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ЭКСПЛУАТАЦИЯ И ПРИМЕНЕНИЕ БЕСПИЛОТНЫХ ЛЕТАТЕЛЬНЫХ АППАРАТОВ (FPV-ДРОНОВ)

Operation and Use of Unmanned Aerial Vehicles (FPV Drones

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named after Prof. N.E. Zhukovsky and Y.A. Gagarin".

OPERATION AND USE OF UNMANNED AERIAL VEHICLES (FPV DRONES)

Study guide

Voronezh
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LIST OF ABBREVIATIONS

ABC - Unmanned Aerial System
BWS - Unmanned Aircraft
BPLA - unmanned aerial vehicle
AIR FORCE - Air Force
GLONASS - Global Navigation Satellite System of the internal combustion engine - Internal Combustion Engine
THE NAM - Directional pattern
SPARE PARTS - Spare parts, tools and accessories of the TDF
- Airspace utilization
INS. - Inertial Navigation System
EFFICIENCY - Efficiency factor
VSWR - Standing wave coefficient
L.A. - Aircraft
LZP - Line of a given path
LFP - Line of actual track
POWER LINES - power line
OSH - Signal to noise ratio
AIR DEFENSE - Air defense
PC. - Flight controller
W.O.W. - Software
PU - control panel
REB - electronic warfare
SWO - Special Military Operation
SNA - Satellite Navigation System
TTX - Tactical and technical characteristics
PWM - Pulse Width Modulation (PWM) AUX - Auxiliary port - A linear asynchronous port. serial audio input
WEIGHT. - From Battery Eliminator Circuit - Battery Eliminator Circuit
CCD - Charge-coupled device - a device with a reverse charge link
CCW - Counterclockwise CMOS. - Complementary metal-oxide-semiconductor. complementary metal-oxide semiconductor
CW - Clockwise Clockwise DVR. - Digital video recorder - Digital. video recorder
ESC - from Electronic Speed Controller - electronic speed controller
FOV - Field of view.
FPV - First Person View FC. - Flight Controller - From Flight Controller.

GPS - From Global Positioning System - a system of global positioning

IMU - Inertial Measuring Unit - Inertial Measuring Unit measuring unit

LiPo - From lithium-ion polymer battery - lithium-ion polymer batteries

OSD - On Screen Display - On Screen Display (OSD) UAV telemetry

PAL / NTSC - Video formats used in FPV cameras and displays.

PDB - Power Distribution Board - Power Distribution .

PID - Proportional-integral-derivative - Proportional-integral-differivative.

RTX - Radio transmitter is a control device. FPV drone flight by the operator

RX - Receiver

TX - Transmitter - Transmitter.

TVL - TV Lines - TV Lines.

UART - Universal Asynchronous Receiver/Transmitter - Universal Asynchronous Receiver/Transmitter

UBEC - Universal Battery Eliminator Circuit - Universal Battery Eliminator Circuit -

universal USB battery disconnect circuit -

Universal Serial Bus - Universal Serial Bus.

serial bus

WDR - Wide Dynamic Range - Dynamic Range.

INTRODUCTION

The current stage of the world aviation development is characterized by the creation of complexes with unmanned aerial vehicles (UAVs) of various functional purposes and continuous expansion of their nomenclature. The rapid development of UAV complexes is due to their potential advantages and benefits, primarily in terms of efficiency-cost ratio, both in comparison with manned aircraft complexes and other types of weapons and military equipment.

In the course of a special military operation, battlefield UAV systems and barrage munitions are most actively used. It should be noted that in the units of the Army, Airborne Forces, Marines, and Special Operations Forces, the main UAVs of the battlefield are multi-rotor UAVs. They are used for about 80% of all missions. Moreover, at low cost, multirotor-type UAVs provide a fairly high efficiency of hitting enemy objects, about 75%.

The existing multirotor UAVs can be divided into reconnaissance and strike UAVs. Highly maneuverable kamikaze UAVs (FPV drones) are a special type of multirotor attack UAV. FPV (First Person View) drones are quadcopters or multi-rotor UAVs equipped with a camera and transmitting real-time video to the pilot's device (goggles or monitor). This means that the pilot can control the drone as if he or she were in the drone's cockpit.

The peculiarity of FPV drone application is related to the need to control a UAV with high speed and maneuverability characteristics, while the drone is controlled in manual mode, with a first-person view. This requires from operators highly specialized knowledge in the field of UAV design, operation and tactics, as well as specific skills that can be obtained only as a result of training on simulators and during practical flights both in open areas and in confined spaces. Therefore, FPV drone operator training should include theoretical, simulator and flight training.

The need to train cadets of military professional educational organizations and military educational organizations of higher education of the Ministry of Defense of the Russian Federation in the operation and use of unmanned aerial vehicles (FPV-drones), taking into account the peculiarities of training FPV-drone operators, as well as the lack of systematized training literature predetermined the need to develop a single training manual.

The training manual was developed by the team of 4 faculty of unmanned aviation Military training and research center Air Force "VVA named after prof. N.E. Zhukovsky and Y.A. Gagarin" and allows for up to 10 training days.

(54 training hours) for cadets of military educational institutions of the Defense Ministry of the Russian Federation to obtain knowledge, skills and abilities in accordance with the requirements to the minimum content and levels of training, approved on 27.10.2023 by the State Secretary-Deputy Minister of Defense of the Russian Federation, Army General Nikolai Aleksandrovich Pankov, on the operation and use of UAVs (FPV-drones).

The manual describes the issues of device, aerodynamics and flight dynamics of multirotor UAVs, peculiarities of training and tactics of FPV-drones application, recommendations on practical training of FPV-drone operators on simulators, as well as on open terrain and indoors.

The team of authors expresses its gratitude and appreciation to the Reconnaissance Strike UAV Training Center of the Group of Forces (Forces) "Zapad" represented by M.N. Matveev, N.V. Saveliev, A.A. Efremov and others, who took an active part in the development of the manual, as well as the Internet community, contributing to the active introduction of FPV drone combat application methods within the framework of the NWO, for systematization, generalization of experience and analysis of the peculiarities of application and operation of multirotor UAVs, which brought advanced ideas in the field of training FPV drone operators to the manual.

1 TITLE, COMPOSITION, SPECIFICATIONS И PRINCIPLES OPERATION OF UNMANNED AERIAL VEHICLES

The development of unmanned aviation has determined the diversity of applications of UAVs. They are most actively used in military applications, which has significantly influenced the tactics of using many types of weapons and military equipment.

The purpose of unmanned aerial vehicles used in military applications is determined by the tasks to be accomplished. The tasks are subdivided into strike, reconnaissance, special, training and others. UAVs of various designs with specialized payloads are developed for their solution.

UAVs are distinguished not only by their method of application, but also by their design, tactical and technical characteristics (size of the vehicles themselves, takeoff weight, range, altitude, speed, flight time, etc.). Let us take a closer look at the classification of UAVs by design.

1.1 Classification of UAVs by design

As is known, the design of an aircraft (LA) depends on the principle of generating lift force, which is the basis of its flight. The following flight principles are known [1]:

1. Ballistic.
2. Aerodynamic.
3. Rocketodynamic (reactive).
4. Aerostatic.

The ballistic principle of flight is the flight of a freely thrown body occurring under the action of gravity. The lifting force is determined by the force of inertia of the flying body. To perform ballistic flight, the body must have an initial reserve of altitude or velocity, so ballistic flight is also called passive flight.

The aerodynamic principle of flight is based on Newton's third law of ***flight***, according to which a plate placed at some angle in an air stream presses against it and experiences reciprocal pressure from the stream.

The reactive principle of flight is also based on Newton's third law of flight, but the interaction of the aircraft with the surrounding air is not a prerequisite for it. The essence of the reactive principle is that the lift force necessary for flight is created as a result of combustion of fuel, which produces gases with high energy. These gases, flowing outward from the engine nozzle at high velocity, create a reactive force of the opposite direction.

The aerostatic principle of flight is based on Archimedes' law, according to which a lifting force equal to the weight of the displaced gas acts on a body in a gas medium. Airships, aerostats, balloons fly according to this principle.

Currently, the most widespread designs of UAVs using aerodynamic and aerostatic principles of lifting force creation (Figure 1.1).

Aerostatic UAV

Airplane-type UAV

Helicopter-type UAV

UAV with hybrid design

Multirotor UAV

Figure 1.1 - Types of UAVs by design

Aerostatic UAVs are a special class of UAVs in which the lift force is generated primarily by the Archimedean force acting on a cylinder filled with a light gas (usually helium).

This class is represented mainly by unmanned airships, which are light-air vehicles that are a combination of a balloon with a propulsor (usually a propeller (propeller, impeller) with an electric motor or internal combustion engine) and an attitude control system [1]. The main disadvantage of this type of UAV is low maneuverability, so they are usually used in tethered version (on a tether).

Airplane-type UAVs are a class of UAVs in which the lift force is generated aerodynamically by the head of air impinging on a fixed wing. Airplane-type UAVs are usually characterized by long flight duration, high maximum flight altitude and high speed. The disadvantages of airplane-type UAVs are the need to use launchers, runways, and the inability to hover stationary in the air in one place.

Helicopter-type UAVs are a class of UAVs in which the lifting and propulsive forces during all phases of flight are generated by one or more propellers driven by one or more engines [2]. The wing either does not exist at all or plays an auxiliary role. The obvious advantages of helicopter-type UAVs are the ability to hover at a point and high maneuverability. The main disadvantage of the helicopter-type UAV is its low flight speed.

Hybrid UAVs are a class of UAVs with vertical takeoff and landing. It refers to all UAVs that can change the direction of the thrust vector in a controlled manner and combines the design principles of an airplane and a quadrocopter. It has the advantages of vertical takeoff due to the presence of additional engines mounted in the horizontal plane, and at the same time can reach high speeds, thanks to the aerodynamic scheme with a fixed wing due to the push or pull propeller.

Multirotor UAVs are a special class of helicopter-type UAVs. A multicopter (multirotor helicopter) is an aircraft built according to the helicopter scheme, with three or more main rotors [3]. Their advantages are relatively low cost, ease of control, the possibility of vertical takeoff from an unprepared site and the ability to hover in the air, as well as high accuracy of positioning. The disadvantages are low speed, high energy consumption, limited range, and short flight time.

There are several varieties of multicopters, differing in the number and location of motors relative to the center of the apparatus: bicopter; tricopter; quadrocopter; hexacopter; octocopter.

The quadrocopter is the most popular multicopter because four is the optimum number of electric motors to balance price, performance, stability and flight time.

1.2 Principles of quadcopter-type UAV flight

In order to use FPV drones effectively, the UAV operator must be proficient in controlling this type of UAV. While flying a route and performing combat maneuvering, the FPV drone operator must constantly assess the UAV's position in space and predict its reaction to the movement of the controls. For this purpose, he or she needs to understand what forces act on the quadcopter in flight, and

and on which parameters its dynamic and maneuvering characteristics depend.

The design of a quadrocopter, like a helicopter, realizes the aerodynamic principle of flight, because the lifting and driving forces at all stages of flight are created by several air (carrying) propellers - propellers.

Air propeller (propeller) - a blade propulsor that creates thrust by throwing air backwards with some additional velocity, driven into rotation by an engine and converting engine torque into thrust force T.

