other lightweight components, wood is rare however.
- Blades as in case of planes but common is blades are fixed pitch and note there are always clockwise and counterclockwise needed.
- In small multirotors it is common to use PCB as a frame.
    - Its drawback is, when you hit the ground, it usually breaks electronics and circuits.

Multirotor constructions - rare...

Minor number of drones use variable pitch blades and central rotor with power distribution using gears. Pitch change causes lift change and each rotor has separate control with servo.

Using central motor causes drone to become lighter and has better mass distribution that is essential in racing drones.

This construction is not very common.

Propulsions, servos

UAV constructions

Electric motors

Combustion motors (Piston engines)

Jet motors

Servos

Blades

Electric motors

Most popular in both lightweight (some dozen of g) up to even hundreds of kg.

The only choice for micro and mini drones.

Cheap, simple and reliable construction, easy to maintain

There is no fueling system other than battery and speed controllers needed

They require significant amount of electricity to spin

Brushed DC motors

Small DC motors are usually using BRUSHES.

Simplest construction and lightweight.

Speed control with effective voltage delivered to the motor (using PWM).

Brushed DC motors

Very popular in small UAVs and UGVs, usually indoor operating.

Controlled via MOSFET transistors.

Because of their internal construction there is a limit in size, and over it, power/mass ratio becomes adverse.

They tend to overheat easily and brushes quite quickly wear out.

DC motor is connected using two wires. They have dedicated rotation speed and manufactured with explicit rotation direction (CW/CCW).

Brushless DC motors

Most popular ones at the moment, but most complex ones regarding their construction and control.

They dissipate heat better, have no friction elements (brushes), so they wear out slower than brushed ones.

They are controlled with ESC (electronic speed controller) using 3 wires.

Comparing to the brushed motors, they present better torque and are more energy efficient (more power out of every electrical Watt delivered).

Brushless DC motors -types

In UAVs there are 2 types of brushless motors used, regarding their mechanical structure. Assuming both have same external volume and mass, following is true:

- Inrunner (magnets rotate inside of the enclosure/stator)
  - Lower diameter, longer, lower torque
  - higher Kv (1000 rotations per minute per each Volt delivered to the motor)
  - Slightly better heat dispersion
- Outrunner (stator is surrounded with rotor and case rotates)
  - higher diameter, rather flat than long, higher torque,
  - lower Kv

DC electric motor parameters

- Basic parameters are:
  - Brushless / Brushed
  - Mechanical dimensions and mounting
  - Kv (1000 rotations per minute per each Volt delivered to the motor)
  - Power
  - Maximum voltage, usually given as number od “S”, (1S, 5S, etc.).
    - Each “S” is average 3.7V (see section on batteries).
  - Shaft diameter and blade mounting system
  - Inrunner/Outrunner

Piston engines

Popular in larger planes.

One, eventually 2 piston engines are the most common

Types of the piston engines

- Spark plug engines - a spark plug, same working principles as in petrol car engines is used - electrical spark ignites:
  - They use regular petrol, eventually aviation fuel (avgas, not jet fuel)
- Nitro motors - somehow similar to the idea used in “diesel” - they use glow plug that heats the fuel but does not ignite it directly as a spark plug:
  - A special fuel “nitro” is used. Nitro: methanol + nitromethane 10-40%.

Combustion motors comparing to electrical

- Combustion motors present usually much higher torque than electric motors but their implementation and maintenance is very complex (servicing as well).
- Most of them is two-stroke and requires fuel and lubricant oil mixture
- They require (usually electrical) starter, eventually manual start.
- There is a fuel management system required with a tank and there is liquid fuel inside.
- It is rather in large constructions.
- They operate good in quite narrow of RPMs and are slower in response.

Jet engines (turbines)

At the moment, only turbojets, no scale turbofans are available*

*There is an EDF but it is … electrical ;-)

Jet motor features

- Very expensive in both purchase and management.
- Theoretically they present higher reliability and lower failure possibility than piston ones.
- They are more efficient regarding fuel consumption (there is no forward to rotation movement in jets, as it is in piston based ones).
- They require starter (usually electric).
- Small jet motor can generate even >100Nm of thrust.
- Exhaust gases are hot (even over 1000C) and it impacts drone construction.

EDF motors - hint

- There are electric motor-based constructions that mimic turbofans, so called EDFs (Electric Duct Fan)
- They use Inrunner brushless motors inside.

Servos

Electrical

Usually they rotate within limited angles (common is 180 deg).

Used to drive control surfaces in planes, fold the gear, release payload, etc.

There are analogue and digital servos.

Servos are controlled standardised way (PWM), there are some exceptions, however.

Servos in details

Servos are implemented as a DC (usually brushed) motor with an encoder.

Servos are controlled with 3 wires: GND+Vcc (voltage varies by servo size and power) and PWM control (usually TTL 5V/ 3.3V logic).

There is a standardised control method for so called “analogue” (majority) of servo motors: PWM is 50 Hz (digital up to 300 Hz) and standard duty cycle is in between 1ms and 2ms for high level of the control signal. Changing duty cycle controls rotation, where 1ms = 0 degree, 2ms = 180 degrees.

Servo - specification parameters

Servos technical specification include:

- Physical dimensions, mass
- Operation voltage (range)
- Gear material (common is plastic or metal)
- Torque, given in kg/cm rated at the specified voltage (voltage change causes torque change as well).
- Mounting method for the shaft (diameter, number of teeth)
- Digital / analogue (here it specifies control signal requirements but also digital servos are quicker responding ones due to the higher control frequency)
- Rotation speed: time (in seconds) needed to rotate servo by 60 degrees
    - There are special “anti-bubbling” servos for the flaps.

Servos - explanation of the selected parameters

- Torque (kg/cm with fixed voltage)
  - A standard parameter, presenting an ability to lift a number of kg with a 1cm lever. This parameter is provided for average or maximum voltage: the higher the powering voltage (within the correct range) the bigger the value, i.e. standard servo powered with 4.8V has ability to lift 1.8kg with 1cm lever but powered with 6V (still correct) is 2.2kg.
- Rotation speed as number of seconds (fractal) needed to rotate the servo by the 60 degrees.
  - Full load is assumed
  - It also depends on the voltage, i.e. standard servo, for 4.8V presents 0.1s/60deg while it is 0.08s/60deg when powered with 6V.

Propellers

Basic component, virtually for any UAV

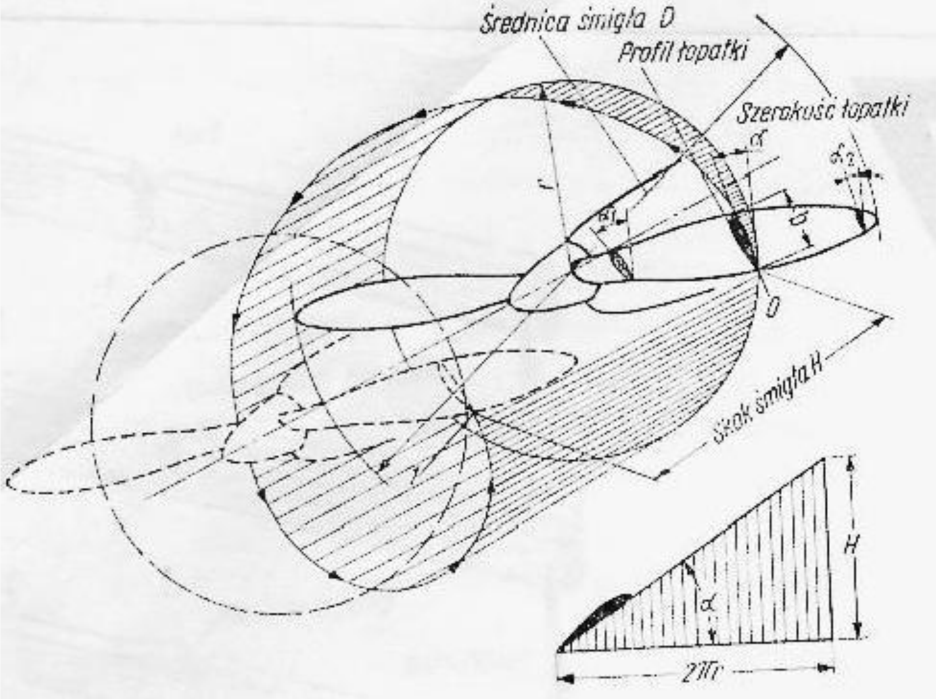
Propeller blades

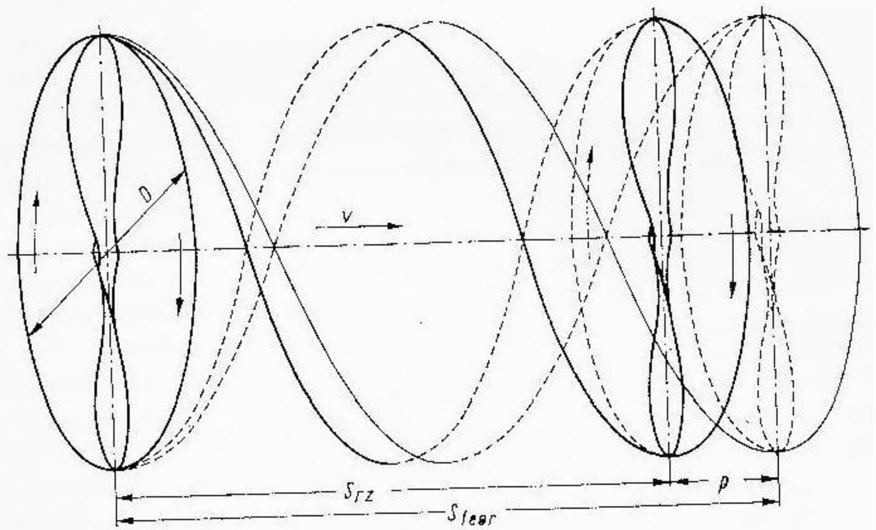
- Single blade behaves like rotating wing - its perpendicular intersection is same as a wing.
- A propeller must be properly balanced. There are balancers and it is possible to modify it to let it be correctly balanced
  - By polishing (with a sand paper) end of the blade at its bottom (**never on the top!**).
  - Eventually you can add a piece of self adhesive tape/film to increase the weight but that is not really advised.
- Mind the flight conditions: if blade is a subject of icing, you lose force thus lift in multirotors or thrust in planes.

Propeller features

- 4 major technical properties for a propeller:
  - Dimension
  - Constant / variable pitch
  - Number of blades
  - Foldability
- Propeller have to be adjusted along with the motor used: it is common that motor specification includes range of accepted propellers:
  - If propeller diameter or its pitch is too high, then you can overstress motor and burn it (overheat).
  - If propeller diameter or the pitch us too low, you will have inefficient propulsion then.

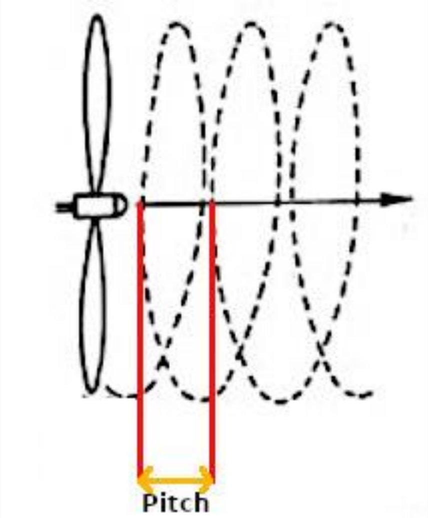
Propeller (blade) pitch





Propeller (blade) pitch

- Propeller screws into the air like a screw into the wood.
- Propeller pitch is a distance that propeller would go forwards during single rotation, if in dense environment.
- Propeller marked 12x5.5 means it is a 12 inch diameter and it will go “forwards” by 5.5 inch if rotated once in dense environment. Obviously this distance is only theoretical and gives in fact relative reference / comparison, as air is a gas (liquid) not solid.
  - Propeller efficiency is not constant along rotation speed. It would be best to have some lower pitch when starting the thrust then increase it along with rotation and increased airflow.
  - Every propeller has its specific forwards speed, that it works most efficient.



Propellers

- There are push-type and pull type propellers, used mostly for fixed wings.
  - The propeller can be mounted in the front of the plane (then pulls fuselage) or it can be mounted at the back (like i.e. in flying wings) so it pushes the body. Front mounted propeller works in the non-turbulent air stream.
  - Pushing propellers are considered to be little less efficient as they work in the airstream flowing by the front wing.
    - Back or mid mounting of the pusher is good in terms of COG of the UAV.

Foldable blades

- Applies to the push and pull type propellers.
  - Regarding the push/pull, folding direction is important.
  - They are used frequently in soarer (sailplanes), to limit drag when not spinning as they are constant pitch blades.

Sensors

UAV hardware components

- IMU (gyro, accelerometer)
- Barometer
- Magnetometer (compass)
- Thermometer
- Navigation GNSS
- Indoor navigation
- Resources monitoring (rotation, fuel, battery)

IMU

Implemented as MEMS (MicroElectroMechanical System)

Described by the number of Degrees of Freedom

Usually 6DOF (3D gyro + 3D accelerometer), sometime integrated with 3D magnetometer (9DOF) and eventually with additional baro (10DOF)

Gyro and accelerometer are usually implemented as single circuit (MEMS).

Connectivity: I2C and/or SPI

6DOF

10DOF

9DOF

IMU - properties

- Gyro and accelerometer are usually implemented as single circuit.
    - Magnetometer and Barometer are separate chips.
- Most common communication protocols are I2C and SPI.
- Some hardware has programmable measurement range (i.e. accelerometer).
- Some integrate thermometer to compensate measurements that vary by temperature, you can use it to read temperature then (temperature of the device can be different from environmental, due to the internal heating of the electronic chips).
- IMU integrates 3 axes (X,Y,Z). Historically there were separate devices for each axis, now they are integrated so you can measure acceleration and pitch/roll/yaw with single device.
- Variations are reported per axis, separate. Rare solutions introduce quaternions.
- The negative gyros' feature is so called drift: inaccuracy of the readings observed as "flowing" or "bouncing" of the fixed device.

IMU - applications

- Obligatory to stabilise for Multirotors and Helis.
- Stabilisation loopback usually goes up to 32 kHz (common is 8 kHz however).
- For MR and Heli it is crucial sensor: its failure usually means lack of stability and uncontrolled fall of the UAV.
- Nowadays usually integrated with FC board.
- In larger and professional drones IMU used to be doubled or even tripled for reliability and safety of the operation.
- In case of the RC fixed wings it is used as supplementary module to smoothen operation, eventually limit max roll, pitch and yaw to correct operator.
    - It is obligatory for autonomous flights, regardless of the UAV type.

IMU - common hardware models

- IMU vendors deliver both chips for soldering as well as development boards.
- Most popular used in drones are:
  - TDK: MPU-6xxx, MPU-9xxx, ITG-3200 (gyro only=3DOF), ICM-20xxx
  - Maxim: MAX2110x
  - STMicroelectronics: LSM6DS3, LM9DS1, etc.
  - Bosch: series BMI xxx, i.e. BMI055
  - Many other
- They are most common in the commercial solutions.
- They vary by accuracy (including temperature compensation and stability) but in common, they are exchangeable, delivering similar quality/performance.
  - Due to the temperature-related variability and necessary compensation, it is common that FCs “preheat” IMU before take-off as the moment before take off is a reference one.

Barometer

Measures absolute air pressure

You can recognize them easily as chips have a small whole to let the air in.

Barometr - properties and features

- Used to keep altitude (eventually change it by desired value).
  - Necessary to implement alt-hold flying mode.
- The reference point is the take-off level (so measure regarding AGL, not AMSL).
- As pressure changes (over the time and location) it impacts the altitude readings so there is a correction mechanism, that “manually” adds or subtracts amount of meters to keep altitude reading reliable. It is important in case of long in distance eventually long in time flights.
- Airflow from the propellers can disturb baro operation and cause false readings. It is necessary to put a foam damper eventually deliver air using some pipe.
- Common interfaces are I2C and SPI.
- Current implementations present quite good accuracy, even up to the cm.

Barometr - applications

- Altitude hold mode, very useful for majority of UAV operations.
- Not used during FPV racing flights where alt-hold mode is not used. Many FC for racing drones do not even include baro, only 6DOF IMU.
- It is obligatory for autonomous flights.

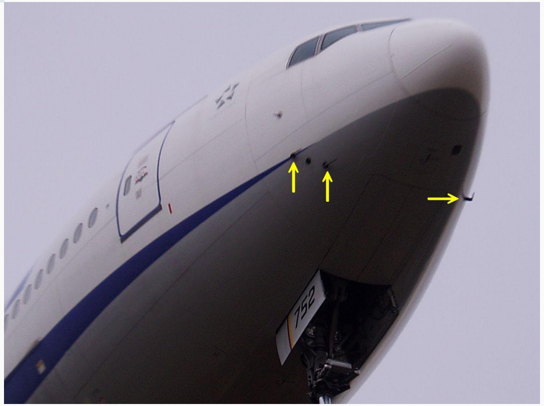
Barometr - modele

- Most common one is:
  - Bosch: BMP xxx series (BMP180, 280, 050)
    - Those are quite frequently integrated with temperature and humidity sensors, used in weather station but also used in drones.
- Other manufacturers:
  - TE: MS5611

Differential barometer

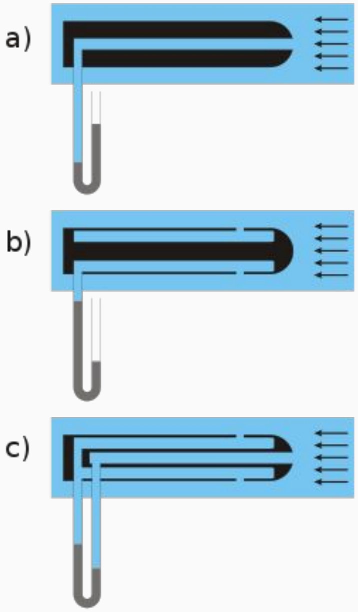
A special, differential barometer with mechanical solution (a pipe or pipes) provides a method to measure airspeed.

Pitot and Prandtl pipes.



Differential barometer - features

- It measures the difference between statical and dynamic pressure:
  - It requires so called “Prandl pipe” (c) composed of the “Pitot pipe” (a), and static pressure sensor (b).
- Essential for fixed wings because provides ability to measure:
  - Wind speed (indirectly using i.e. cruising around and looking for maximum/minimum readings)
  - True air speed (not only ground speed, as GNSS based).
- It is necessary for autonomous landing for the fixed wings UAVs.

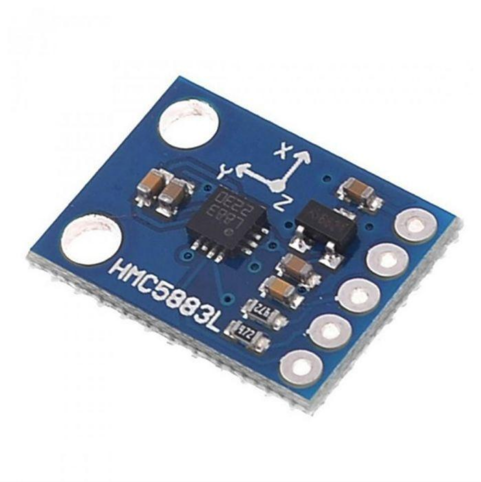


Differential sensor models

- Most common:
  - Sensirion: SDP3x
    - Connection interface is analogue or I2C (version depending)
  - NXP: MPXV7002DP
    - Analogue interface
- Usually requires A/D converter feature in the FC.

Magnetometer

Digital compass



Magnetometer - features

- Used to orientate drone’s yaw in absolute way (heading).
- Sensitive for electromagnetic fields, particularly indoors.
- Drone motors generate strong magnetic field thus may impact readings.
- Most of the magnetometers nowadays are 3D ones, able to precisely point towards magnetic North even if drone is tilted.
- Common communication interfaces include: I2C or SPI
- As it used relative measurements, you need to calibrate it, rotating usually in at least 2 of 3 axes to detect maximum and minimum readings.

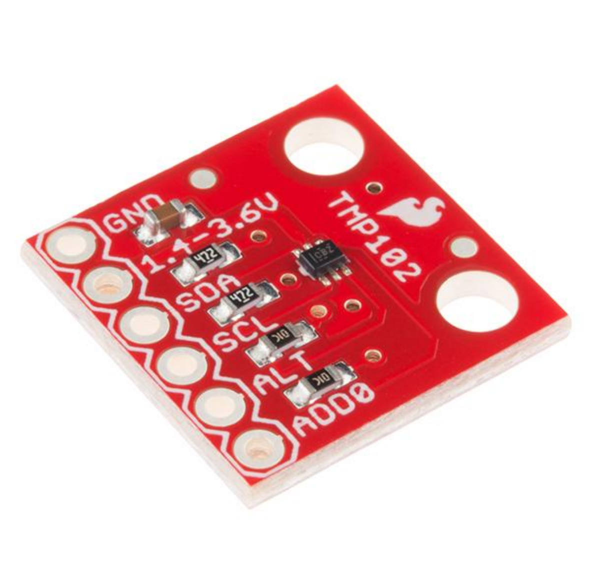
Magnetometr - hardware

- Most common hardware includes:
  - Asachi Kasei Micorodevices: AKM8963, MPU 9xxx (internally uses AKM, not acknowledged) as a 9/10DOF component.
  - Honeywell: HMC5883 - commonly used as additional in the GPS/GNSS modules but available as separate modules as well.
  - iSentek: IST8310

Thermometer

Usually implemented in IMU/other sensors for temperature compensation of the readings.

Pretty frequently integrated with humidity sensor.



Thermometer - features

- Usually integrated with humidity sensor (weather station applications).
- Used commonly to monitor and prevent overheating of the main drone components, i.e. battery, motor, drivers (ESCs)
- In case of the high altitude drones it may be applicated to detect icing possibility.
- Common communication protocols include I2C and SPI.
- Internal implementation usually bases on NTC / PTC, AD converter and tiny microcontroller.

Thermometer - models

- Almost every significant chip manufacturer in the world offers sort of chips/modules:
    - Most popular are DHT-11 i DHT-22 modules but they are quite large. NTC based.
    - Texas Instruments: TMP275.
    - Maxim: DS18B20.
    - Bosch: BME 280 (as a part of air pressure sensor, used for temperature compensation of the readings).

GNSS (GPS, Glonass, Galileo, Beidou)

Satellite constellation based navigation.

GNSS features

- Works outdoors. Requires good sky view, best in full circle, to contact satellites. Does not work indoors, eventually accuracy is low.
  - There is a sort of solutions to use standard receiver indoors, but all are extremely expensive.
- Requires precise, common time base and so called Almanac.
  - Receiver synchronises time with satellites, based on augmentation correction, also downloads Almanac.
  - Almanac download is time consuming (transmission is slow), so it is common to download it via the Internet or other channel to speed up obtaining of the “fix” of the receiver.
- GPS is great for planar positioning but performs bad for altitude positioning.

GNSS features

- Modern receivers use multiple constellations parallel, to provide better accuracy:
    - GPS
    - Glonass
    - Beidou
    - Galileo
    - other
- So called “corrections” are distributed various way: via satellite or via FM radio (eventually via packet transmission through the Internet) - area depending.

GNSS features

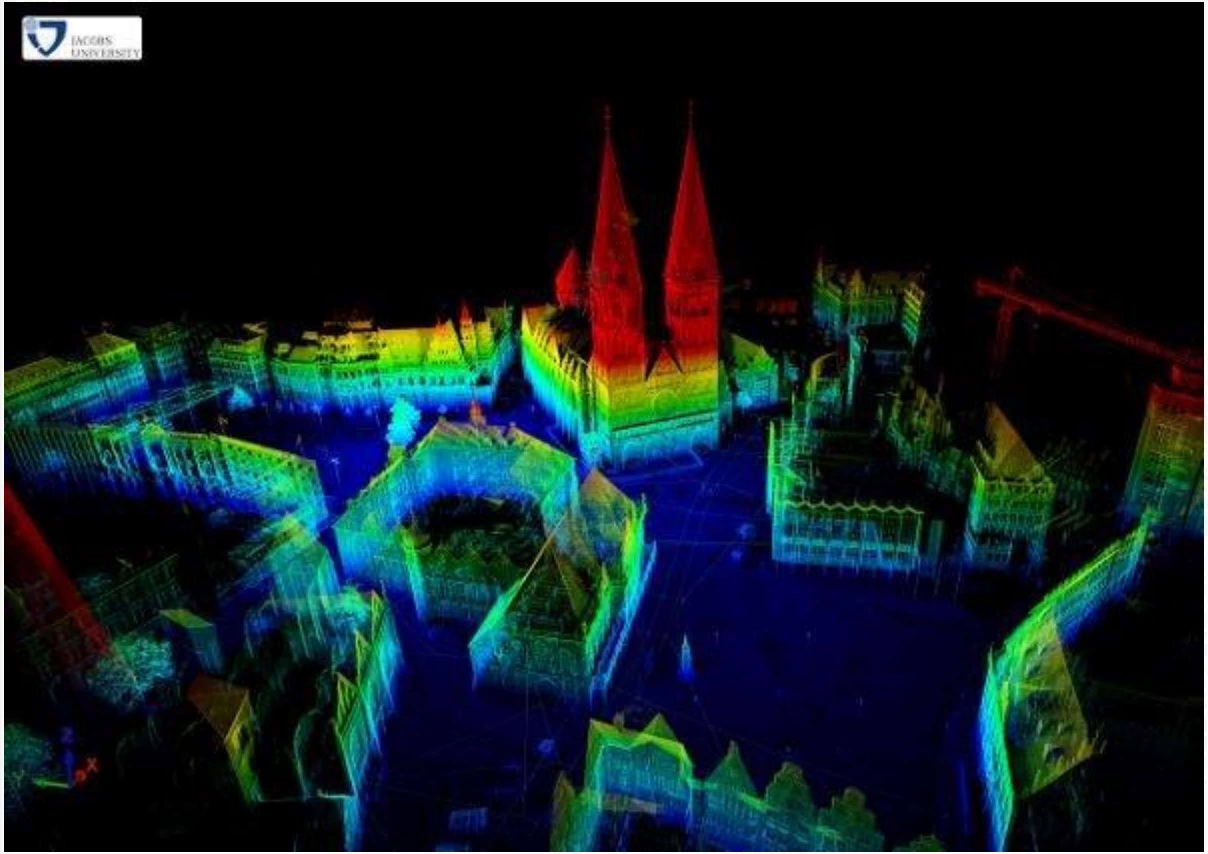
- Drone should remain in position unless fix is obtained.
- Current drone ecosystems use at least two receivers, one for drone, one for operator, so flying UAV knows the position of the operator thus can introduce automated RTH position and also provide operator with information about its direction and distance.
- GNSS receiver + barometer are necessary for autonomous operations.
- GNSS delivers only ground speed.

GNSS interfaces and protocols

- Common is to use UART (serial) at 9600 kbps.
  - Latest models provide I2C and SPI
- Application level protocol is NMEA.
- GNSS modules are usually equipped with external ceramic antenna, that improves positioning accuracy, in particular in demanding environments.
- It is common that is contains a RAM and battery backup to keep Almanac and speed up obtaining of the fix after restarting the device.
- The most common i Neo series from UBLOX.

Indoor navigation

Indirect methods using optical based area mapping, depth cameras, lidars, inertial navigation, beacons (heat maps)/UWB, other.