The propeller blades are mounted on a rotating axis (on the motor or gearbox shaft) in such a way that the leading edge of the blade is directed towards the rotation (this is important to consider when assembling the quadrocopter), and the blades themselves are mounted at a small angle (angle of installation) to the oncoming flow. The aerodynamic forces acting on a horizontally mounted quadcopter propeller are shown in Figure 1.2. The incoming airflow flows around the propeller blades. The distance traveled by the airflow along the upper (curved) edge of the blade is greater than the distance traveled along its lower surface, respectively, the airflow velocity at the upper edge will be higher than at the lower edge. The resulting difference in airflow velocity, according to Bernoulli's law, leads to a difference in pressure. The pressure difference gives the lift force C_y [4].

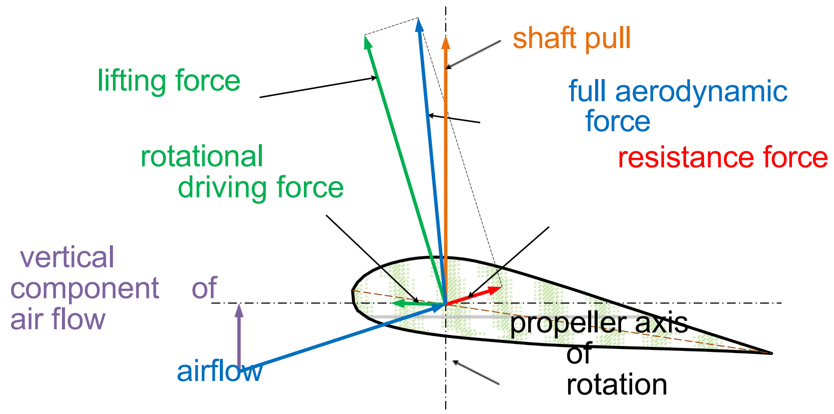


Figure 1.2 - Carrier propeller aerodynamics

The lift force generated on the blades is converted into propeller thrust T applied to the propeller hub. Since the quadrocopter has four propellers, for the quadrocopter to get off the ground the total propeller thrust T_{sum} must be greater than the gravity force $G= mg$.

Figure 1.3 shows a simplified structural diagram of the quadrocopter and a schematic of the forces acting on it.

The quadrocopter has six degrees of freedom. The motion of the quadrocopter is a combination of translational motion in a Cartesian three-dimensional coordinate system, as well as rotational motion around each of three mutually perpendicular axes [5]. In Figure 1.3, the axes of the Earth coordinate system are labeled X, Y, Z; and the axes of the coupled coordinate system labeled x, y, z.

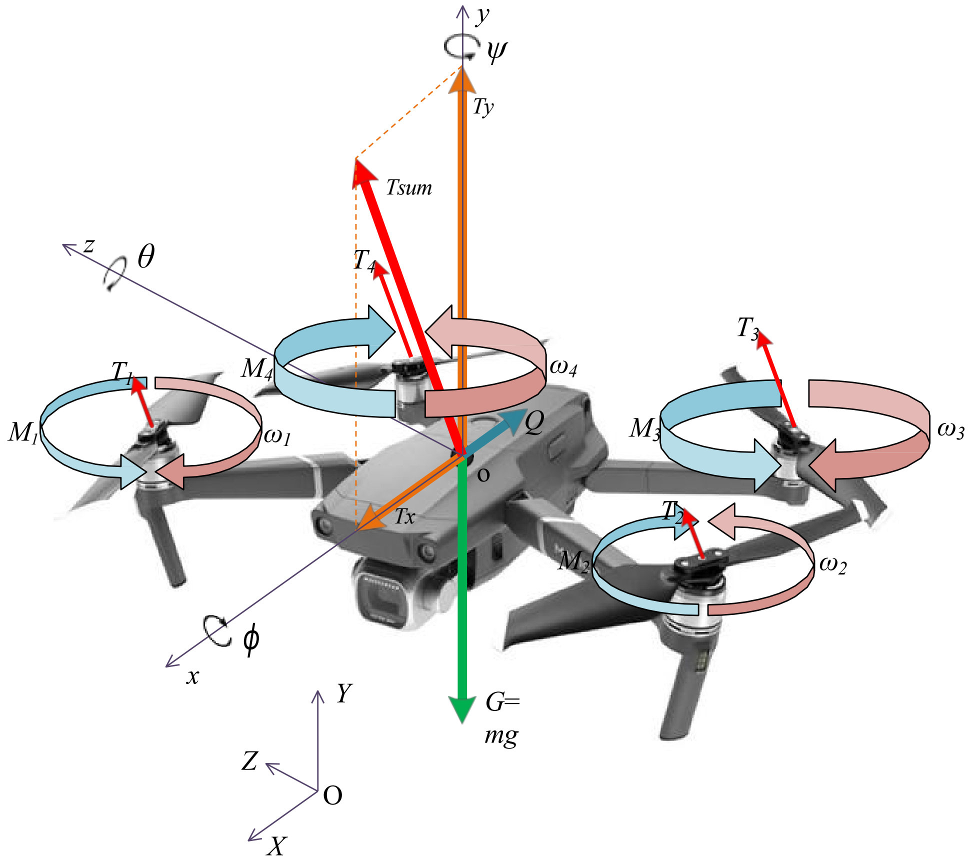


Figure 1.3 - Diagram of forces acting on the quadrocopter in flight

The quadrocopter, like all aircraft, is subject to gravity G and air resistance Q. The lifting (T_y) and propulsive (T_x, - pushing forward and/or T_z, - pushing sideways) forces are generated by the quadcopter's propellers. The thrust forces T_i of each propeller group are added to the total thrust force $T_{sum}= T(1)+ T(2)+ T(3)+ T(4)$, which is generally applied to the center of mass of the quadcopter.

Rotation of the quadrocopter around one of the axes of the associated coordinate system x, y, z leads to the inclination of the thrust vector T_{sum} in the direction of rotation and it is decomposed into components T_x, T_y, T_z. If the quadrocopter hangs horizontally and motionless, it means that the thrust vector T_{sum} is directed vertically upwards and has completely changed into the lifting force T_y, which has balanced the gravity force G, i.e. $T_y= G$.

When rotating at an angle θ around the *z-axis* (***pitch***), the longitudinal thrust component T_x appears and the quadcopter starts moving forward or backward.

When rotating by an angle ϕ around the *x-axis* (***roll - roll***), the lateral thrust component T_z appears and the quadcopter starts to shift to the left or right.

When the copter rotates by angle ψ around the *y-axis* ***(yaw***), the thrust vector T_{sum} is not tilted at hover. If the copter is in horizontal flight, then rotate longitudinal and lateral and side

thrust vector components T_x and T_z, which make the quadcopter velocity vector rotate in the yaw direction.

It is important to remember that if the thrust of the engines is unchanged, increasing the longitudinal or lateral component of the thrust vector leads to a decrease in the lift force T_y. Therefore, when the copter is tilted, it is necessary to increase the thrust of the engines in a coordinated manner to maintain flight altitude.

The magnitude and direction of the thrust vector is changed by tilting and turning the quadcopter in the desired direction, as well as by changing the rotational speed of the propellers. The resulting forces cause the quadcopter to move forward or backward, left or right, up or down. Longitudinal, transverse and vertical components of velocity form the trajectory of the quadrocopter in space, which can be quite complex [5].

In order to determine how the quadrocopter tilts and turns in the desired direction, consider Figure 1.3, which shows the angular velocities of rotation of the motors ω_i and the reactive moments M_i generated by the propeller group. It is necessary to pay attention to the direction and thickness of the arrows, the thicker the arrows, the greater the value they denote.

The quadcopter changes the direction of rotation around the center of mass by changing the rotation speed of each propeller. When the drone hovers, neighboring propellers rotate in opposite directions to keep the drone stable. By varying the rotational speed of each of the motors, the thrust forces T_i and torques M_i that make the drone rotate and move in all three dimensions can be manipulated.

The flight controller is responsible for coordinated changes in motor speed, while the operator only sets the desired total thrust, roll, pitch and yaw using the control knobs (stick controls) on the control panel. The flight controller usually has several automatic modes, such as altitude, roll and pitch control, as well as acrobatic modes for experienced pilots.

The main flight modes of the quadrocopter, their corresponding changes in the positions of the controls, and how they are realized by the flight controller by changing the rotation speed of the motors are shown in Figure 1.4. The direction of rotation and rotation speed are indicated by arrows, the thicker the arrows, the higher the rotation speed.

More complex spatial maneuvers are achieved by combining the simple maneuvers listed above. Therefore, the drone operator must be able to operate both sticks in a coordinated manner, controlling pitch, roll, yaw and thrust simultaneously to make the copter move along a given trajectory.

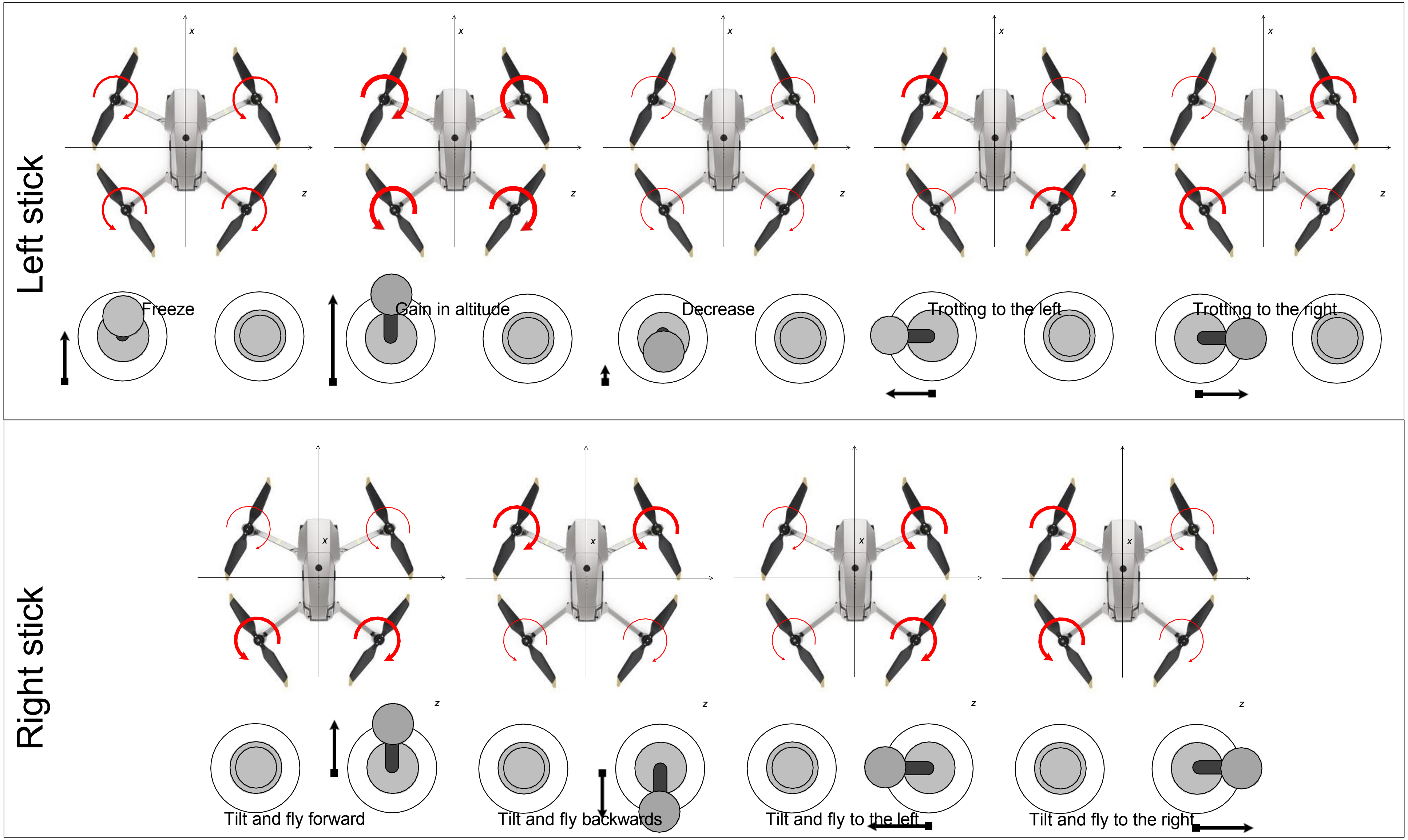

Left stick
Freeze
Gain in altitude
Decrease
Trotting to the left
Trotting to the right
Right stick
Tilt and fly forward
Tilt and fly backwards
Tilt and fly to the left
Tilt and fly to the right
x
z