Indoor navigation

- The most dynamically developing research area for UAV.
- Formerly, using markers (similar technology to the AR) = low quality and problematic data processing.
- Inertial navigation may be supplementary, but not as a main one in indoor UAV flying.
- LIDAR and SLAM (Simultaneous Location and Mapping) - currently LIDARS are planar and limited in vertical range, also heavy, so are more suitable for UGVs.

Indoor navigation

- Depth cameras (i.e. Intel Realsense) - short range and rather sparse. Usually used to detect obstacles nearby.
- Distance sensors - ultrasound, infrared. Used supplementary, for short distances i.e. during landing, to precisely measure distance to the ground.
- Optical flow, to position hold (using camera facing down).
- Optical image processing - currently most drones rely on this technique and it develops. Uses AI and motion analysis against stable surrounding objects.
- Requires decent CPU/GPU resources, i.e. FPGA based image processing.

Indoor navigation with external infrastructure

- Using beacons i.e. BLE, WiFi, with so called heatmap. Requires environment to be calibrated (measured) in advance and map has to be known to the UAV.
- IR-based positioning systems: signal generators located in the environment ar needed, that position UAV “externally” to it, so constant communication is required. It works somehow opposite, it is not drone that positions itself, rather it is environment that positions the drone and delivers its position.

Other sensors

Measuring any other physical phenomenon than aforementioned...

Other sensors - examples

Motor rotation sensors (i.e. for piston engines), using optical barrier and i.e. rotating element (can be a propeller as well), eventually reflection from the rotating element.

Liquid fuel level measurements.

Battery voltage measurement - common in all drones as it tells that battery is running out of energy and it is time to finish the mission.

Other sensors

General telemetry, reporting drone components state and delivering information to the operator.

Flight Controller / Remote Control

UAV hardware

Flight Controllers (FCs)

RC Transmitters (Ground Section)

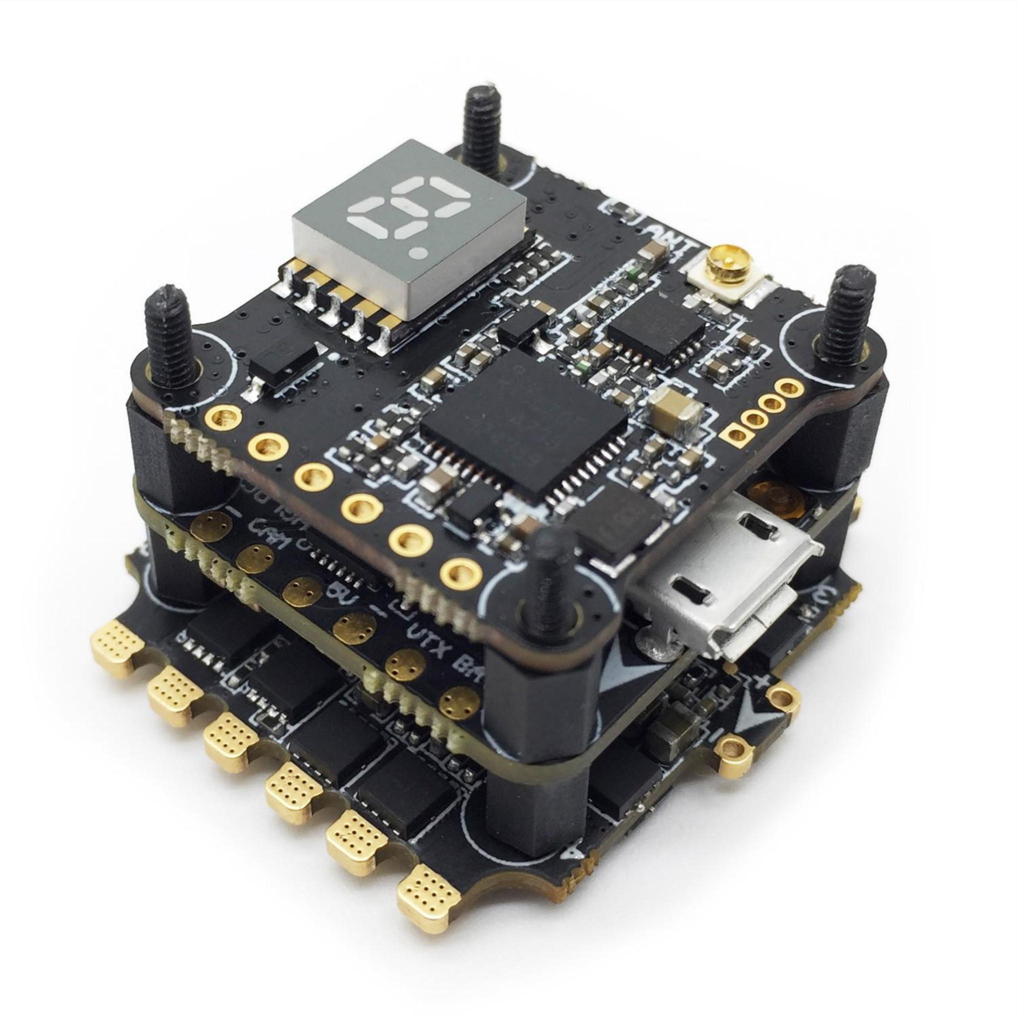
RC Receivers (Aerial Units)

Flight Controllers

They manage the drone operation implementing actions necessary to perform flight and introduce commands.

Usually offer variety of flight modes (software and hardware depending).

Starting from simple MCUs, finished on complex systems.



Flight controllers

Flight controllers provide help or even ability to fly (i.e. flight stabilisation).

Here all data from the sensors is integrated and actuators are managed.

They tend to implement variety of flight models including different autonomy levels:

- Fully manual flight modes (RC)
- Indirect control (i.e. RC with cap for training or smoothing operator’s decisions)
- Autonomous flights through the predefined waypoint list
- Fully autonomous flights where FC decide on flight parameters and mission.

Flight Controllers - characteristics

Flight controller drives indirectly actuators: motors, servos through power distribution module(s) depending on the motors used. Ultralight drones used to have this module (here MOSFET transistors) integrated with FC board.

FCs also manage telemetry tasks (OSD, telemetry) and handles utility management (i.e. PTZ camera, payload release).

Kontrolery lotu - procesory

Most popular FCs are:

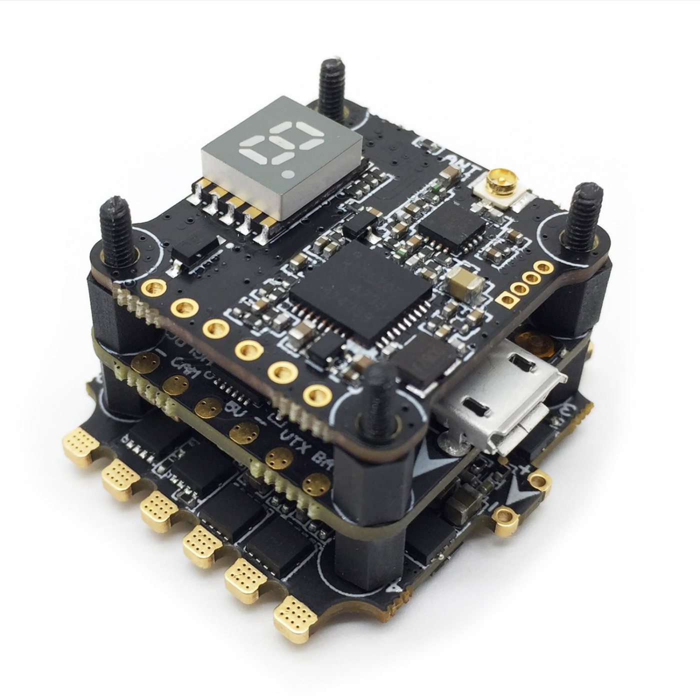
- SoC: Atmega (Arduino 2560, so called 8-bit Ardupilot) - limited in performance, nowadays rather obsolete still supported including autonomous flights.
- SoC: STM F1, F3, F4, F7 - ARM core, currently most popular for FC. Provide quite good performance with high reliability and low power consumption. Flexible in hardware implementation, including port multiplexing.
- Broadcom BCM - ARM core - i.e. Raspberry Pi and its clones.
- LPC1768 - ARM core, used in DJI drones (i.e. Naza M).
- Intel Atom - x86 / x64, for large drones due to the size and power consumption.

FCs example - racing ultralight drone with brushed motors

- “F3 EVO Brushed”
- Integrated 6DOF IMU
- SoC: STM32 F3 (mostly STM32F303CCT6)
- Integrated, MOSFET based power distribution board for quad/hex configuration.
- All-in-one lightweight construction.
- Limited extensibility.
- Powering 1s (theoretical 2s but there is lack of 2S brushed micro motors).
- Integrated input voltage stabiliser.
- Integrated USB (COM over USB) for configuration, updates and firmware change.
- Small flash memory.
- There are versions integrating DSM RC receiver.
- Only 3g !!!!

FCs example - racing drone with brushless motors

- Omnibus F4
- Processor STM32 F4 (common is STM32F405RGT6)
- Separate power distribution board with set of ESCs
- Provides OSD overlay for the analogue video signal
- Integrated tf card (micro SD) for logger
- Integrated voltage and currency monitor (can calculate total power consumed during flight).
- Integrated IMU, there are 6, 9 and 10 DOF versions.
- Power voltage between 1s and 6s
- There are stack extensions with 5.8GHz analogue video transmitter for FPV.
- Controller board (without power board) weights about 10g only
- Size is compact.

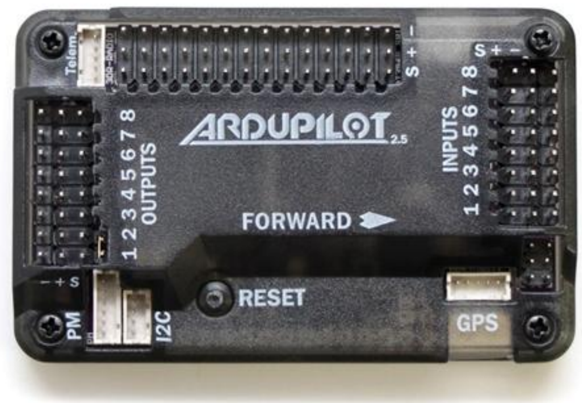


FCs example - aerial video drone

- Pixhawk PX4
- Processor STM32 F7 (usually STM32F765) + STM32F100 for I/O acceleration)
- Integrated double IMUs, magnetometer, barometer
- Multiple I/O extension ports, capable to handle I2C, SPI, UART, CAN, PWM (8 from the main MCU + 8 from the supplementary MCU)
- Analogue inputs for voltage/current measurements
- Integrated transflash (micro SD) card reader
- Dedicated inputs for a variety of RCs, including bidirectional
- No power board integrated
- Weight about 16-25g

FCs example - old but still working 8-bit

- APM 2.6 (no more updates, considered to be fixed)
- ATmega2560, 8 bit MCU.
- Small memory still enough to implement autonomous flights through waypoints. Used mostly in fixed wings, some decade ago.
- Integrated one IMU, magnetometer, barometer
- 4MB of flash for logs
- Constrained in resources, requires external module to implement OSD.
- Set of universal and dedicated ports, including GNSS, telemetry.
- Requires external RC receiver, no built-in RC possibility due to the constrained resources.



RC Receivers

Used both to remotely control UAV as well as switch flight modes and even upload flight plan ad hoc.

Wireless, FM based. There is variety of protocols.

RC receivers short characteristics

- Receivers usually meet with dedicated transmitters eventually family of transmitters.
- Formerly analogue (AM) transmission using open bands (27/35 MHz). Currently digital, using 2.4 GHz and 5.8 GHz.
- Commonly use in between 4 and 16 radio channels.
- Formerly, it is RC receiver that was controlling control surfaces in fixed wings directly. Nowadays it communicates FC.

RC receivers short characteristics

- RC range - in reality some 1-2 km using directional antennas. Some professional solutions deliver 4-8 km range. Using amplifiers (illegal) even up to the radio horizon.
- RC receivers are also telemetry / downlink transmitters.
- FC configuration, mode changes etc. used to be driven this way.
- There is a number of solutions using Bluetooth and WiFi, where you can virtually use i.e. mobile or tablet as a transmitter. Yet it is limited in range and problematic in use in WiFi “crowded” areas.

RC receivers short characteristics

- Some larger drone constructions introduce separate “virtual” remote controller that is implemented using external to the FC, additional board (i.e. RPI, nVidia Jetson, x86) that communicates to the FC. Then this external board communicates with operator and ground station via some other link.

RC Transmitters Ground Segment

Used to remotely pilot UAV, change flight modes, configure parameters and manage flight plans.

Wireless, mostly over FM radio - there are many transmission protocols with variety of features

RC Transmitters - Short Characteristics

- RC Transmitters:
  - Dedicated to the particular drone / family of drones, usually closed in hardware and software i.e. DJI, Yuneec commercial drones.
  - Open controllers with capability to insert variety of radio transmitter modules, so can operate with variety of receivers.
  - Universal protocols i.e. control via serial (COM) using Bluetooth or WiFi as communication channel.
    - It is pretty common that mobile phone is used as a controller
- RC Transmitters are pretty common to be telemetry (downlink) receivers, eventually they present camera view.
  - Sometimes mobile phone is used to present video and let the software application act as configuration interface to the drone.

RC Transmitters - UAV control (uplink)

A controller can be also software (virtual), i.e. PC or Mac computer, eventually Android device.

A mission can be defined in the software running on the PC class computer and uploaded using aforementioned serial port and separate radio link, eventually via RC transmitter connected to PC.

RC Transmitters - UAV control (uplink)

- In general, almost every UAV has at least 4 degrees of freedom / control (multirotors, helis, planes) as there are rotation axes:
    - pitch,
    - roll,
    - yaw,
    - throttle.

RC Transmitters - UAV control (uplink)

- RC Transmitter sends control signals from the UAVO to the UAV.
- Additionally it sends auxiliary information, i.e. waypoint list, flight mode change, additional control surfaces, gear control, lights control, utilities control (i.e. camera parameters, rotation, taking photo / video) and many other
- RC Transmitter, when bidirectional, presents the visual (and also voice) way flight parameters, regarding its construction.
    - Telemetry and video channels are separated. Sometime it is FC that overlays image with information (as in FPV), sometimes it is RC Transmitter holding this duty (is in popular, commercial video recording drones).

RC Transmitters - UAV control (uplink) - control interface

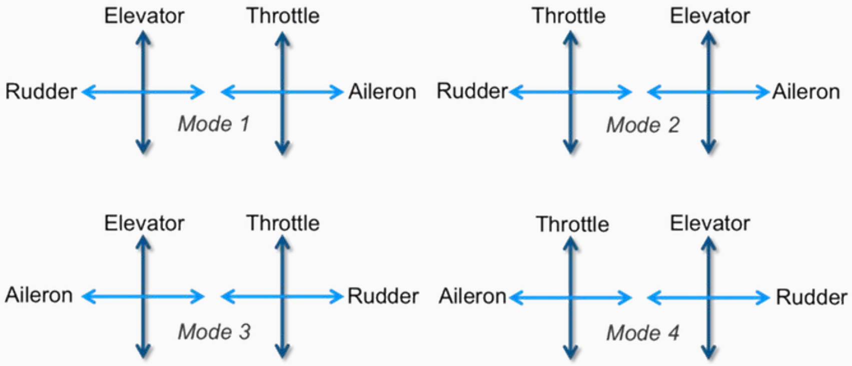
- Majority of universal, modern controllers has ability to freely bind controls to the transmission channels. Some include so called mixers (i.e. for Rudnicki tails), curve characteristics and correction, dead zones for control sticks, neutral points and so on.
- There are used to be many switches (bi-stable, with triple-positions), and rotation knobs. One can bind switches to let their position represent particular PWM duty cycle value (referenced as 0..1023) so it can "simulate" separate RC channel and its changes.

RC Transmitters - manual control logic

- The most common mode used is Mode 2:
  - Left stick is throttle, rudder;
  - Right stick is ailerons, elevator;
- Warning, not all of the switching components are universal, i.e. throttle used in FPV flight (or in planes control) can have different mechanical implementation than the other one.
  - i.e. some drones use auto-return of the released sticks to their central position (regarding throttle), while some other use auto-lowering to the 0.

RC Transmitters - manual control logic

- The most common is Mode 2
- Throttle behavior:
  - In case of planes there is no auto-centering spring, so when you release throttle it remains at preselected value, so neutral position (throttle=0) is in most lower (down) position. This is co called “absolute control”.
  - In case of MRs, as they hoover with active motors, there is auto-return spring to let the throttle return to the central position. Moving throttle up causes ascent, down causes descent. It is so called “relative control”.



Powering

UAV hardware

Batteries

ESC, BEC

Chargers and balancers

Flight controllers*

Batteries

Battery delivers current to both flight control equipment as well as for actuators and utilities carried by the drone.

It is common to use more batteries than one, i.e. one for actuators and one for other devices (why?)

Batteries in general

Here we mostly focus on UAVs that are propulsed with electrical motors but even in case of the combustion motors, it is necessary to use battery for the electronic equipment.

- UAV batteries present following features
  - Amount of the energy accumulated, calculated as battery capacity (mAh) multiplied times average (or integrated) voltage (V),
  - Maximum constant and burst current (A),
  - Voltage and current discharge characteristics
  - Connector
  - Maximum charging current
  - Charging method

Types of batteries and their features

- Most common technology up to date is Lithium-Polymer:
  - LiPo - presents highest energy density still in reasonable price
- In case of the ground stations, as weight to energy ratio is not so crucial, it is common to use:
  - NiMH, NiZN (formerly NiCD, but they present memory effect)
  - It is common that RC Transmitters are equipped with built-in (sealed) Li-Ion batteries, same type as in mobiles and laptops.
    - Li-Ion present slightly lower energy density still they are considered to be safer in use (anyway not always, mind infamous Samsung Galaxy Note 7 problem)

LiPo batteries and their features

- LiLo battery voltage in UAV applications is given by a number of serial cells, referenced as number “S”:
  - 1S = 3.7V nominal voltage for a single cell.
  - 2S means there are 2 cells connected in serial, so it is 7.4V, then 3S, 4S, and so on.
  - Warning: 3.7V is a nominal cell voltage.
    - Fully loaded cell is 4.2V
    - **Never fully discharge cells, do not discharge below 3.3V (3.1V) / each cell!**
    - **You should store batteries in so called “storage” mode, that is about 3.7-3.8V per cell. Never store batteries fully charged or fully discharged.**
- Rare still existing is appearance of the “P” in the battery specification. It means, there are parallel connected cells:
  - 2S2P simply means there are two sets of batteries connected in serial, whereas each set is composed of 2 batteries connected parallel.

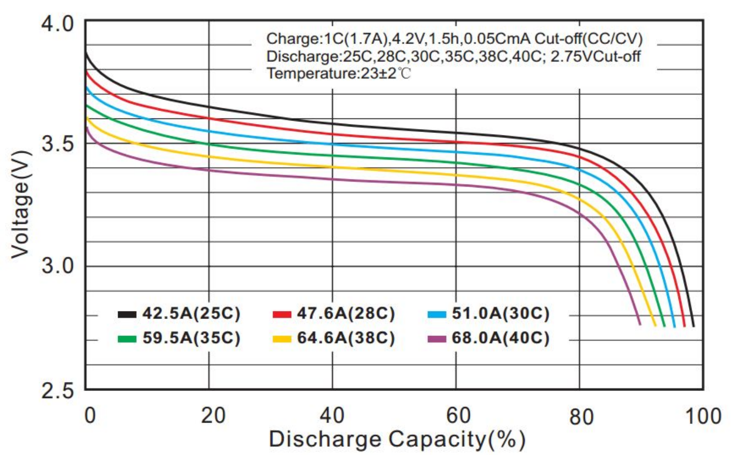
LiPo batteries and their features

- Battery capacity is usually given in mAH, so battery marked with 1000 means there is 1000mAh. Larger batteries used to have their capacity given in an A magnitude, i.e. 5.4 means it is 5400mAh.

- Maximum discharge (continuous, nominal) current is provided in “C” (Capacity) units and relates to the battery capacity. So i.e. 20C for 1000mAh battery is 20A, while 20C for 5400mAh battery is 108A.
  - Additionally there used to be another parameter specifying maximum burst current (usually much higher than nominal) but there is no exact information, how long time the “burst” can last.
- Some batteries also provide maximum charge current. If it is not specified, common assumption is 1C, so for 2800mAh battery it is 2.8A.

LiPo batteries and their features - discharging

- Each battery cell has its own internal resistance
  - The lower, the better.
  - We measure it in milli-ohms and battery chargers can measure it. Following reference gives an idea about the value:
    - 0-6m - perfect
  - >50m - battery wears out
  - >80m - do not use, replace with new
- A battery with high internal resistance overheats but most of all it has different discharge curve thus it is dangerous to use, because voltage monitoring wont let you correctly estimate remaining flight time! Voltage can drop significantly in any moment of use, unexpectedly.

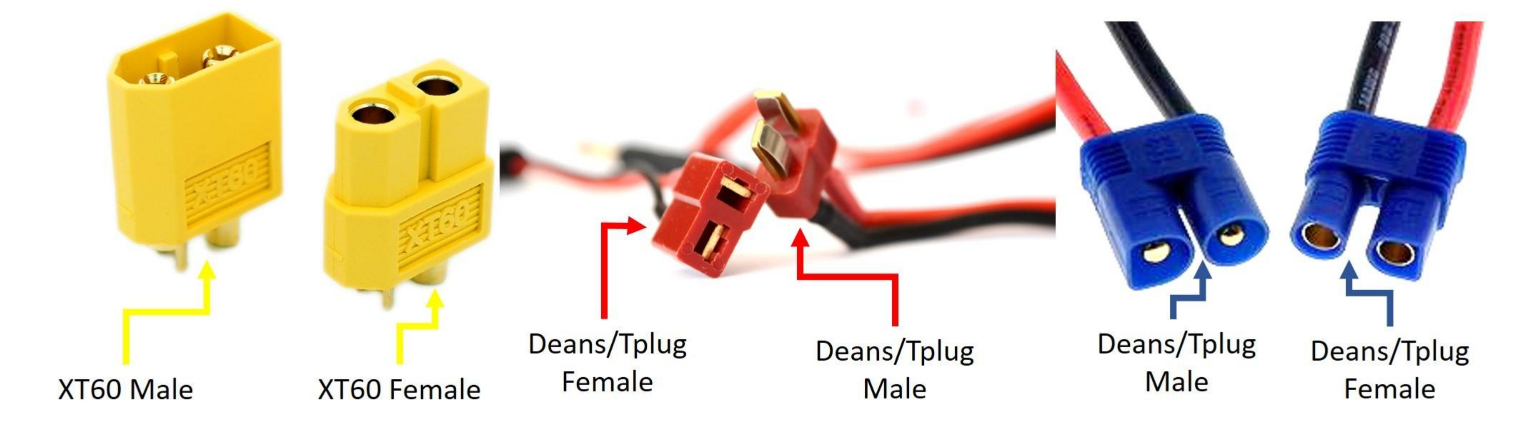


LiPo batteries and their features - charging

- **Never charge nor use puffed or damaged mechanically battery!**
  - **It can easily start a fire, eventually even blow!**
- Current state, finishing charging and cut-off discharge is based on the battery voltage.
- As batteries >1S are connected in serial, it is essential to charge each cell equally and they tend to have different parameters. So there is a balancer needed to equalize voltage during charging. **To charge LiPo >1s it is obligatory to use balancer:**
  - Imagine, one of the cells of the 2S battery is already charged to the 4.2V (full) while other is 3.6V. When not using balancer, external connectors will present 4.2+3.6=7.8V in total and charger will try to charge up to 4.2+4.2=8.4V. It can cause however that first cell with overcharge and burn. It is balancer's duty to take care to charge each cell individually.

Battery connectors

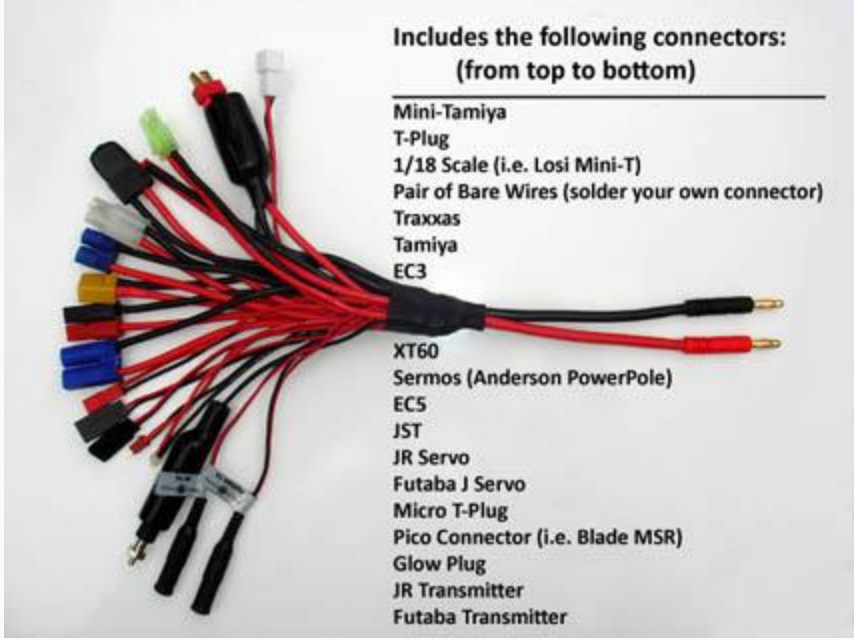
- There are many standards but about 3-4 are commonly used in open UAV constructions:



Battery connectors

- Because of variety of standards, battery chargers and balancers used to be sold with a bunch of adapters for mains.

- Regarding balanser connector there are 2 standards:
  - A JST plug variable size (most popular).
  - A JST plug fixed size (up to 6S) and variable number of cables (less popular).



LiPo batteries - summary

- It is very important to care about batteries.
- You need a good charger/discharger/balancer with storage mode and internal resistance measuring capabilities.
- Commercial manufacturers pretty frequent equip batteries with some “smart” electronics that takes care about it. I.e. DJI batteries used to self discharge for storage mode if not used for a longer period.

LiPo battery - sample calculation

Note!

A 6S battery (nominal voltage is 22.2V, 25.2V when fully charged) and capacity of 12Ah, presenting constant discharge current 15C and burst 30C (as on the image) weights about 1.6kg.

Assuming common power calculation equation: P=U*I=25.2V*12A*15(C) = > 4.5kW continuous power delivered and over 9kW in burst.

Such devices are NOT TOYS and should be used with special care.

Lithium-Ion batteries (Li-Ion)

- Li-Ion batteries are manufactured mostly in the cylindrical shape.
- There are standardised sizes, most common is 18650.
- Similar to the LiPo, each cell has nominal voltage of the 3.7V.
- They are usually longer lasting than LiPos
- Some are equipped with overcharge protectors and even integrate charger with i.e. micro-USB port for charging.

ESC, BEC

ESC - Electronic Speed Control

BEC - voltage stabiliser

The most common problem is to adapt battery (changing) voltage to the electronics requirement. It is common to use DC-DC converters so called BECs/UBECs.

BEC - Linear stabiliser, currently not very common as the tend to heat much and are heavy due to the heat dispersion elements.

UBEC - Pulse stabilisers DC-DC converters, able both to increase and decrease voltage. They present higher efficiency than BECs.

SBEC - an UBEC integrated with ESC (common for brushless ESCs).

ESC is an electronic speed controller for brushed and brushless electric DC motors. There are different for brushed and different for brushless motors. One ESC per motor is needed.