Figure 1.4 - Basic quadrocopter maneuvers

1.3 Main specifications of commercial quadcopter-type UAVs

UAVs are usually divided into three groups according to their intended purpose: commercial, consumer and combat. Commercial UAVs, unlike consumer UAVs, have advanced capabilities and functionality, which is why they are in demand for military applications. There are many different types of commercial drones available on the market, each with its own set of features and advantages. Based on the experience of combat use of commercial multirotor UAVs, the most popular are quadcopters made by DJI, Autel, and Xiaomi (Table 1.1) [6].

Table 1.1 - Main types of commercial quadcopter UAVs

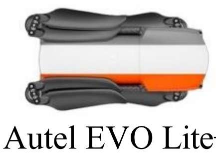
Name	**Camera**	**Flight time**	**Declared flight range**	**Data channel frequencies**
 DJI Inspire 3	8K	up to 28 minutes	up to 15 km	2.4GHz
 DJI Mavic Mini	4K	up to 30 minutes	up to 4 km	2.4GHz
 Autel Robotics EVO	4K	up to 30 minutes	up to 7 km	2.4GHz
 Xiaomi FIMI X8SE 2020	4K	up to 35 minutes	up to 8 km	5.8GHz
 DJI Mavic Pro (Platinum)	4K	27/30 minutes (Pro/Pro Platinum)	up to 7 km	2.4/5.8GHz
 Autel EVO Lite+	5K	40 minutes	up to 12 km	2.4GHz/5.1-5.8GHz
 DJI Mavic Air 2	4K	up to 34 minutes	up to 10 km	2.4/5.8GHz

Table 1.1 - Continued

Name	**Camera**	**Flight time**	**Declared flight range**	**Data channel frequencies**
 DJI AIR 2S	5K	up to 31 minutes	up to 12 km	2.4/5.8GHz
 DJI Phantom 4 Pro V2.0	4K	30 minutes	up to 10 km	2.4/5.8GHz
 DJI Mavic 2	4K	up to 31 minutes	up to 10 km	2.4/5.8GHz
 XDynamics Evolve 2	4K	up to 33 minutes	up to 11 km	2.4GHz/5.1-5.8GHz
 Autel EVO II	8K	up to 40 minutes	up to 9 km	2.4GHz
 DJI Mavic 3 Classic	5K	up to 46 minutes	up to 15 km	2.4/5.8GHz
 DJI Matrice 30T	5K+ IR	up to 36 minutes	up to 15 km	2.4/5.8GHz
 DJI Matrice 300RTK	8K+ IR	up to 55 minutes	up to 15 km	2.4/5.8GHz

1.4 Types of UAV payloads

The payload is the equipment that the UAV carries on its body to perform various combat missions. It may include video cameras, thermal imagers, range finders, jettison systems, kill vehicles, etc. (Figure 1.5).

The type of , as well as the type of UAV, depends on the type of combat mission to be accomplished. The main types of commercial UAV payloads and their combat missions are summarized in Table 1.2.

The payload can be replaceable and non-replaceable.

Figure 1.5 - Types of UAV payloads Table 1.2 -

Types of UAV payloads and their purpose

Payload type	Assignment	Tasks to be solved
Photo or video camera	Capturing still images or video from the air	Air reconnaissance, objective control, target designation, aerial photography, search and rescue.
Thermal imager	Shooting objects in infrared	Air reconnaissance, objective control, target designation, search and search rescue efforts.
Radio technical and radar surveillance	Solving intelligence problems	Solving intelligence problems
Relay and communication equipment, staging equipment disturbances	Repeating and increasing the signal range, interfering with signals	Organization of communication channels, REB systems

Table 1.2 - Continued

Payload type	Assignment	Tasks to be solved
Lidar, laser rangefinder	Instrument for determining heights and distances to targets, target designations	Fire correction, target designation, aerial photography.
Gas analyzer	Instrument for analyzing chemical composition air environment	RCB reconnaissance
Multispectral cameras	Obtaining data in different spectral projections	Air reconnaissance
Suspension and dumping systems	For load handling and load dumping	Use of means of defeat, delivery of cargo, equipment
Magnetometer, barometer, thermometer. and other sensors	To measure the geomagnetic field vector, pressure, temperature, etc.	Navigation

1.5 Design of a copter-type UAV

FPV drone flight requires a complete set of equipment consisting of a UAV, control equipment, video display equipment from a course camera that allows direct first-person control of the UAV.

A typical copter-type UAV consists of the following components:

– hull or fuselage;
– propulsion system (engine);
– autopilot (flight controller) with sensors;
– control equipment;
– propeller;
– transmitter and receiver of information signal and telemetry;
– on-board electronics;
– power source (battery, generator);
– chassis (struts).

The great variety of components for FPV drone assembly requires from persons engaged in their operation and maintenance, knowledge of the basic characteristics and principles of operation of devices included in the equipment set of FPV drone.

Based on this knowledge, it is possible to optimally select components, qualitatively perform pre-flight and post-flight maintenance, efficiently operate it, perform diagnostics and, if necessary, repair various systems of the FPV drone.

Let us consider the composition, main parameters and characteristics of the equipment included in a typical FPV drone kit [6].

Figure 1.6 shows a typical FPV drone kit.

Figure 1.6 - FPV drone kit

The kit includes the following equipment:

– FPV drone with battery;
– goggles (monitor, helmet);
– control equipment (console);
– battery charger.

The FPV drone includes the following elements:

– frame;
– propeller motor group (electric motors, propellers, electronic speed regulator);
– flight controller;
– power distribution board;
– radio receiver (interfaced with the radio transmitter on the control panel);
– video transmitter;
– rechargeable battery;
– GPS module (optional);
– camera mount;
– camera;
– acoustic signaling device with built-in battery (optional);
– connecting wires;
– fasteners.

Let's take a closer look at each of the elements of an FPV drone.

The *frame* is the main and supporting element of the drone structure, to which all other components and motors are attached. The frame is responsible for important functions of the drone: it provides reliability and stiffness of the structure when its

low weight, protection of all electronic elements. The rigidity of the design increases control stability by reducing unwanted vibrations, and the low weight increases flight time.

The quadrocopter frame has four beams made of a single piece of material or individual beams fastened with screws (Figure 1.7) [7].

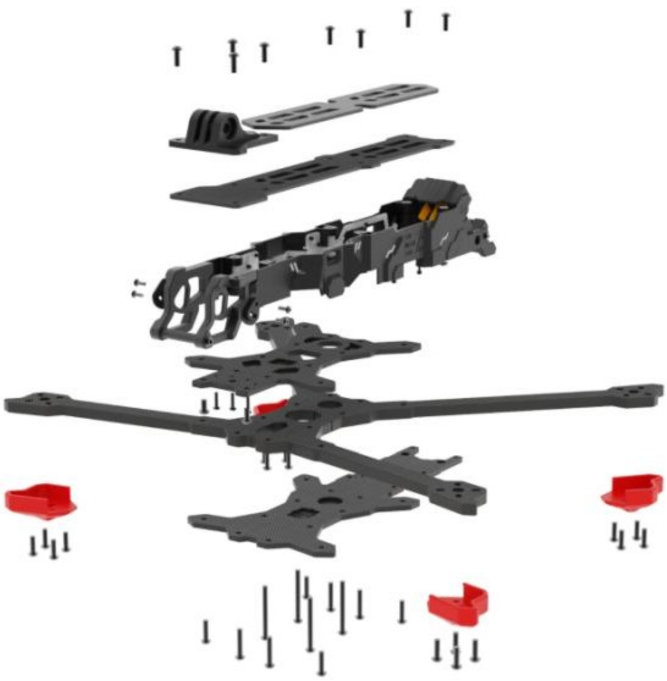


Figure 1.7 - FPV drone frame in disassembly

The fuselage is the place to house the electronics (flight controller, camera, etc.) and the kill drop system. The central part of the frame consists of two plates, lower and upper, connected by struts.

Rays - guides for installation of motors and regulators (Figure 1.8).

Figure 1.8 - Frame beams of different thicknesses and frame components

These parts must be strong enough to withstand not only the weight of the UAV structure itself, but also to withstand impacts and drops.

The size of an FPV drone is determined by the maximum propeller diameter that can be mounted on it. The propeller diameter is usually specified in inches. The size can also be specified in millimeters (e.g. 450 mm) and defines the largest distance between two motors on the UAV (Figure 1.9). The size can also define the UAV's "class" (micro, mini, etc.).

Figure 1.9 - Measuring the largest distance between two motors on a UAV

The farther the motors are from the center and the longer the beams, the greater the moment of inertia of the structure.

size of the frame affects:

– propeller size;
– the size of the engines;
– type of speed controllers - separate or in a 4-in-1 controller;
– compatibility with certain FPV or HD cameras;
– air resistance;
– inertia;
– weight.

The shape of the frame and the configuration of its beams are determined by the way and shape of beams connection to the frame. The main types of FPV drone frames are shown in Figure 1.10.

Figure 1.10 - Types of FPV drone frame

In addition, the frame can be one-piece (single plate) or prefabricated. Monorama is much lighter and does not require assembly, but if the beam breaks, the whole plate will have to be replaced, so the prefabricated frame is more repairable [8].

The frame of a mini-class BPLA is made from a variety of materials: plastic, textolite, fiberglass, aluminum, carbon fiber, etc.

Carbon is often used for the frame. Its advantages are lightness, strength, durability and rigidity. The disadvantages of carbon fiber are its electrical conductivity and, consequently, shielding of radio signals.

The design and material of the frame determine how crash resistant it is. Sturdy frames are usually heavy but more stable in the air, while light frames are maneuverable [9].

The propeller ***group*** is a UAV assembly that includes three components: *electric motors*, *propellers*, and *speed controllers*.

One of the most important parts of a quadcopter is the electric motors. Quadcopter motors are divided into collector (brushed) and collectorless (brushless) motors.