BEC parameters

- Valid input voltage range
- Nominal output voltage and maximum current:
  - There are BEC components delivering more than one voltage (integrated), i.e. 3.3V and 5V (separately) for variety of devices used.
- Weight, size (non-linear are rather small)

ESC parameters

- Motor type:
  - Brushed / Brushless
- Electrical features:
  - Maximum input voltage given in S, as in LiPo batteries.
  - Maximum output current (continuous and burst), in A
- Physical:
  - Weight! Note, there is one ESC per motor, so total weight has to be multiplied by the number of motors.
  - Dimensions

ESC parameters

- Configurability:
  - Active hold (important i.e. for foldable propellers in planes/soarers)
  - Constant RPM enforcement capability, for the drones with variable pitch propellers/blades.
  - Rotation direction change possibility (but you can swap two of the 3 wires to switch rotation in brushless motors, if only possible)
  - Ramp-up/down characteristics, many other.
  - For the configuration it is necessary to use “dedicated cards” that are actually programming/configuration writing devices, operating via regular port. Sometimes it is possible to enforce configuration mode via changing PWM signal, usually to maximum (2ms as in standard servo) during boot.

ESC features

- ESCs used to be hot during operation.
- In case of the multirotors it is usually not a problem because they used to be mounted close to the motor so there is an air flow.
- Larger ESCs used to contain radiators for heat dispersion and even active cooling (fan).
- UGV dedicated ESCs used to have active cooling as there is not much airflow to cool them down.

Chargers

Simple

Universal, processor based

Dedicated

Common, simple battery chargers

Simple chargers used to have following features:

- Maximum voltage and maximum charge current, cut-off (charge finish) detection algorithm.
- Battery type
- Connector
- Input voltage range

Common, universal battery chargers

Universal, processor-based chargers used to have following features:

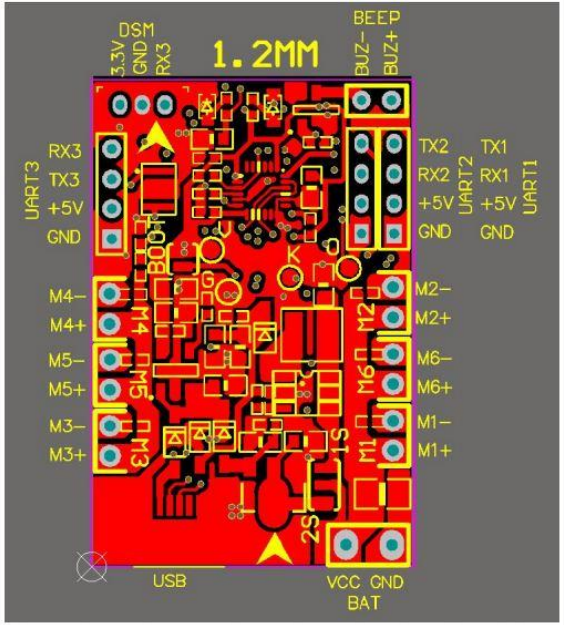
- List of accepted types of batteries (usually all)
- Minimum and maximum charging voltage and maximum charging current.
- Maximum current on discharge feature (usually small).
- Input voltage range and type (AC, DC, sometimes both).
- Connector types and cables included.
- How many batteries can you charge in parallel?
    - Depends usually on accessories attached.
- Monitoring interface (i.e. serial, WiFi), temperature monitoring.

Dedicated chargers and their features

- Dedicated chargers are delivered along with particular UAV model (or family of models) and it is solely limited to those ones.
- They used to have unique construction, special, proprietary connectors to not let you easily exchange battery with 3rd party solution.

Flight controllers

In terms of powering



Flight controllers

- Common logic is 3.3V and 5V.
- FCs used to integrate voltage stabilisers (Step-UP/Down) but...
  - Miniature FCs use STM microcontrollers with 3.3V logic. Assuming drone works on 1S battery (3.7V-4.2V), there is assumption that voltage won't go down below 3.3V. If you drain it more, FC can shut down and you won't have control over a drone anymore.
  - Worn out batteries presenting high internal resistance may cause significant voltage drop in such applications, thus FC can shut down.

Other components

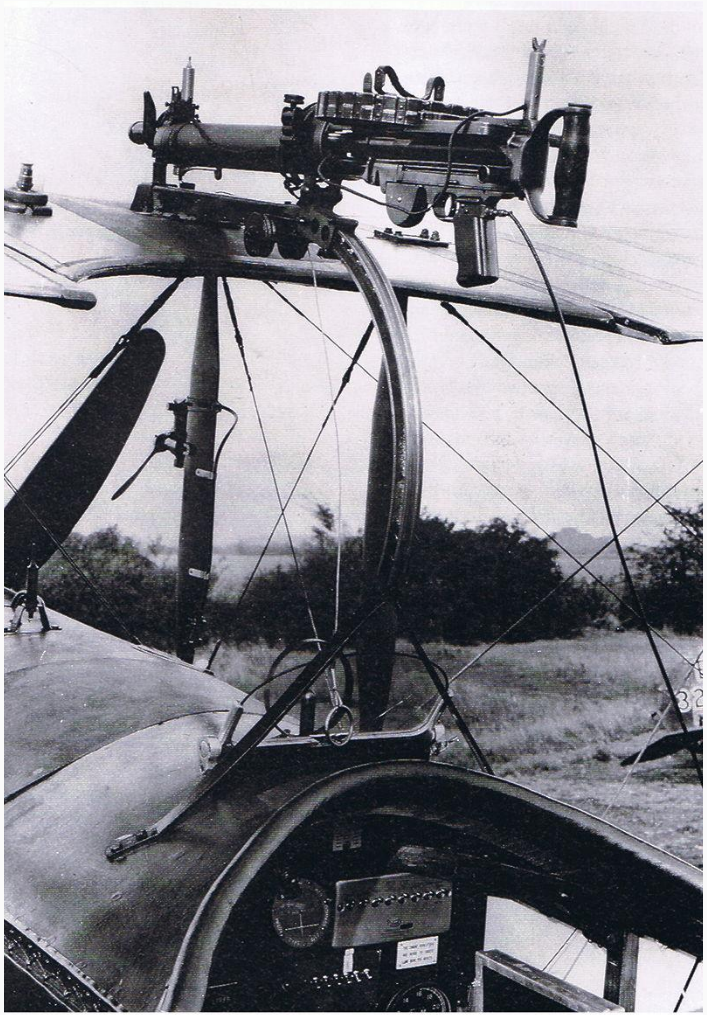
UAV hardware

Other mechanical components

Cameras

FPV gear, monitors, antennas, stands, etc.

Other mechanical components



Other mechanical components

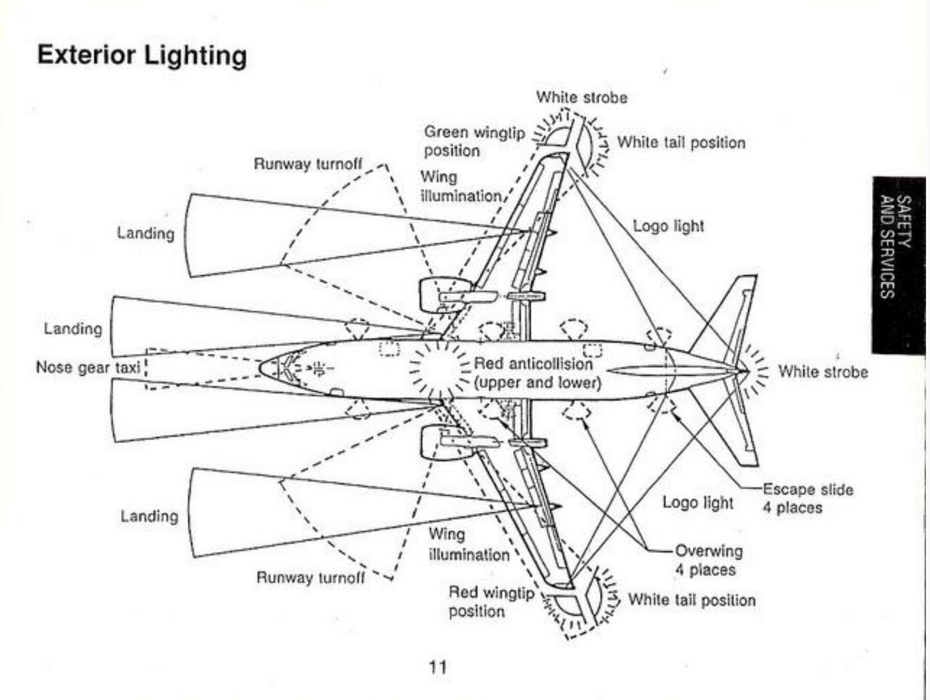
- There is a variety of other components related to the drone construction, such as: bowdens, gears, wheels, mounting components.
- It is essential to use lightweight materials, yet durable enough.Whenever possible one may use plastic (nylon), alloy or titanium instead of the stell, carbon-fiber rods for construction strengthening and styrofoam.
- Using a glue instead of screws and rivets is beneficial.
    - Warning - a special, non-dissolving chemically glue is necessary when styrofoam is used.

Other mechanical components

- Loctite building adhesives is common to ensure fixing i.e. propeller to the shaft
- Covering films - improves laminar flow over the wing.
- Positional lights - obligatory at the moment in larger UAVs. Also used for detail scale models.
  - There are exact standards for aircrafts as defined by ICAO.
  - So far, drone manufacturers implement their own ideas.
  - Racing drones use “car style” lights, i.e. 2 white in the front, 2 red in their back.

Other components: external light

- ICAO exterior lighting guidance
- Drones require light for operation in the darkness:
  - Flashing green, professional constructions require full set of lights, according to the ICAO guidance



Cameras

Common component virtually for any UAV.

In case of the FPV it is for orientation and navigation and also for aerial mission recording.

Advanced constructions usually integrate many cameras, including depth cameras used for collision avoidance and also for SLAM based navigation and optical-based positioning.

FPV, racing cameras

- Camera is front-mounted. Even if it is digital, downlink video transmission used to be analogue, not to introduce additional latency. Common transmission is classical analogue video 480 / 576 lines (NTSC / PAL).
- Sometimes, FPV cameras are mounted on one or 2 axes gimbals, that can be integrated with an accelerometer integrated into the headset of the UAVO. Operator then can “look around” the natural way.
- Most of the FPV racing drones use fixed camera, however.

FPV racing cameras

- It was pretty common to use popular action cameras (like i.e. GoPro) because of their durability. Nowadays lightweight solutions are more popular.
- FPV cameras used to record flight locally, i.e. to the microSD card with much higher resolution than downlink.
- They require good, omnidirectional antenna - it is a “stinger” in the drones.
- FPV uses OSD to inform operator about critical mission factors, i.e. artificial horizon, power used, voltage, direction to the home point, etc. When UAVO uses headset, it cannot see other displays.

Drone cameras

- I case of the aerial footage and photography, camera quality is essential.
    - By the photo-related specification, it is essential to let the camera hold good stabilisation.
    - Cameras are mounted in multiaxial gimbals, using stabilising dampers but also digital image stabilisation in a form of live postprocessing.
- In majority of the drones, same camera is used for operator to let it observe surroundings and used for manual orientation and positioning. The downlink is usually digital, with high latency (even 1s), thus excluding FPV racing. Common downlink resolution is 720p, while locally, camera can record even in 8k. There are high resolution downlinks for professional live aerial video broadcasting, however.

Drone cameras

- Majority of the commercial drones use dedicated cameras. Sometimes exchangeable in a range/family.
- Heavy drones can carry gimbals able to accommodate professional cinema or SLR (DSLR) cameras along with optics.

Aerial moviemaking

- The drone on the photo is an “elite” in the aerial footage:
  - xFold Rigs Dragon X12 U11.
    - The price is about 35 000 USD nett, without camera, obviously.
    - It can easily accommodate professional, hollywood-style video camera
- In professional applications there is separate UAVO and additionally a cameraman.

UAV firmware that helps to record

- Popular commercial drones provide number of features to help operator to create great aerial footage. It is essential when UAVO an cameraman is the same person. Such features include (among others), following moviemaking modes:
    - Follow me - drone follows and tries to keep the object in the middle of the scene
    - Round - cruising around operator, and filming it from different angles, frequently operator can even move and the drone will follow)
    - Selfie - popular in small drones: take-off, fly away to take photo of you, then return, all in one click.
    - Other modes.

UAV firmware and hardware that helps to record

- Modern firmware and drones used to track operator position using optical flow and object (UAVO) following:
  - Open Source solutions currently barely support this kind of solutions but commercials do.
  - Other method is to use GPS positioning both for drone and UAVO.
- Elementary feature is ability to keep camera heading constant even if drone changes its direction. It is common in drones with gimbals located under the drone, to let it freely rotate 360 degrees.

UAV camera mounting types (and gimbals)

Number of degrees of the freedom and FOV clearance

FPV gear, displays antennas and stands

Ground section.

Camera view is not essential to the VLOS missions still is helpful to monitor it.

In case of the FPV, it is crucial.

FPV headsets and displays

- Ground station visualises remote view.
- Sometimes it is simple radio, video downlink, sometimes pretty complex including OSD, tracking, camera gimbals and other features, even remote configuration.
- During FPV racing it is always FPV headsets that are used.
  - In other application those can be various solutions, i.e. LCD displays.
- Recently, LCD displays for visualisation are built in into the RC transmitters.
- In general, high resolution is not essential. It is transmission reliability and range that is crucial.
- To extend range, directional reception antennas and gimbal positioned antennas can be used.

FPV headsets

- Starting from very cheap and simple, as i.e. … Google Cardboard ;-))

- Finishing on pretty expensive ones with built in variety of features

FPV headsets parameters

- Pixel resolution
  - Usually not very high, some 480 vertical is usually enough
- Optics (variable, possibility to use along with glasses, etc.)
- Number of displays (1/2)
  - 2 displays theoretically enable ability to present stereoscopic view but that requires stereoscopic/double camera and double bandwidth on downlink.
  - Using separate displays is essential for user's comfort: as you can adapt optics separately and ensure better eye accommodation.

FPV headsets parameters

- Compatibility
  - Sometimes there is just analogue and/or digital input, but pretty frequent is is built in video receiver.
  - One of the popular standards is “Boscam”. It is easier to find compatible “pair” from different manufacturers among analogue video transmission channels than among digital devices
- PT control
  - Headset can be equipped with 3 axes IMU, that can send via RC transmitter (or separately) additional commands to rotate camera as looking around. That usually requires 2 or 3 separate AUX channel connected to the servos controlling camera gimbal.

LCD/LED/OLED Displays

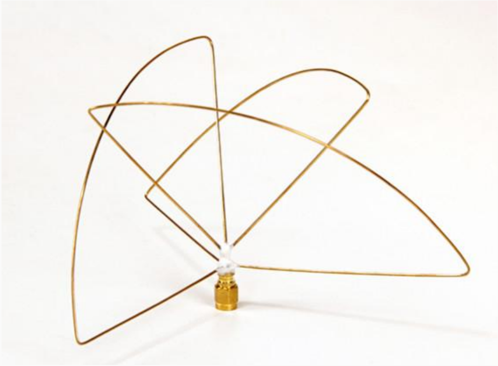
- It is common to use mobile's display to present video stream (as in basic DJI drones). Digital signal, usually MPEG H264/H265 is decoded in the device and presented to the users.
- There are dedicated displays however.
- In general, some other features are important:
  - Sunshade is necessary for outdoors operations.
  - Display should not be glass, rather matt.
  - Connectivity:
    - Digital use HDMI, DVI, D-SUB, DP.
    - Analogue - RCA, S-Video, Euro, Jack.
- Monitors used to have built-in recorded (usually to the USB and/or TF card).

Antennas

- Good antenna is better than power transmission booster.
  - i.e. 10mW transmitter with good antenna works better than 600mW transmitter with unaligned antenna.
  - Range depends on many factors but in general, using ISM bands it is possible to get some 6-10km video and command range. Obviously using directional antennas.
  - If directional antenna is used, tracker (GPS based) is very helpful to keep drone in the maximum transmission efficiency zone.
- Maximum transmission power is limited by law for ISM bands.

Omnidirectional antennas

- It is hard to implement directional antenna in the air unit (in the drone) as it tends to rotate and tilt. It means, omnidirectional antennas with high gain are commonly used. Sample circular antennas (so called “clover leaf antennas”) presented on the picture hold:
  - 3 leafs for transmitter
  - 4 leafs for receiver
- Directional and gain antennas are used also in telemetry and remote control.



UAV components

Software

FC firmware

Telemetry

FC software (ground station section)

Development software

FC firmware

There are many closed solutions that are commercial. Here we focus on open software.

Many closed, commercial solutions base on open software principles.

Open software market position is so strong that hardware manufacturers pay attention to deliver compatibility software modules along with hardware, for popular firmwares.

Universal FCs use open software (eventually closed software with open configuration capability) and need frame-specific and model-specific configuration and tuning.

Dedicated FCs are pre-configured for particular drone model and version and usually cannot control other model / frame unless cracked and firmware is replaced.

FC firmwares review

- The most popular and oldest solution for variety of drones:
  - Ardupilot - universal, virtually for any UAV, also for UGV
- Following are similar projects with common origin:
  - Cleanflight - stable, new version is every quarter, slowly evolving,
  - Betaflight (Cleanflight fork) - a developers field, changing rapidly and introducing new hardware and features. If you have a decent and latest FC hardware, look for software here. Updates appear weekly.
  - Baseflight - outdated, do not use, unless you had to (some STM32F1 based FCs require this one due to the limited update capabilities)
  - INav (Cleanflight fork) - for autonomous drones, navigation oriented.
  - Raceflight - compact and quick for FPV racing. Navigation support removed.

FC firmwares review

- PX4 flight stack - similar to Ardupilot, also used in commercial drones (i.e. Yuneec)
- LibrePilot - ground station oriented, still not very popular. Descends from OpenPilot.
- Paparazzi - a University-based project, hard to find suitable hardware off the shelf but there is a github documentation, presenting how to build one, including electronics and PCB. Linux based solution.
- dRonin - OpenPilot clone, updates frozen since 2018

FC firmwares review - former solutions

- MultiWii - this project is closed without maintenance, it had a serious impact on most firmwares available as for now. There is variety of protocols that became de-facto standard. Originally developed for 8-bit MCUs only.
- OpenPilot - times ago the only 32-bit FC. It is available as aforementioned forks now.

FC firmwares review, development

- There is a number of niche FC firmwares available on the web, usually outdated, eventually bound to particular hardware.

- Nowadays it is quite easy to modify/update majority of OpenPilot forks (i.e. iNav, Cleanflight, Betaflight) to fit individual needs and some different hardware, as compilation toolchain is fully documented and there are even ready virtual machines with development environment available.

FC firmwares review, development

- Number of firmwares precompiled and available via github (and others repos) is compatible with cheap FCs available on the market. They are not fitting in 100%, however, some functions may not work:
    - I.e. firmware can be uploaded to the FC and it offers logging into the micro SD card but majority of cheap, small FCs do not contain SPI reader/writer integrated = code is not optimised towards particular model, it is rather working “by chance”.
    - I.e. firmware is not able to follow appearance of the new hardware with new features (i.e. LED stripes).
    - Luckily, major functions work well, presenting quite reliable Flight Control solution.

Flashing of the new firmware / upgrading

- There are two major steps need to be done when building a new UAV:
  - 1. Upload (flash) a new/other/updated firmware to the hardware FC:
    - Most common is via COM (usually implemented as COM over USB)
    - You need to short pads on the PCB to switch FC into the bootloader / iupdating mode then flash.
    - Almost every firmware holds some portion of the flash that is not updated during flashing and it contains i.e. configuration and identification data. It is advised t force clean this area during updating as new / other firmware can present incompatible set of settings (other variable mapping) that may cause serious malfunction, even dangerous (i.e. full throttle on startup)
      - It is common need when not updating firmware for a longer time and major changes were introduced by developers meanwhile

Flashing of the new firmware / upgrading

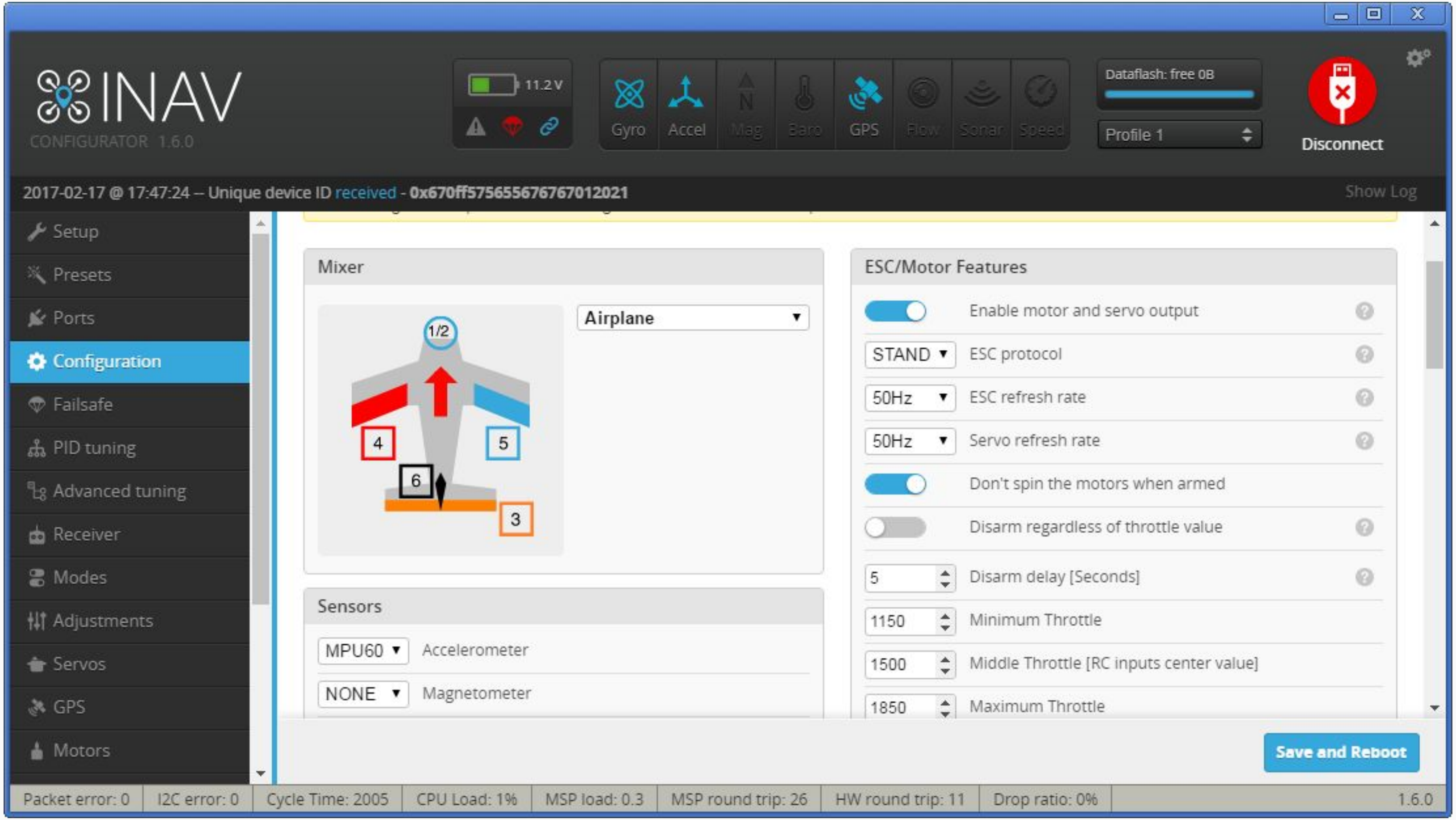
- There are two major steps need to be done when building a new UAV (...):
  - 2. Configuration of the firmware towards particular frame, functions, utilities, in general, most common it to configure UAVs airframe and PID controllers.
    - It can be done manually using GUI, RC transmitter/ground station (when landed), command line via serial port (usually COM over USB) using software for PC/Mac/Linux, accompanying firmware.
    - Interestingly it is common recently that OpenPilot forks user Chrome-based browser extension instead of the dedicated binary that is bound to particular operating system.
- There are some controllers that you can update and configure remotely, i.e. via WiFi (so called FOTA - firmware over the air).

Flashing of the new firmware / upgrading

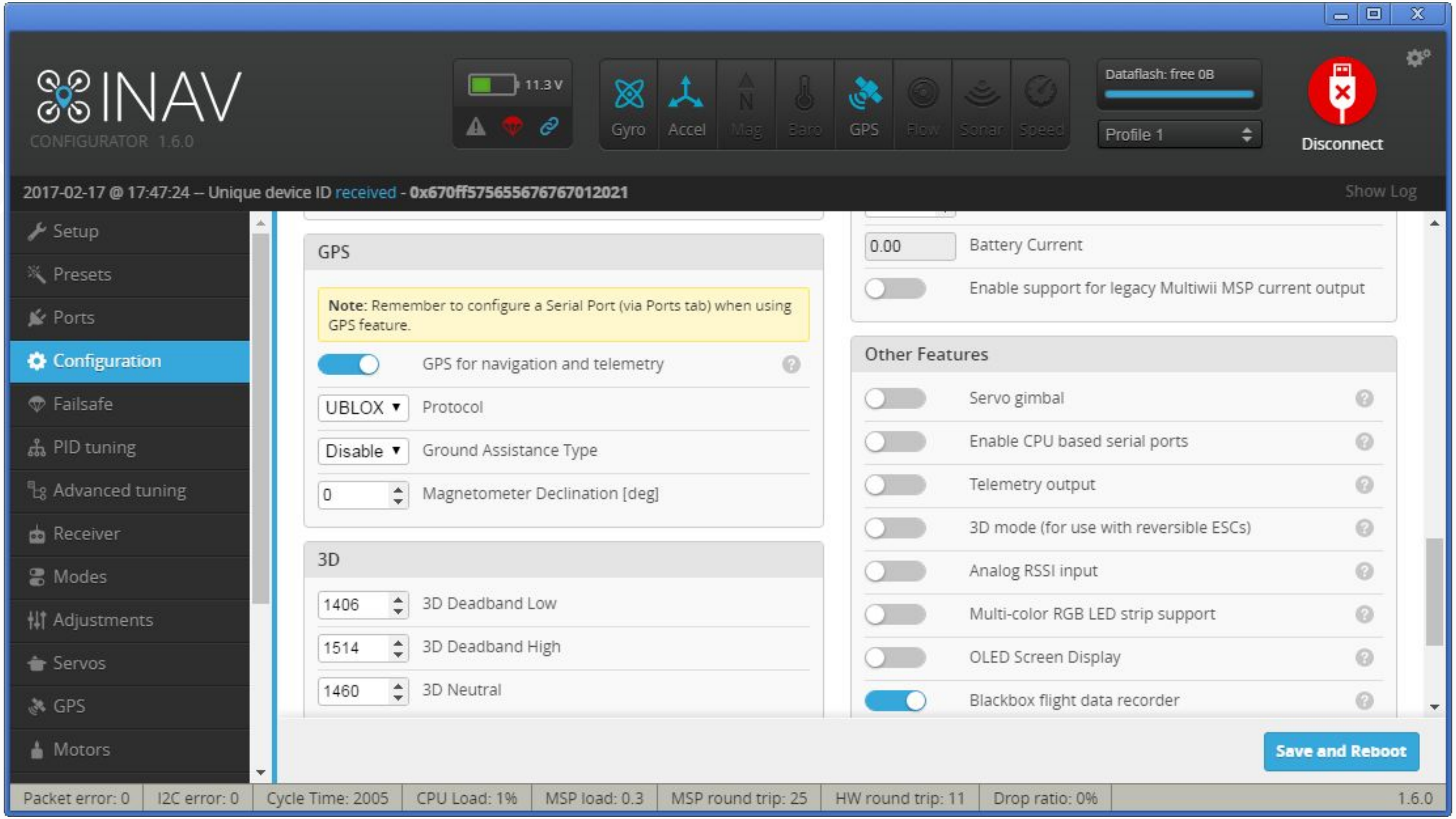
- Current FCs in majority do not provide during the flight updates / configuration, as configuration reading is usually implemented as reading once after the reboot. So never try to update when in mission.
- Some parameters can be tuned during flight however, i.e. PID. **Warning - that may cause platform instability and drone may even start bouncing eventually flip!**
  - Perform such tuning with special care and away from other people.