An electric motor is an electrical machine in which electrical energy is converted into mechanical rotational energy by means of a magnetic field. The efficiency of this process - the coefficient of performance (COP) of an electric motor - depends on the motor design as well as the current source (DC or AC).

Figure 1.11 shows two types of DC motors collector and collectorless.

Collector motor Collectorless motor Figure 1.11 - Types of electric motors

A collector motor consists of a housing with magnets inside (*stator*), the housing is stationary and the *rotor* with winding is driven by brushes that supply electricity to the winding (Figure 1.12).

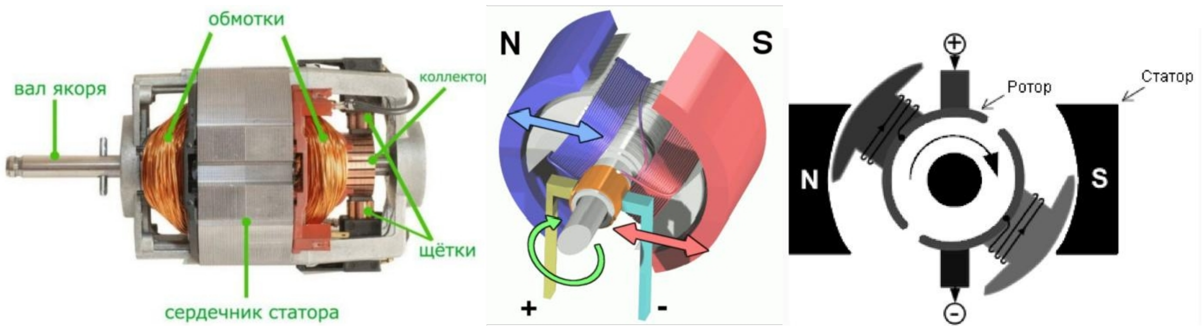


Figure 1.12 - Collector motor design and principle of operation

The direction of rotation of the rotor depends on the polarity [1].

Collector motors develop negligible rpm and power. Collector motors are mainly used on entry-level light aircraft. This type of motors is prone to breakdowns due to the peculiarities of the brush-collector assembly. Therefore, in multirotor-type UAVs, collectorless motors are used.

A collectorless motor consists of the following elements (Figure 1.13): stator, magnets, housing, shaft.

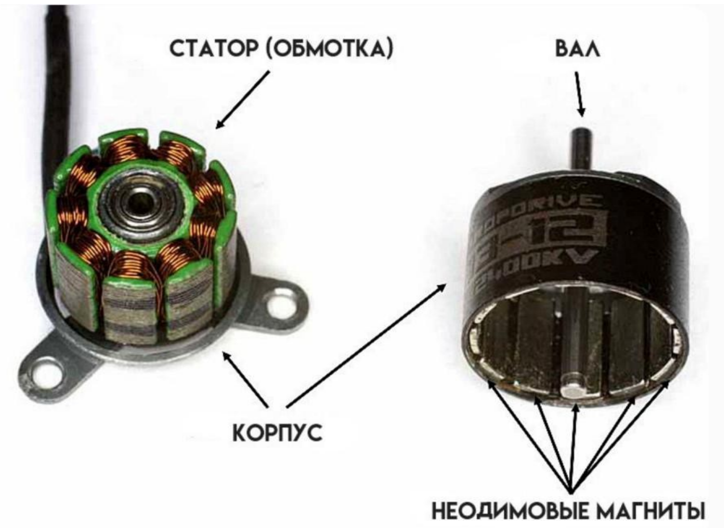


Figure 1.13 - Collectorless motor design

The stator of a collectorless motor is the motor winding, which consists of three phases of long, thin wires that are wrapped around a core. The wires are coated with enamel (varnish) to prevent short circuits in the winding. The current flowing through the wire creates a magnetic field. When the wire is wrapped around some object, it causes the magnetic field to increase. The greater the current, the greater the strength of the magnetic field and the greater the torque of the motor. However, high currents cause the winding to become very hot, especially if thin wires have been used. In such a case, the protective enamel may melt, resulting in a short circuit, and the motor will fail [10].

Magnets made of rare-earth metals (neodymium, etc.) create a magnetic field. The elements are glued with epoxy resin or cyanoacrylate glue to the motor body (bell).

The motor housing protects the magnets and winding. It is usually made of a lightweight metal such as aluminum. Some motors have housings that are made like fans, i.e. they push air over the core winding to cool it as it rotates.

The motor shaft is rigidly attached to the top of the motor. This is the working component of the motor that transmits torque to the propellers.

The direction of rotation of the motor is changed by reversing the polarity of the windings (two out of three contacts are reversed). Such electric drives have different number of poles, and the more poles there are, the slower, but with significant force, the rotor will rotate [11].

Collectorless motors are divided into two groups according to their design:

– Motors that have windings (stator) on the inside of the housing and a magnetic rotor (Inrunner) rotating inside;

– motors that have fixed windings (stator) in the center around which the housing with permanent magnets (rotor) placed on its inner wall rotates (Outrunner) [1].

The principle of operation of the collectorless motor is that the control electronics (electronic motor speed controllers - ESC) creates a rotating magnetic field in the stator windings, which, interacting with the magnets on the rotor, causes its rotation (Figure 1.14) [13].

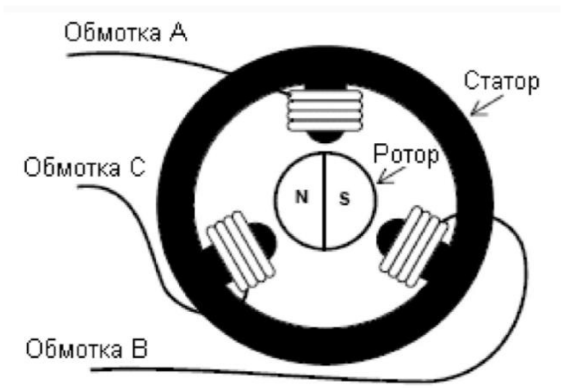


Figure 1.14 - Principle of operation of a collectorless motor

Advantages of a collectorless motor:

– high rotational speed;
– wide variation range;
– resistance to external influences, possibility of use in aggressive or explosive environments;
– high energy performance (more than 90% efficiency);
– lower level heating during during operation compared to compared to compared to collector motors;

– high reliability and increased operating life due to the absence of sliding electrical contacts;

– lower operating noise level and lower weight compared to collector motors [9].

Disadvantages of the collectorless motor:

– relatively complex engine management system;

– high cost of the motor due to the use of expensive materials in the rotor construction (magnets, bearings, shafts);

– complexity of repair.

The main parameters of collectorless motors are:

Motor mass. The less mass the motor has, the easier it is to spin up. The larger the motor, the more powerful it is, but the slower it spins up. It is important to balance the power to weight ratio.

Rated useful power is the power that the motor can deliver to a mechanical load (propeller) with the stated parameters without overheating.

Electrical power consumption is the power that the motor consumes during operation.

The efficiency of an electric motor is the ratio of electrical power input to rated useful power.

The ***torque of*** an electric motor is the rotational force of its shaft.

Motor thrust is a characteristic of an electric motor that indicates how much weight the motor can lift with the propeller attached. For a quadcopter, a general rule of thumb for determining the ratio of thrust to total weight is that the thrust of each of the motors should be at least half of the UAV's weight.

RPM per unit voltage (KV) is a parameter that indicates how many revolutions per minute a motor will make. It is not a measure of power, thrust or efficiency. In other words, the KV parameter shows how much the RPM of an electric motor will increase with a 1V supply without a propeller. For example, KV 8000 would mean that if you apply 1 volt to the motor, it will spin at 8000 rpm. If a propeller is installed, the number of revolutions will decrease due to air resistance. Drives with a higher KV will spin the propellers faster while drawing more current. Therefore, it is recommended to install large propellers on motors with low KV and compact lightweight propellers on motors with high KV [12].

A general rule to remember is that the heavier the aircraft, the lower the KV value of its electric motors, and it is common for small UAVs to use motors with very high KV values.

Direction of rotation. Motors designed for multicopters are labeled CW (from

Clockwise) and CCW (Counterclockwise).

The dimensions of collectorless motors are usually indicated by four numbers, the first two being the stator diameter (in millimeters) and the next two being the stator height (in millimeters). The greater the stator height, the more powerful it is at higher speeds. The larger the diameter, the more torque at low rpm [13].

In accordance with generally accepted standards *labeling*
electric motors are constructed follows:

1. The first letter identifies the drive class, and indicates the quality of workmanship:

– The "V" series is a designation for the motors of multicopter racing or premium segment, made of the best materials with high assembly precision;

– X" series - a series of multicopter motors of medium price category of appropriate quality and assembly;

– series "A" - electric motors of the budget segment.

2. The numbers indicate the parameters of the magnetic core. The first two digits are the diameter (in millimeters), the next two digits are the thickness of the set (in millimeters). After the fraction sign, digits denoting the number of turns are indicated. The last letter is responsible for the winding type.

Consider the following example: A2212/15T, wherein:

– A is an electric motor belonging to the budget segment;
– 22 is a magnet wire with a diameter of 22 millimeters;
– 12 - the thickness of the set is 12 millimeters;
– 15 - 15 turns;
– T - (designation may occur) - delta winding type.

The marking may also indicate the number of revolutions per minute per unit of voltage (Volts) - KV.

B descriptions electric motors may there may be values of the form:
"12N14P". Numbers before "N" mean the number of electromagnets in the stator, and before "P" - the number of permanent magnets in the rotor (Figure 1.15).

Figure 1.15 - Disassembled collectorless motor

Different sizes of electric motors have different number of poles, which determines the distance between them. A larger number of poles ensures smooth rotation, a smaller number of poles ensures higher power [7].

***Air propeller (propeller)* is a** blade propulsor that creates thrust by throwing air at a certain speed during rotation. The propeller blades, when rotating, capture air and throw it away in the opposite direction to the movement. A low-pressure zone is created in front of the propeller and a high-pressure zone behind the propeller. The greater the mass and velocity of the air stream thrown by the propeller, the greater the propeller thrust force.

There are four main parameters to consider when selecting propellers:

1. Size.
2. Pacing.
3. Propeller Configuration.
4. Material.

Pitch (Figure 1.16) refers to the distance a propeller can travel in one revolution, in some dense medium.