Flashing of the new firmware / upgrading

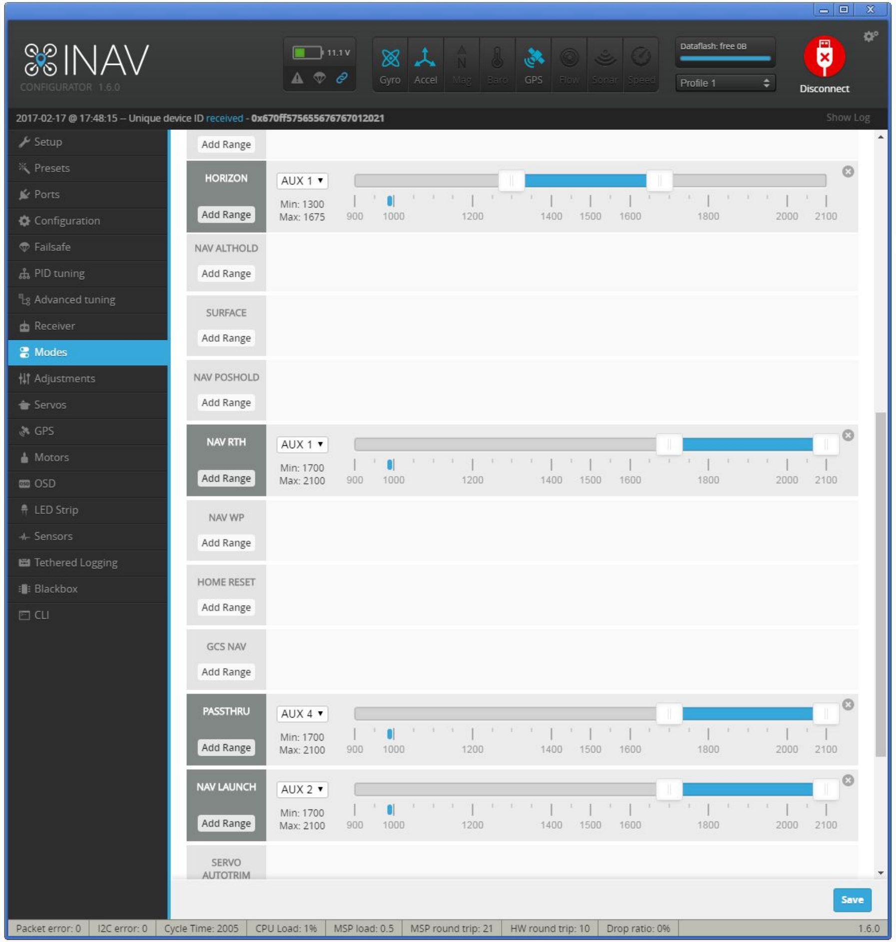
- In the case of the closed FC solution (i.e. DJI), updates are maintained via dedicated applications still follow similar steps internally. It is common that applications rarely provide low level configuration capabilities.
- It is a matter of commercial approach and assumption that many users are not trained enough to understand demanding technical details. Moreover, as FC is dedicated to the specific frame, physical parameters do not change significant (or at all).



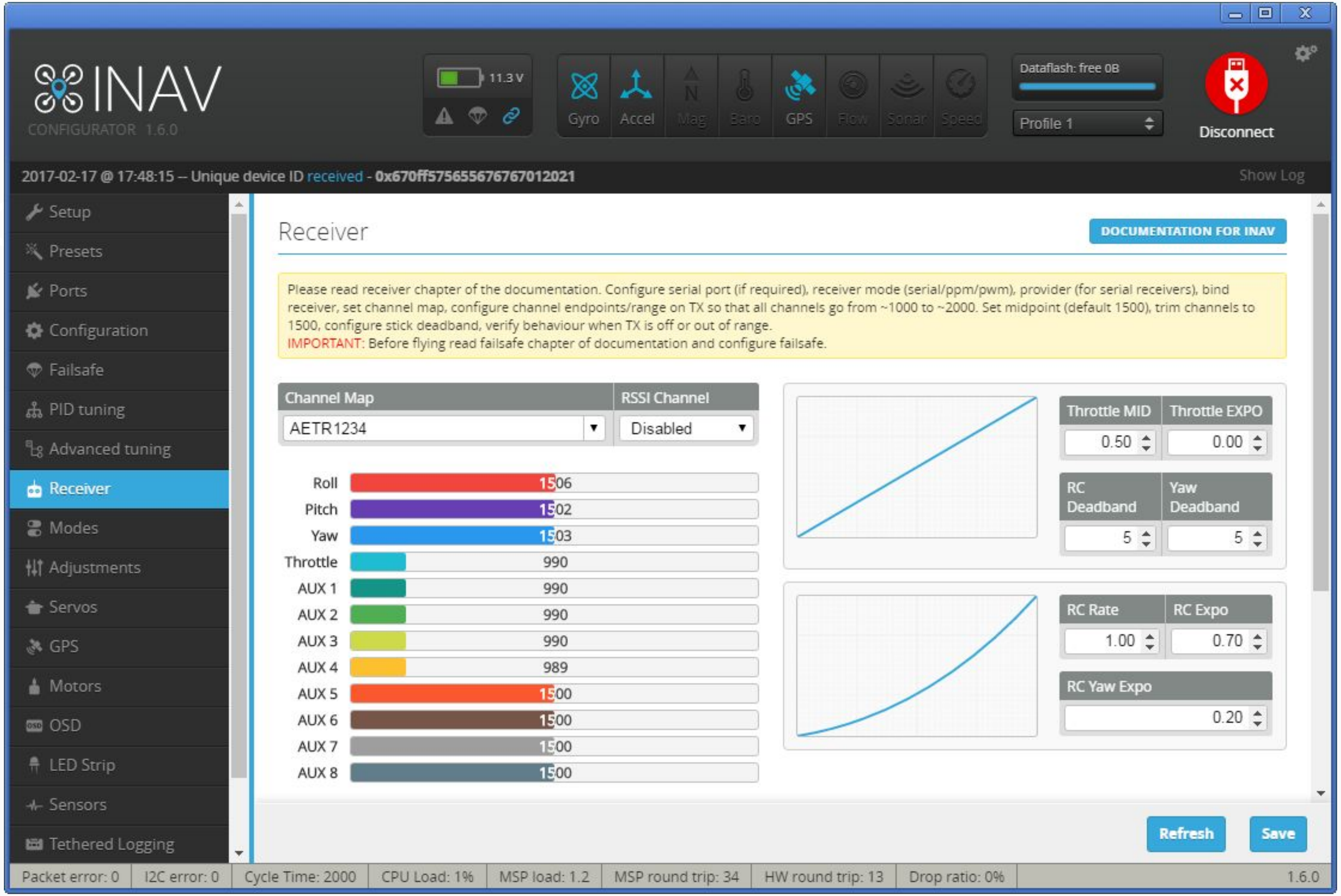
Configuring a drone, iNav application



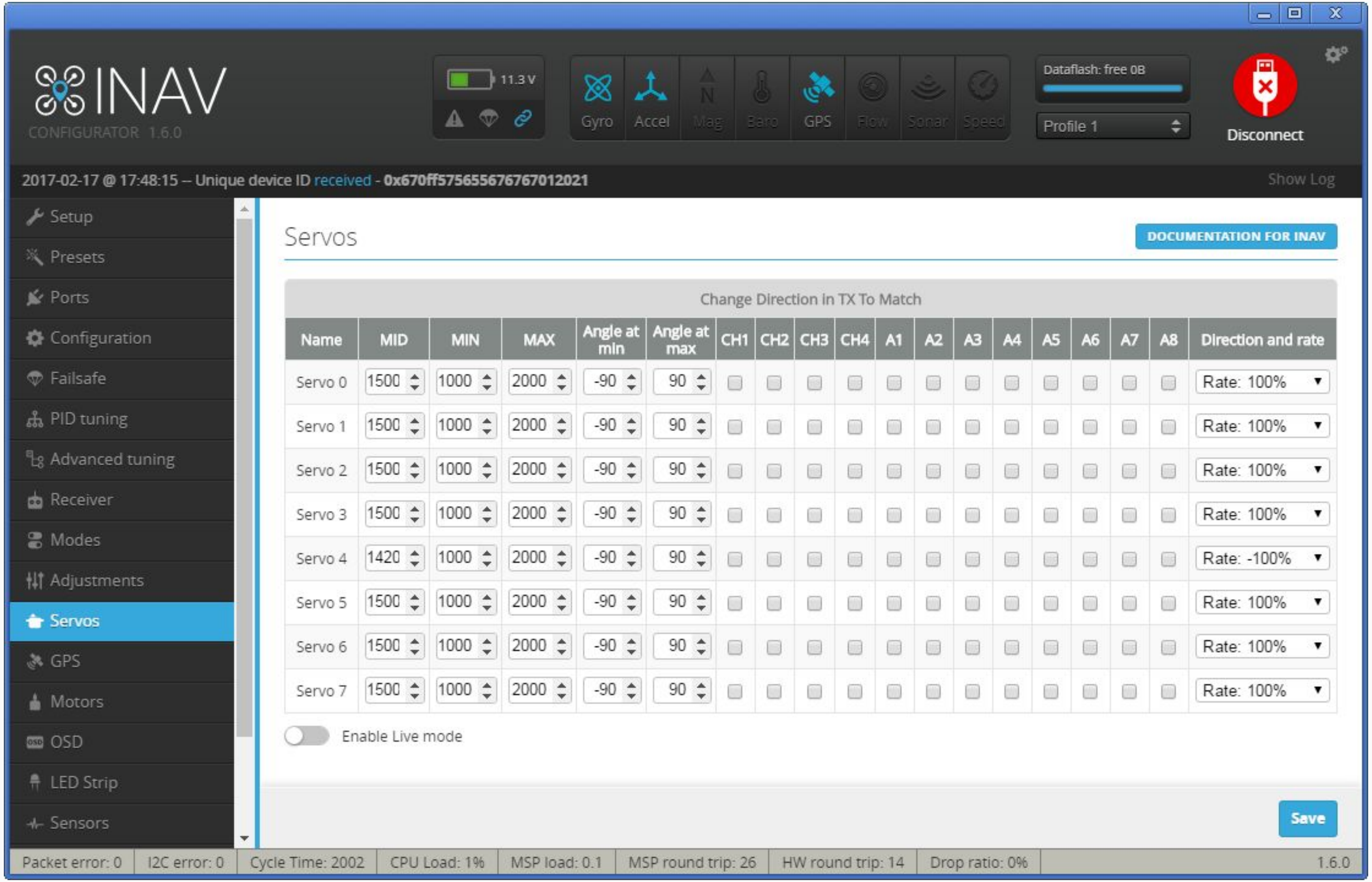
Configuring a drone, iNav application



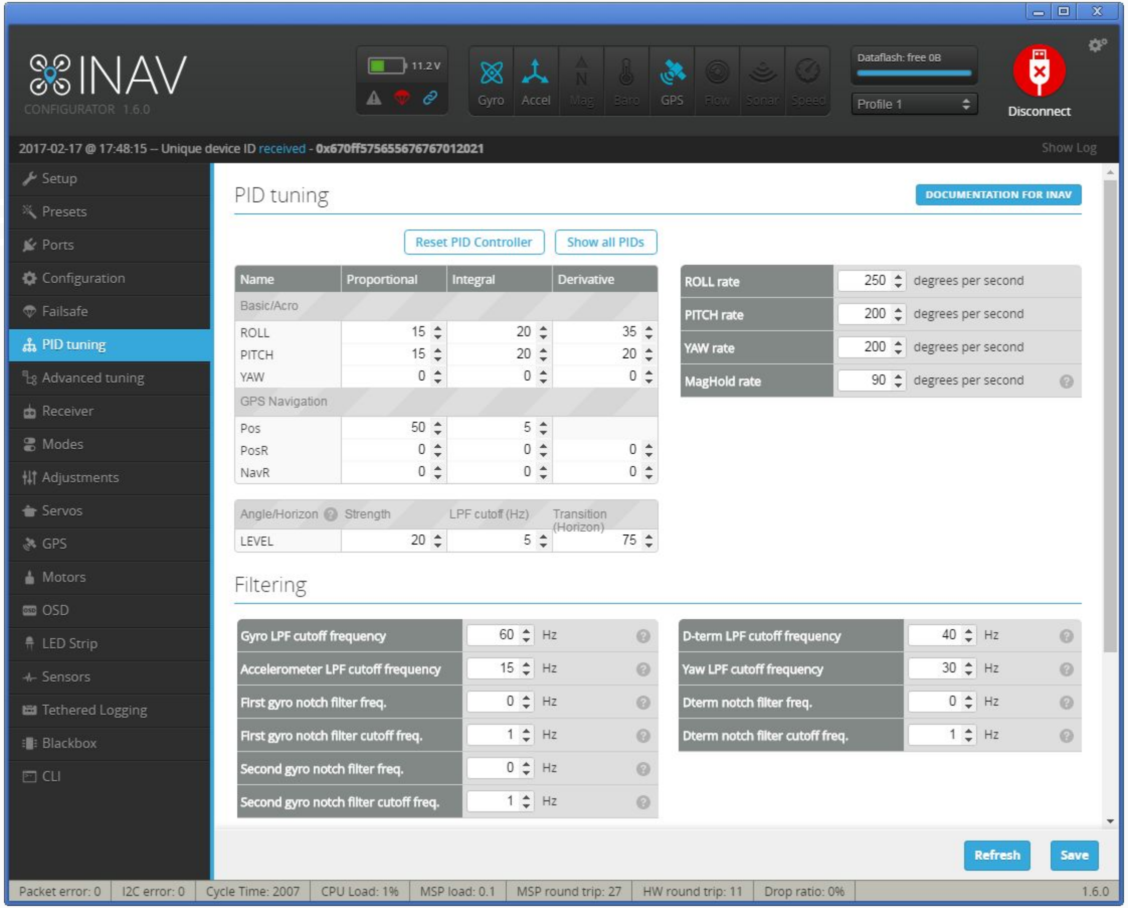
Oprogramowanie kontrolera lotu - konfiguracja iNav