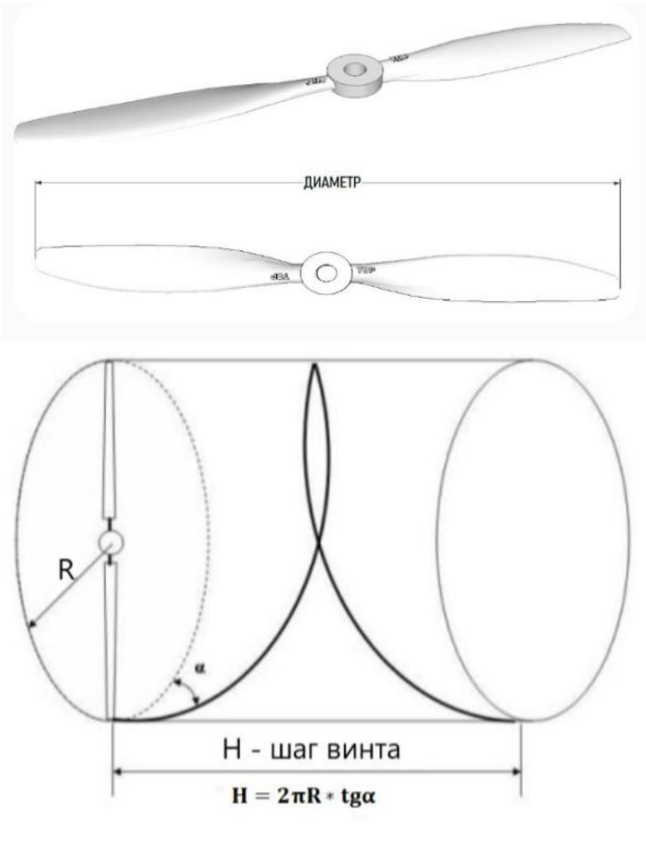


Figure 1.16 - Screw diameter and pitch

The pitch of the quadcopter blades depends on the angle of attack of the blades. A propeller with a larger angle of attack raises the device upwards by a greater value per revolution, but at the same time, it loads the motor more heavily.

Smaller propellers respond more quickly to changes in the speed of motors. They push through themselves less air, The smaller propellers are used for maneuverable quadcopters, while the larger diameter propellers are used for more payload-carrying copters. Small propellers are used for maneuverable quadcopters, and propellers with a larger diameter are used for heavier copters.

The propellers must match the power of the motor.

The most popular propeller is considered to be is the 5-inch propeller, which fits motors in the 2204-2307 size range.

The configuration of a propeller is the number of blades used in it. Propellers are categorized by the number of blades (Figure 1.17):

– two-bladed;
– 3-bladed;
– 4-lobed;
– 5-bladed.

Figure 1.17 - Two-blade and 3, 4, 5-blade propellers

Increasing the number of propeller blades compensates for the size of the propeller, which is why four-blade propellers are most commonly used in microassemblies and three-blade propellers in larger UAVs.

Due to complex physics and aerodynamics, increasing the number of blades is not as effective as increasing the size. A smaller number of blades is preferable if faster engine response is required and thrust is not as important.

In the most common category of 5-inch propellers, it is generally accepted that propellers with three blades provide the best balance of efficiency, thrust and traction.

An important factor that is often overlooked is durability. During flights, especially if the pilot is a beginner, there will be a lot of accidents and falls, so the propellers will become a consumable item.

Propellers can be made of polycarbonate, which is ductile and highly durable, as well as carbon fiber and ABS plastic. Carbon fiber has high structural rigidity, is lightweight, balanceable and does not lose its shape. ABS plastic is also a very strong material, but more brittle. Keep in mind that the choice of propeller material also depends on the time of year. Plastics for propellers are thermoplastic, that is, their rigidity and plasticity depend on temperature. Propellers made of different materials are shown in Figure 1.18.

Figure 1.18 - Air propellers made of different materials: plastic, carbon, wood

Propellers have the following designations that correspond to the direction of rotation (Figure 1.19):

– CW is a standard system with clockwise operation;

– CCW - rotation of the blades.

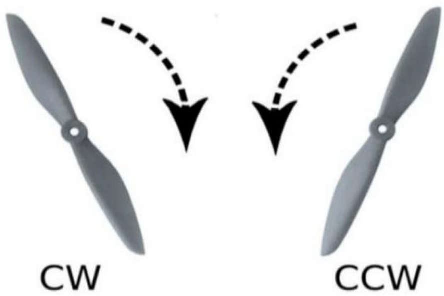


Figure 1.19 - Propeller rotation direction marking

You can determine which propeller is suitable for the desired direction of rotation by the raised edge of the blade on it. This part of the part points in the direction of rotation.

Before installing propellers on a quadcopter, you should know if the motors will spin in the correct direction. Most quadcopters fly in the configuration shown in Figure 1.20

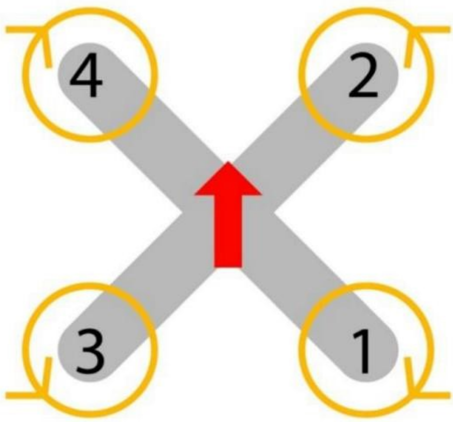


Figure 1.20 - Configuration of propeller rotation directions in a quadcopter

The red arrow shows the direction of the quadcopter flight. Yellow arrows show the direction of propeller rotation.

Propeller markings consist of 3 numbers, of the following kind: 5045 and DP5x4.5x3V, where 5045 is the abbreviated digit of the common marking. General marking - DP5x4.5x3V: the first digit means the size (in inches), in this case it is 5 inches, 4.5 is the pitch or angle of the blades, which indicates the distance traveled by the propeller in one complete revolution around its axis. The third digit (3) is the number of blades on the propeller.

Electronic Speed Controller (ESC, Electronic Speed Controller) - a special device for controlling the speed of the electric motor (Figure 1.21).

a) б)

Figure 1.21 - Electronic speed controllers: a) labeled: b) mounted on frame beams

The main task of ESC is to transfer energy from the battery to the collectorless electric motor. The need for their application arose due to some features of the collectorless electric motor. The battery supplies direct current, while the collectorless electric motor consumes three-phase alternating current.

The ESC input is supplied with voltage from the battery and signals from the flight controller (throttle level), and the regulator outputs the control voltage to the collectorless motor, changing its rotation speed [11].

The regulator shall provide:

– flight controller compatibility;

– maximum current for the motor (calculated from motor and propeller specifications plus 20 - 30%);

– current consumption is less than the current delivered by the battery divided by the number of ESCs.

Speed controller components:

– microcontroller;

– key drivers;

– power transistors (keys, MOSFETs);

– microcontroller power stabilizer (LDO);
– capacitors (filters);
– current sensor;
– LEDs.

In addition to the main function, the speed controllers can also transmit power to other components of the UAV: flight controller, servos and so on. This is achieved by implementing a Battery Eliminator Circuit (BEC) in the controller.

The use of a BEC greatly simplifies the design of the UAV, but this scheme has a number of disadvantages. Battery Exclusion Unit can overheat at high voltage drops and high loads. As a rule, speed controllers with BEC are more expensive than those without it.

A simpler solution is to use an ESC and a single BEC separately. Such a solution is called Universal Battery Eliminator Circuit (UBEC), which has a higher efficiency and is connected directly to the battery to power the corresponding node [10].

The speed controller can be configured for different modes of operation and a separate *software* called *firmware* is written for it. Software updates include bug fixes and better control algorithms. There are several ways to change the controller software:

– using a special control board;
– using the flight controller;
– using the programmer.

Based on all of the above, specific criteria for selecting an RPM controller for UAVs can be identified:

– compatibility with the flight controller. The flight controller must support BEC and ESC firmware.
– compatibility with motor and battery specifications;
– presence or absence of WEIGHT;
– heat dissipation and sealing.

Flight Controller (FC - Flight Controller) is an electronic device that is a computing system operating according to complex algorithms and controlling the UAV flight. The functions of the flight controller can be determined by additional peripherals (GPS/GLONASS, modem, OSD, photo/video camera pendant, current and voltage sensors, search tools, etc.) installed on board the mini-class UAV. In essence, a PC is a board with a large number of different sensors that monitors the position of the aircraft and commands from the user [8].

Using this data, it controls the speed of the electric motors to make the UAV move as the pilot intended. All flight controllers have a basic set of sensors: gyroscopes

(Gyro) and accelerometers (acc); some advanced configurations also have a barometer (a sensor that measures air pressure, thanks to which it is possible to measure flight altitude) and a magnetometer (compass). Peripherals such as GPS, LEDs, sonars, etc. are also connected to the PC. Controllers for racing UAVs are evolving very rapidly: they are getting smaller, with faster processors, more advanced sensors and more built-in features (Figure 1.22).

Figure 1.22 - Flight Controllers

The flight controller performs the following tasks.

1. Stabilization of the vehicle in the air - collecting and processing information from the inertial measurement unit (IMU), acceleration and angular velocity sensors, providing aerodynamic stability of the vehicle in the horizontal plane. Some IMUs include magnetometers, allowing stabilization of the vehicle's orientation relative to the magnetic meridian and keeping the direction of motion.

2. Automatic altitude *hold* - collection and processing of information from barometric, ultrasonic, infrared sensors or radio altimeters. The sensors calculate the altitude and stabilize the vehicle in the vertical plane. It is possible to fix the position of the mini-UAV at a given altitude and at a given point using the GPS/GLONASS module.

3. Autonomous flight - fulfillment of a pre-constructed flight task created in special software, maintaining the flight parameters set by the operator and automatic return to the starting point with the help of GPS/GLONASS module.

4. Stop in front of and overcoming obstacles - provides stopping in front of and overcoming obstacles using a set of sensors that determine the distance to the object. If equipped with a vision system, the flight controller must have high computing power, which allows it to accumulate and process data from sensors that constantly scan the environment in real time. In different copters, the composition of the vision system may differ in the type and number of sensors, the principle of operation, mathematical algorithms, and the order of interaction between these sensors [7].

5. Transmission of current flight parameters - collection and processing of data from external data sources (GPS/GLONASS, current, voltage, temperature sensors) and standard data sources (barometer, accelerometer, magnetometer) with subsequent transmission of the data stream to the OSD (On-Screen Data) module, which are displayed to the operator in FPV goggles or on the display. Telemetry data can also be transmitted directly from the flight controller using a radio modem, which provides two-way communication via UART (Universal Asynchronous Transceiver Transceiver) protocol via radio channel.

Flight controllers can have a different set of sensors and functionality, depending on its purpose. As a rule, FPV drones have a simpler flight controller than classic quadcopters designed for video shooting (Figure 1.23). The latter PCs have a full autopilot that performs advanced functionality such as point-to-point flight, payload control, tracking of the object of interest, or autonomous navigation. At the same time, the FPV drone PC mainly performs only the task of stabilizing the UAV in the air and controlling it by operator commands (Figure 1.24).

a) б)

Figure 1.23 - Types of flight controllers: a) - FPV drone PC, b) - UAV autopilot

Figure 1.24 - Difference between FPV drone PC and autopilot

Let's look at the main components of an FPV drone flight controller.

A microcontroller is a single-chip microcomputer typically from the 32-bit STM32 family from by STMicroelectronics. Family of

STM32 consists of microcontroller series: H7, F7, F4, G4, F3, F2, F1, F0. Microcontroller models differ in internal architecture, performance, memory size for storing programs and data, number of interfaces for connecting external and internal peripherals and others. These parameters determine the number of control channels, the number of sensors and actuators that can be connected to the PC, and how quickly it will perform the necessary calculations.

The minimum requirement for the *number of flight controller* channels is to have a minimum of four control channels as they are required to control the 4 main functions of the UAV:

– throttle channel - responsible for reducing and increasing the RPM of the UAV's engines;

– pitch channel - responsible for tilting the vehicle forward and backward;

– roll channel - responsible for tilting the UAV to the left and right;

– yaw channel - responsible for rotation of the vehicle around its axis.

Digital buses and CAN, I2C, SPI and hardware serial interface UART are used to connect external devices to the PC.

The digital connection buses CAN, I2C and SPI are used to connect various sensors to the PC. It is best to use SPI as it allows for higher sensor polling frequencies than I2C.

The UART (Universal Asynchronous Receiver/Transmitter) *hardware serial interface* is used to connect peripheral devices (GPS signal receiver, telemetry, transponder, video transmitter control, etc.). Each serial port has two pins: TX for data transmission and RX for reception. Remember, TX on the peripheral connects to RX on the flight controller and vice versa [6]. The number of serial ports in the flight controller depends on the PC model and the microcontroller used in it. For example, a microcontroller of type F1 usually has only 2 UART ports, F3 and F4 may have 3 to 5, and F7 may have 6 or 7.

Built-in sensors: accelerometers, gyroscopes, barometers, magnetometers (compasses), outdoor temperature sensors, and various measuring units such as the Inertial Navigation Unit (IMU).

The telemetry unit is designed to transmit copter flight parameters (location, battery charge percentage, altitude, speed, current consumption, etc.) to the control panel or via a video transmitter to FPV goggles.

Figure 1.25 shows the main elements of the flight controller and contacts for connecting peripheral devices.

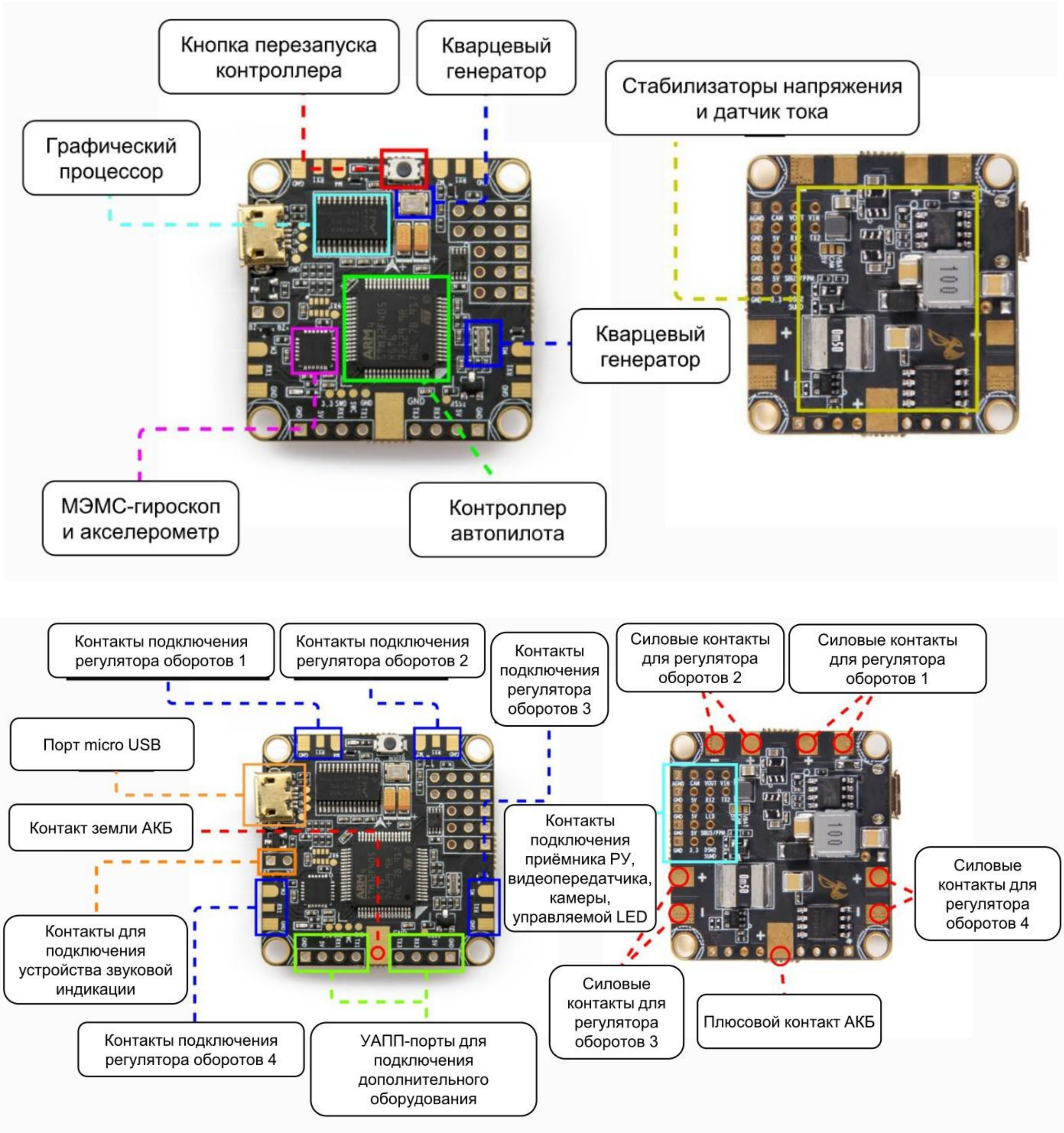


Figure 1.25 - Flight controller components

Peripheral equipment is additional external devices that are connected to the UAV flight controller as needed. For example, satellite and inertial navigation modules, OSD, bluetooth, Wi-Fi, current and voltage sensors, etc.

Let's take a look at some of the peripheral elements that are included or optionally connected to flight controllers:

– flight controller sensors used to orient and position the UAV in flight:

accelerometer - measures linear accelerations along three axes (x, y, z).

gyroscope - measures angular velocities of UAV rotation along three axes (x, y, z), Euler angles, quaternions necessary for determining its spatial position.

– sensors that are included in advanced versions of the flight controller:

Magnetometer (compass) - measures the direction of yaw angle (heading) relative to north.

Barometer - measures the barometric altitude of the UAV. It is used at high (over 50 m) altitudes.

– facilities that are optionally connected to the flight controller to provide additional functions (not normally used in FPV drones):

Altimeter - measures altitude relative to the surface. Designed for "soft landing" of UAVs. Used at low (up to 50 m) altitudes.

The following types of altimeters are available:

- sonars (sound waves);
- radio altimeter (radio waves);
- laser rangefinder, LiDAR (optics).

Satellite navigation system (SNS) (Global Positioning System - GPS) is a satellite navigation receiver that allows to determine the coordinates of a UAV anywhere in the world and automatically or semi-automatically fly along specified routes and return to the landing point. The satellite receiver includes antennas and a calculator. The main used SNA: GLONASS, GPS, BeiDou, Galileo, QZSS. Advantages of SNA: all-weather, global, rapid, accurate and efficient. Disadvantages of SNA: the need for direct radio visibility with at least four satellites; possibility of suppression by REB systems; substitution of satellite signals by false signals (GPS - spoofing).

An Inertial Measuring Unit (IMU) is a navigation device that utilizes accelerometers, gyroscopes and a calculator to continuously determine, through accurate calculation, the position of the UAV's orientation and velocity. The advantages of an ANN are complete autonomy (independence from external signal sources) and independence from external factors (interference and suppression). The main disadvantage of ANN is the accumulation of errors if there is no correction from non-inertial systems.

OSD (On Screen Display) is a system of displaying additional flight information on the screen, which overlays additional information from various sensors of the quadrocopter on the video stream (Figure 1.26), for example, battery voltage, altitude, speed and so on. The OSD system can be designed as a separate device or integrated into the flight controller.

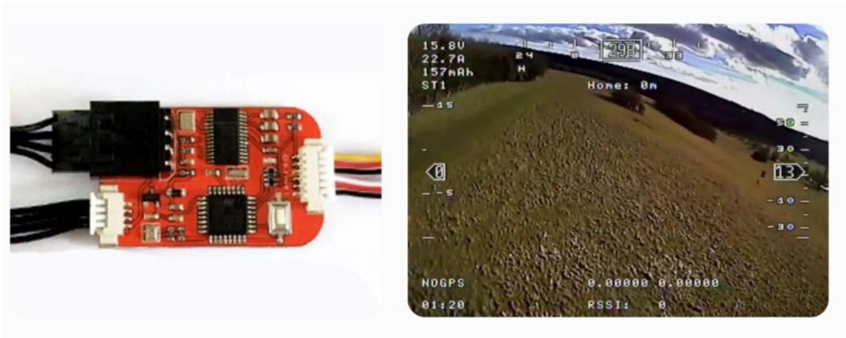


Figure 1.26 - OSD board appearance and telemetry display on video

The *flight data* logging *system* is needed to record the quadcopter flight parameters (operation logs) from the flight controller into a special file. There are two places where you can record logs: the flash memory of the flight controller and the SD card (flash drive).

Figure 1.27 shows an example of connecting various peripheral equipment to the flight controller.

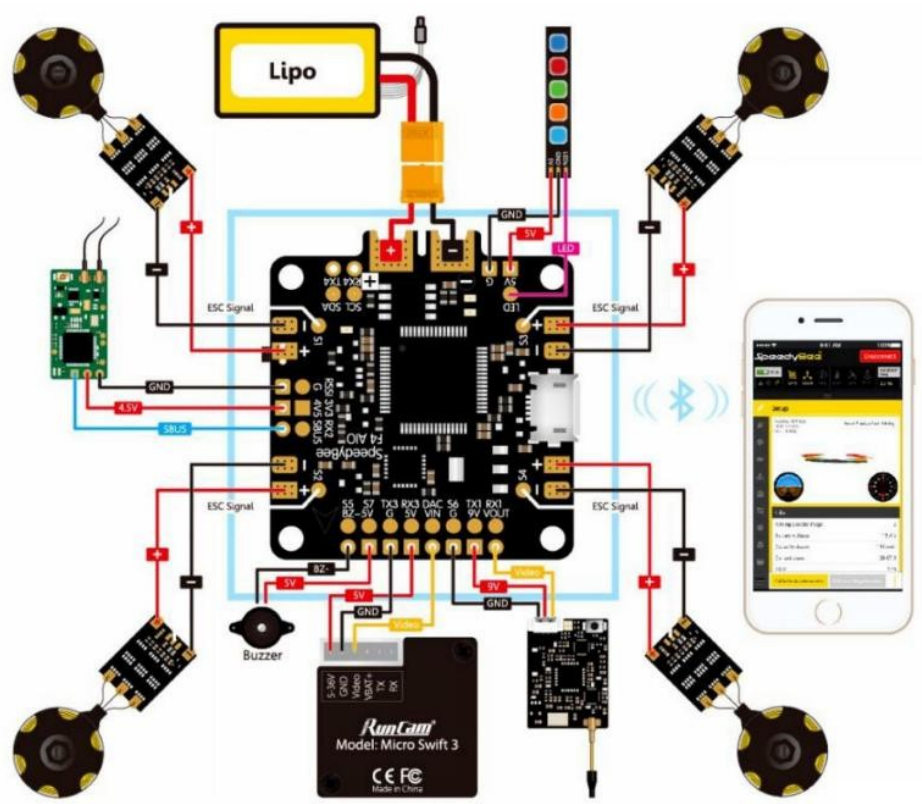


Figure 1.27 - Example of connecting peripherals to the flight controller

The FPV drone'***s power system*** consists of a battery pack, power distribution board, and connecting wires.