Configuring a drone, iNav application



Configuring a drone, iNav application

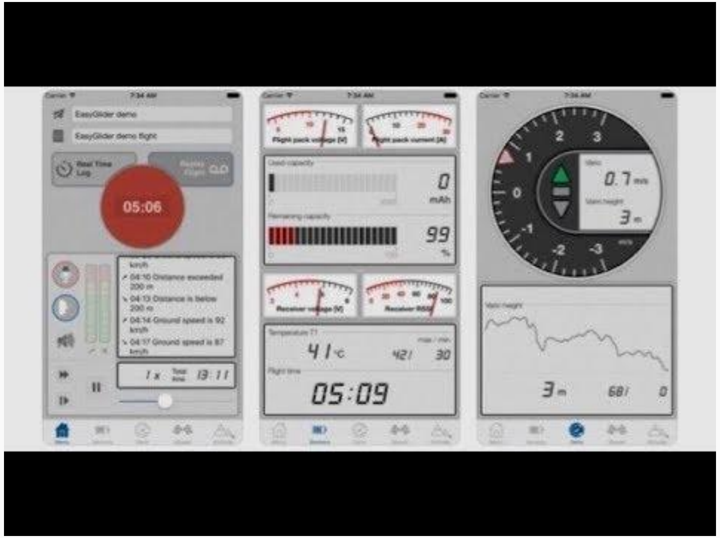


Configuring a drone, iNav application

Telemetry

Again, there is variety of closed solutions but we will focus here on open source ones.

It is intended to deliver all information from the aerial section to the ground station.



Telemetry features

- Monitoring mission status, progress, drone hardware components state, it delivers all information presented by the ground station, regarding aerial unit.
- Data is sent via so called downlink, from the UAV to the ground station (via RC Transmitter, bi-directional communication or via separate radio channel).
- There is a number of popular protocols constituting some common standards, formerly dedicated, now open, i.e. FrSky Telemetry, as well as universal i.e. Mavlink or MSP (MultiWii). Eventually commercial drone manufacturers use closed solutions, like i.e. DJI commercial products (non-professional).
    - Most of those solutions use serial port (serial over radio) to transmit data.

Telemetry features

- Visualisation can be implemented using dedicated displays (usually small LCD modules), on the computers acting as ground stations, mobile phones and tablets and also on the integrated displays in the RC Transmitters. Data can be also present using OSD, in particular for FPV activities.
- Common feature is to report current position, i.e. for collision avoidance (USpace/UTM).

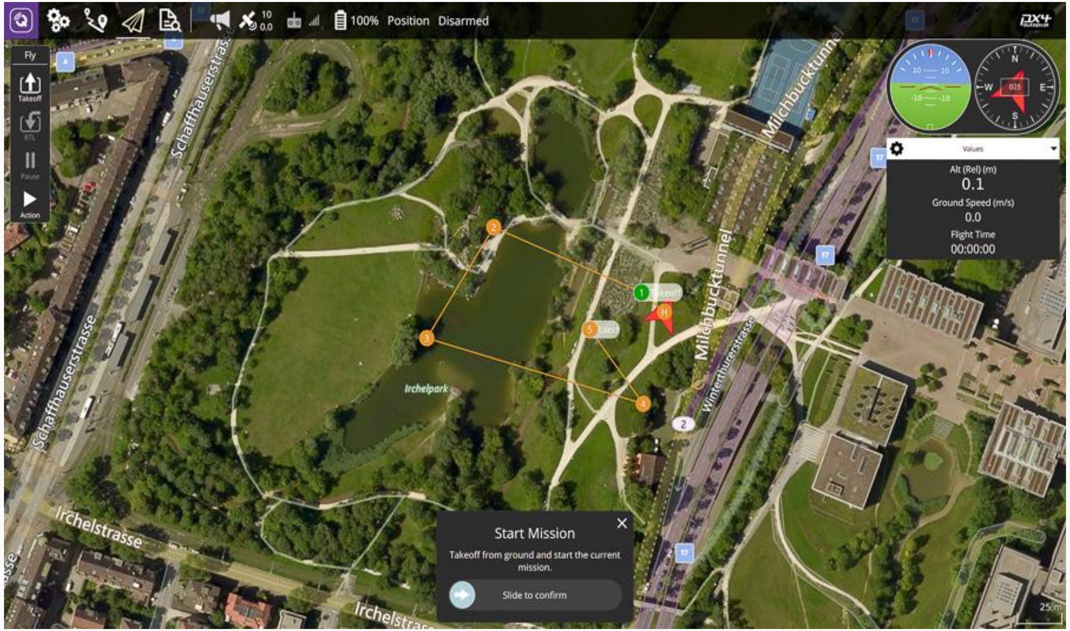
Telemetry challenges

- Long distance transmission is serious telemetry challenge.
    - Omnidirectional antennas used to be common as exact relation between drone heading and ground station may be virtually any possible and unknown in advance.
        - Receivers may use directional antennas with active tracking.
    - Constrained power resources and limited maximum power transmission as by law.

Ground station software

As in any other components there is a variety of closed, proprietary solutions as well as open source ones. We will focus on the open software.

Many commercial solutions are based on the open ones.



Mission control software

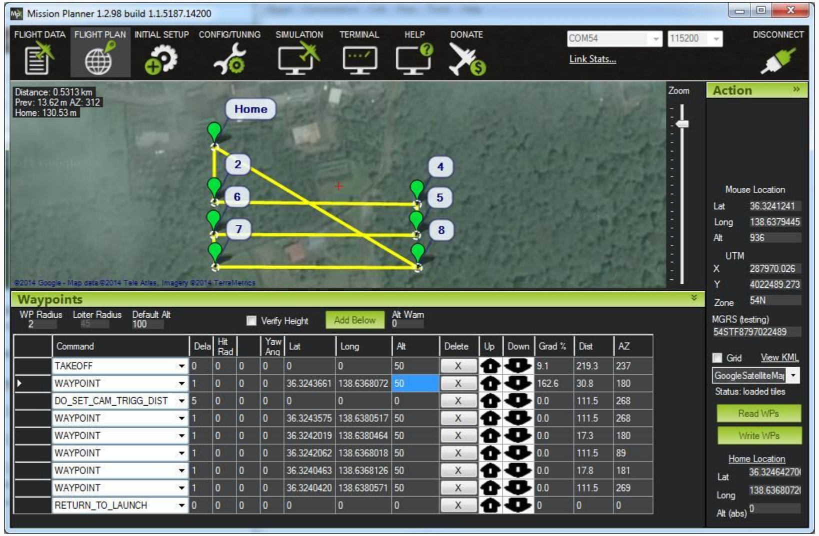
- Usually software pack for PC/Mac, eventually for mobile device.
- There are some solutions integrating RC transmitter.
- A direct connection to the FC is needed and it may be wire (usually COM over USB) or wireless (serial over WiFi, Bluetooth, other radio).
- Software is usually related to the particular firmware and comes as a bundle.
- As miniature drones usually are too constrained to handle complex autonomous missions (in both FC resources as well as in sensors, i.e. lack of navigation), mission control and planning software is a domain of rather larger drones.
    - This tend to change along with technology development

Mission control software - features

- RC control (manual autonomous).
- Flight plan planning and uploading then monitoring via telemetry channel.
  - So far, Mavlink seems to be most flexible and versatile protocol and to some extent enables use of variety of mission control software.
- In case of the commercial products it is common that dedicated software and hardware is delivered as an integrated solution.

Mission control software - features

- Mission planning and control software used to contain advanced features, i.e. calculating if waypoints are in the flight distance assuming drone used, check airspace zones, etc.
- Software is able to deliver current drone position into the drone management system and flight control (integrates with UTM/USpace). At the moment, those functions are at the development level, still integration seems to be possible
- Flight mode change enforcement is common, i.e. mission cancellation and RTH enforcement.
- Software supports automated flight plan generation, i.e. for the photogrammetry tasks or 3D object/area mapping.



Flight control software - uncommon scenario

- One of the possibilities to extend constrained FC is to add external flight mission controller that drives FC internally (simulates RC)
    - This sort of solution is used in i.e. Intel Aero Drone. The FC is PX4 while flight is managed by the linux-based computer located in the drone and it is the one that mission control software (ground segment) communicates with.
    - Similar approach is used when RPI is in charge to control the flight: FC is one of the constrained and popular, small boards like CC3D and NAZA32 so there are two devices controlling drone
- Obviously this approach is for rather larger UAVs.

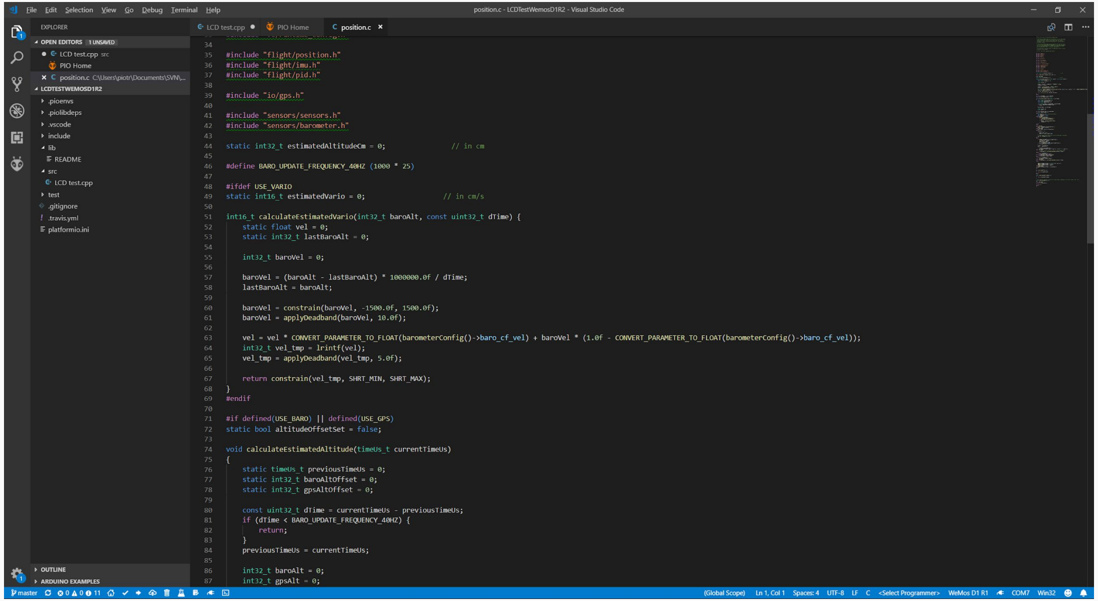
ROS

- ROS (Robot Operating System) is getting more and more popular to control drones.
- In practice it presents almost limitless possibilities to configure services, including integration of various devices (UAVs, UGVs, robots) in one, solid solution.

Development software

There is a number of development layers related to the flight control software development:

- FC Firmware code
- Ground station code
- Integration code (i.e. drone cloud management, airspace management, etc.)



Development

- In case of the open source projects, majority of the source code is available on the GitHub or GitLab.
- In case of the FC firmware, dominating source code language is C++
  - It is because of a demand to generate reliable, compact and efficient code for constrained devices and also because of the need to use real time solution that use low level methods i.e. DMA.

Development

- When AI is introduced (i.e. image recognition, object tracking, usually via external to the FC, additional computer) the common language to solve AI tasks is Python solution running on Linux distribution (commonly Ubuntu / Debian and its clones)

Development

- Popular and freely available IDEs are usually used. It is common that repositories contain project configuration files already. Most common are Eclipse, Visual Studio Code, Atom.
- The notable FC firmware development is a fact that one compiles code for different target platform than the development one: you author and compile code under x86/x64, eventually ARM, but compilation target is i.e. ATMEL or STM32. That requires compilation toolchain to be installed and maintained and to simplify it, there are ready, pre-configured environments distributed as virtual machine images or docker components available on the web.
- The most commonly used C++ compiler is GCC.
    - Code is usually compiled using make scripts that compile binaries for number of preconfigured target FC hardwares, parallel.

Development

- As FC development is sensitive task and even slight changes can cause FC malfunction, it is not advised to use a machine that one uses for daily tasks. It is better to use isolated environment, in particular as source code update involves development toolchain updates (i.e. code requires particular GCC version).
    - Usually, compilers delivered with linux distribution via standard repositories are outdated.
    - If you use machine for variety of development tasks, there may be glitches and a need frequent path updates and control.
    - The best solution is to use separate isolated environment as a virtual machine, eventually Docker container.

Development

- Sometimes, instead of full code editing it is more reasonable to change compilation configuration to i.e. fit different hardware, i.e. to remap ports using port multiplexer (if available, as i.e. in STM32 microcontrollers), module removal (to optimise size for constrained FC hardware) that is physically absent (i.e. car reader for logging). Source code modifications are rare nowadays, but additional modules and new configurations are common to appear.

100%

The end