The PDB (Power Distribution Board). The main task of the PDB is to transfer current from the battery to the ESCs, as well as to power the flight controller and some peripherals. Typically, a PDB is a small board the size of a flight controller, which has at least 5 pairs of contact pads (plus and minus) (Figure 1.28). A battery connector is soldered to one of the pads (often these pins are off to the side), and the other 4 (if the quadrocopter is assembled) are soldered to the ESC pins, i.e. this board distributes the current from the battery throughout the entire quadrocopter system [6].

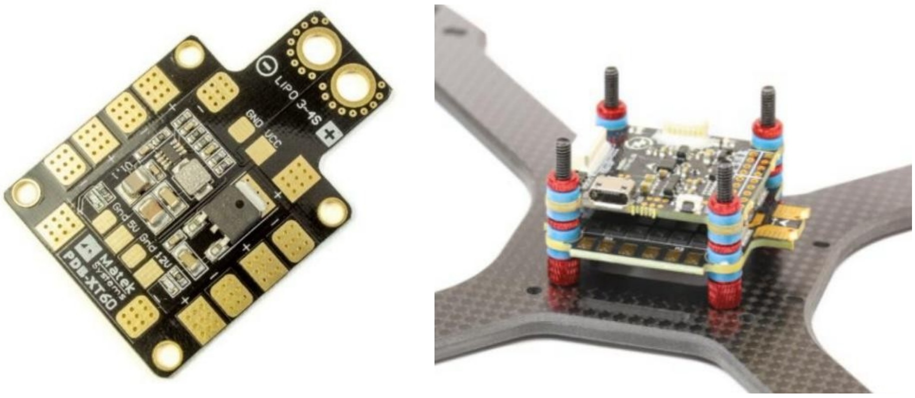


Figure 1.28 - Power distribution board separately and assembled with flight controller

Most PDBs contain voltage regulators for connecting peripherals. Typically, peripherals, including the flight controller, operate from a 5V supply voltage, the quadcopter battery produces a 12 - 16V supply voltage.

The primary purpose of the PDB is to transfer current from the battery to the ESCs and to power the flight controller.

A battery (Batteries) is a device for storing energy later use.

Modern FPV drones use two types of batteries:

– Li-Ion (lithium-ion);
– Li-Po (lithium polymer).

Lithium-ion battery (Li-Ion) is a type of electric battery that is widely used in modern consumer electronics and finds applications in it as a power source in electric vehicles, energy storage in power systems.

Advantages of Li-Ion batteries:

– high energy density (capacity);
– low self-discharge;
– high current output;
– high number of charge-discharge cycles;
– do not require
maintenance. Disadvantages of
Li-Ion batteries:

– are often extremely flammable if overcharged, if charging conditions are not met, or if mechanically damaged;
– loss of capacity in the cold.

One of the major technological advances that have led to the surge in popularity of civilian UAVs has been lithium-polymer batteries (Li-Po - lithium-ion polymer battery). Very similar in design to smartphone batteries, lithium-polymer batteries have a much larger ratio of
"capacity/weight compared to nickel cadmium (NiCD) and nickel metal hydride (NiMH) batteries. This elimination of excess weight *has allowed their use in UAVs*.

Lithium polymer battery (Li-Po) (Figure 1.29) is an advanced design of lithium-ion battery. A polymer material is used as the electrolyte.

Figure 1.29 - Li-Po rechargeable battery with labeling data

Benefits of Li-Po Batteries:
– high energy density per unit mass;
– low self-discharge;
– the possibility of obtaining very flexible shapes;
– a slight voltage drop as it discharges;
– wide operating temperature range from -20 to +40 °C.
Disadvantages of Li-Po batteries:
– fire hazard due to overcharging and/or overheating. To combat this phenomenon, all household batteries are equipped with built-in electronic circuitry that prevents overcharging and overheating due to overcharging. For the same reason, they require special charging algorithms (chargers);
– number of operating cycles 800 - 900, at discharge currents of 2A up to a capacity loss of 20%.
The main characteristics of the batteries are:
– Tension;
– capacity;
– current output;
– the number and method of connecting the cells in the battery.

Voltage - All lithium polymer batteries are formed from single cells connected in series and structurally combined into blocks to achieve the required voltage. The nominal voltage of each cell is 3.7V (4.2V at full charge). This means that in our example the nominal voltage will be $3 \times 3.7 = 11.1$ V and can reach $3 \times 4.2 = 12.6$ V at full charge.

Capacity is the capacity of the battery, measured in ampere hours or milliampere hours.

Example: A 1000 mAh battery says that it will deliver a current equal to 1000 mA or 1 A to the load for hour. Discharge time is directly related to the current in the circuit, if you connect a light bulb that draws 100 mA or 0.1 A to such a battery, it will shine for 10 hours and vice versa - if you connect a motor that draws 6 A, this battery will be enough for only 10 minutes of operation of such a motor.

Knowing the capacity, you can calculate the run time by dividing the capacity by the load current, from the example above. For example, if there is a 1 battery and a 1 Ah load, divide by 1 Ah = 1 hour, $T=C/I$, T is the discharge time, C is the battery capacity, I is the load current. Example with a light bulb 1 Ah divided by 0.1 A = 10 h and with a motor 1 Ah divided by 6 A =0.16 h - 10 minutes. It is worth noting that not every battery is capable of discharging at such a rate as with the motor in the example (6 Ah), some batteries will fail at such a rapid discharge. To prevent this from happening on the batteries, another parameter [1] is written on the batteries.

The current capacity is the allowable rate of discharge of a given battery, on batteries or single cells. It is denoted by "number and letter C", it indicates that this battery can give all the stored energy in time, which is defined as one hour divided by the number in front of "C", that is, let's take a 1Ah battery, its current capacity is 10C, it means, that it can give all the energy in 1h, divided by 10C= 0,1h, that is 6 minutes, it turns out that the motor from the example above will not damage it by discharging it in 10 minutes, as it is 4 minutes longer than the maximum discharge rate of 6 minutes before it is completely discharged. This is how to calculate the time in which you can discharge the battery without harming it. You can calculate the maximum current it will deliver by multiplying its capacity of 1 Ah by the number given as the current capacity "C" 1 Ah× 10C= 10 A.

Example: An unmanned airplane consumes 10 A at maximum speed, and the battery has a capacity of 2 Ah, this means that the airplane will discharge this battery in 2/10=0.2 h - 12 minutes, and now let's calculate what value of current output "C" is required for this. The current output can be calculated as follows: 1 hour divided by the time obtained above. For convenience, the hour will be divided into minutes, and so 60/12 = 5 - it turns out that for a 12-minute flight he will need a battery with a capacity of 2 Ah and a current output of 5C.

It is worth paying attention to the fact that the current output does not affect the flight time. You can take a battery with the same capacity and 100C current output, the flight time will remain 12 minutes and no other way, because only the battery capacity affects the operating time of the model. Often beginners choose a battery with

with a giant "C" and hardly look at the capacity. For example, if we take the model from the description above and install a 500 mAh battery with 60 C current output (we already know that it flies for 12 minutes on a 2 Ah battery), we calculate the flight time - 0.5 Ah, divided by the load current of 10 A = 0.05 h - 3 minutes, and this is assuming that the battery is 60 C. And how much "C" do we need for a three minute flight on such a battery? 60/3=20 C, so why then overpay for an extra 40 C, if the flight time has not changed though 20 C, though 60 C is still 3 minutes [1].

The number of cells in a Li-Po battery and how they are connected. The battery cells are called cells or banks. The nominal voltage of one Li-Po battery bank is 3.7 V. To obtain a higher voltage they are connected in series (Figure 1.30), and to increase the capacity - in parallel. The order of connection of banks in the battery is defined by symbols S - series connection; P - parallel connection [6].

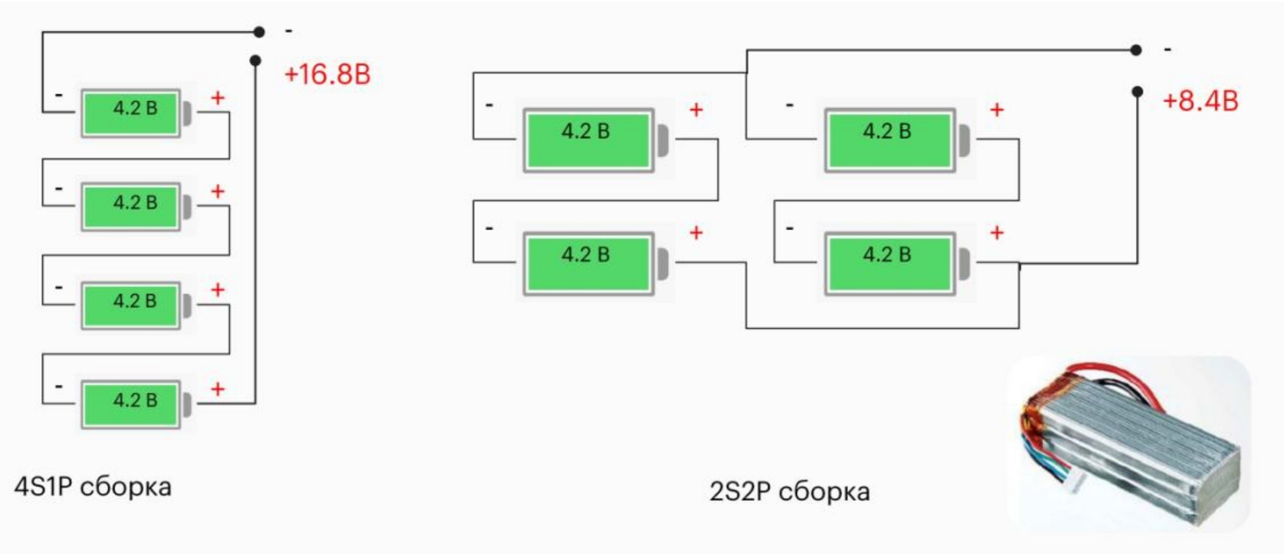


Figure 1.30 - Li-Po battery cell assembly diagram

The main parameters of the battery are usually indicated in the markings on its case. As an example, consider Infinity 1500mAh 4SP1 battery (Figure 1.31):

– Infinity is the trade name for the battery;

– 1500mAh is the capacity of the battery which is measured in milliamp hours, the higher the capacity the longer the quadcopter will fly, but the weight of the battery also increases;

– 4S - number of cells connected in series in the battery, in the presented case there are 4 cells. Each cell has a voltage of approximately ,.7V, and in total all 4 cells produce a voltage of 14.8V.

Figure 1.31 - Infinity 1500mAh Li-Po Battery 4SP1

– 1P - number of parallel connected units in the assembly, in the presented case 1 unit;

– 70C is the current output.

Battery selection. The choice of battery parameters depends on the copter weight, installed payload, additional equipment, as well as the required speed, range and flight duration.

The operation of Li-Po and Li-ion batteries has its own peculiarities:

– limited number of charge-discharge cycles;

– sensitivity overcharging and deep discharge;

– sensitivity to high temperature (operating mode from -20 to 50°C);

– sensitivity to vibration and shock loads;

– reduced battery life at high discharge currents. Correct operation of Li-Po and Li-ion batteries, taking into account their specific features, will ensure a long service life. The most important steps in the operation of a battery, which have a significant impact its life, are proper charging and storage.

Charging procedure of Li-Po batteries. To charge Li-Po batteries consisting of several cells, it is necessary to use special chargers (Figure 1.32), which ensure uniform charging of cells.

Figure 1.32 - Battery Charging Device

The peculiarity of this charger is that it knows how to balance the battery cells - the battery is connected to it not only by the power connector, but also by an additional balancing connector, to which all the cells are brought out separately.

When the balancing connector is connected to the charger, the display should show the number of cans that make up the battery (Figure 1.33).

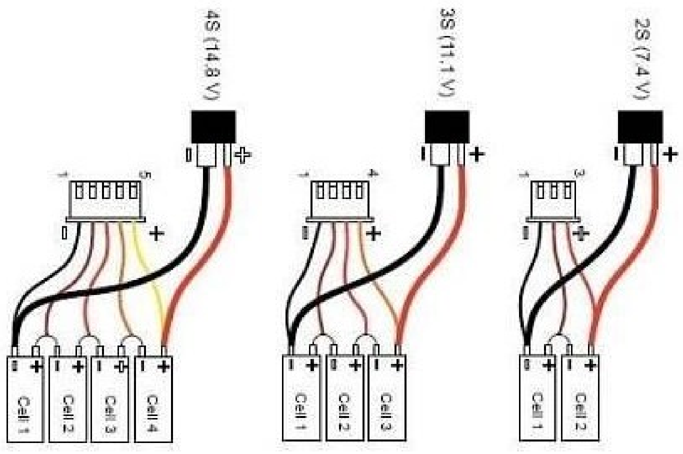


Figure 1.33 - Diagram of battery cell connection to the balancing connector

The balancing connector is needed to make sure that all battery banks are charged equally. This makes it possible to charge the battery by evenly distributing the load on the battery banks during operation. The charger is able to measure internal resistance and perform a capacity measurement cycle. In the latter case, it fully discharges and charges the battery and provides information on the actual capacity of the battery.

It is recommended to charge the battery with currents not exceeding 1C, e.g. if the battery has a capacity of 1500 mAh, it can be charged with 1.5A. If it is necessary to charge the battery as quickly as possible, use the maximum allowable charging current indicated on the battery. However, it is better not to charge with currents greater than 3C, for 1500 mAh it is 4.5A.

In order to protect against fire, special fireproof bags must be used. The Li-Po battery is connected to the charger and placed in this bag for the entire charging period.

Do not charge batteries near any flammable materials. It is advisable to use fireproof bags to safely charge the batteries.

A powder or carbon dioxide extinguisher must be used to extinguish batteries, Li-Po batteries must not be extinguished with other extinguishers!

The storage of Li-Po batteries is an important point to which you should pay close attention. If you simply charge a Li-Po battery to the end and do not use it, it will rapidly begin to lose capacity and will soon become unusable. If you discharge a Li-Po battery and do not use it, it will also lose capacity and become unusable within 1-2 months. It is necessary to use a special mode STORAGE, i.e. storage, which is available on the charger. In this mode, each section is charged or discharged to 3.85V. At this voltage, the chemical processes in the battery are not so intensive, so the battery will last much longer [7].

Once the battery is put into storage mode, you should put it in a cold place and store it at a low temperature to slow down the chemical processes.

FPV drones are equipped with *FPV directional cameras* for target missions. The cameras can be visible, thermal or night vision. Course cameras for a particular FPV drone are selected according to the dimensions of its frame. It is possible to install cameras on frames of smaller size, but for this purpose it is necessary to use special holders. Options for mounting FPV cameras on drone frames are shown in Figure 1.34.

Figure 1.34 - FPV camera mounting options

FPV camera sizes are divided into the following types: full-size or standard (28mm); mini (21mm); DJI O3 Air Unit cameras (20mm); micro (19mm); nano (14mm).

FPV cameras have the following characteristics:

- CMOS and CCD sensor type and its resolution;
- 4:3 or 16:9 aspect ratio;
- TVL resolution;
- PAL or NTSC signal encoding system format;
- Lens and lens size;
- light sensitivity (ISO);
- presence of IR filter;
- form factor (without housing, plastic or metal housing);
- camera weight.

The appearance of CMOS and CCD matrices is shown in Figure 1.35.

Figure 1.35 - CMOS and CCD matrices

CMOS matrices are used for digital signals, CCD for analog signals.

Advantages of CCD cameras:

– high performance under large changes in illumination due to wide dynamic range (WDR). For example, if you fly directly towards the sun on a sunny day, the CCD sensor will adapt to this very quickly and darken the image. The same works in the opposite direction in low light conditions. Cameras with CMOS sensor cannot work so quickly.

– CCD has a very low latency. Cameras with this sensor send a signal to the video transmitter much faster than cameras with CMOS sensor. However, new modern CMOS cameras are starting to catch up with the speed of CCDs, but the latter are still ahead.

– CCDs don't have line-by-line. Most CMOS build the picture on lines to make an image. From a strong vibration on a UAV, these lines can "move" and the picture will become wavy. This effect is also called "Jello" or Jello Effect. With CCDs, the picture is displayed in its entirety at once, rather than being drawn line by line.

Advantages of CMOS cameras:

– higher resolution;
– better color rendition;
– higher frame rate;
– lower power consumption.

In the process of FPV drone flight the advantages of CMOS cameras (except for power consumption) are less important than the advantages of CCD cameras, so at the moment the most common cameras used in FPV drones are CCD cameras.

Most cameras are capable of displaying 4:3 and 16:9 *aspect ratio* video. However, most UAV operators fly at 4:3 aspect ratio because some cameras simply crop the top and bottom edges of 4:3 video to get 16:9 aspect ratio.

TVL resolution characterizes the number of horizontal lines that fit in the frame. The larger the TVL, the better the picture quality.

Two basic color encoding formats are known for analog cameras:

- PAL;
- NTSC.

PAL delivers 25 frames per second and 720 × 576 resolution, while NTSC delivers 30 frames per second and 720 × 480 pixel resolution. Keep in mind that PAL supports higher resolution and NTSC supports higher frame rate.

Lens and lens size

FPV cameras with a 1/3 inch lens are always used for standard mini and micro quadcopters. These lenses are universal and can fit any such camera, making it repairable.

The shape of the lens determines the angle of view - the space that can be seen with the camera. Some manufacturers try to make their lenses with a larger angle of view or, conversely, with a smaller angle of view. Wide-angle (with a large viewing angle) lenses are not always good. The point is that such lenses worsen the perception of the depth of space, you may not understand how close the object is, which is very important for FPV drones [1].

Some cameras have an *IR filter*, it can be either blocked or unblocked, the description indicates this as follows:

- IR blocked;
- IR unblocked.

The IR unblocked lens transmits a picture with dim colors and is designed for night and twilight flights.

The IR blocked lens transmits colors naturally and is not intended for night flying. With this lens, the picture in sunlight will be very bright and saturated, but at night you will not see anything.

Some FPV drones for night flying are equipped with thermal imagers, special devices that detect infrared (IR) radiation emitted by heated objects. In a thermal imager, a sensitive element changes resistance when IR radiation hits it. A thermal imaging camera has a special lens, usually made of a germanium lens, which allows infrared radiation to pass through.

Thermal imaging cameras are much more expensive than cameras working in the visible range, so they are used on FPV drones only in exceptional situations.

Additional equipment for FPV drone applications

Buzzer (Buzzer, signaling device) for quadcopter is an important element of quadcopter design. The buzzer signals various events occurring in the software part of the UAV, ranging from errors to a low battery signal. A loud buzzer makes it much easier to find the quadcopter.

Soft mounting bushings - absorbs vibration and shock loads.

Cases or backpacks - for convenience in carrying drone components, special cases should be used that have compartments or pockets for the equipment included in the UAV complex.

Fireproof bags - to prevent the spread of fire in case of fire of Li-Po rechargeable batteries.

Powerbank and charging stations - for charging the battery. The charging station can be connected either to the regular power supply or to a generator. The Powerbank should be used as a backup power source.

The launch pad or stand is used to prevent the lower part of the UAV from scratching from frequent contact with the ground and to give the drone a tilt angle corresponding to the FPV camera mounting angle.

Remote repeaters and signal amplifiers - used to increase the flight range and maximize signal coverage [11].

Drop and delivery systems - for suspending payloads on UAVs. Drop systems that are attached to the fuselage can be used. They are usually 3D-printed for each type of UAV. The jettison system has a sliding mechanism to release the payload, which is servo-controlled by a sensor signal.

Control questions

1. How are UAVs categorized based on design?
2. What type of aircraft do multirotor UAVs belong to?
3. Explain the principle of operation of the main propeller.
4. List the forces acting on the quadrocopter in flight.
5. What kind of equipment is included with an FPV drone?
6. List the basic elements of FPV drone design.
7. Name the main characteristics of an FPV drone frame.
8. Name the purpose and types of electric motors used in FPV drones and their features?
9. Describe the principle of operation of collectorless motors.
10. Name the purpose and types of propellers used in FPV drones.
11. Electronic speed regulators: purpose, composition and principle of operation.
12. Flight controller: purpose, composition and main functions.
13. List the types of peripheral equipment used in FPV drones.
14. Power supply system: purpose and composition.
15. What are the markings on a Li-Po battery pack?

2 VIDEO CONTROL AND TRANSMISSION EQUIPMENT

The most important component of an FPV system is the control and data transmission equipment. The main data transmitted are telemetry and video stream from the FPV camera. The principle of operation of the equipment is based on the use of radio signals to transmit control signals from the operator to the drone and data from the drone to the operator's console and FPV goggles.

2.1 Basics of radio wave propagation

A radio signal is a signal transmitted using a radio wave. In turn, a radio wave is an interconnected oscillation of electric and magnetic fields that can propagate in space at the speed of light. Radio signals have such properties as reflection, attenuation, refraction.

The main parameter of a radio wave is its *length*, which is related to frequency through the speed of light. Frequency is measured in Hertz (Hz).

The propagation range of radio waves depends on the *frequency of* the radio wave and the power of the transmitter. UAV control and data transmission equipment uses ultra-high frequency signals (ultrashort waves).

The wavelength of ultrashort waves (UHF) is from 1 cm to 10 m, they include meter (MV), decimeter (DMV), centimeter (CMV). A feature of VHF propagation is the need for the receiver and transmitter to be in line of sight.

2.2 FPV drone frequency ranges

Analysis of the experience of FPV drone use by the Armed Forces of Ukraine (AFU) showed that frequencies located in the 900 MHz, 2.4 GHz and 5.8 GHz bands were mainly used for video information transmission. At the same time, the publicly available frequency bands, which were located near 433 MHz and 2.4 GHz, were used to transmit control and telemetry signals. The results of the analysis are presented in Figures 2.1, 2.2.

The frequency ranges presented above have their own characteristics:

2.4 GHz is the most common frequency range for control and data transmission. It allows unobstructed control of the drone at a distance of up to several kilometers. However, due to its widespread popularity and the use of other devices operating on the same frequency, there is a risk of interference and signal loss. The 2.4 GHz band is standard for most commercial drones. It has a longer range and less interference. Drones in this frequency range can be used for most reconnaissance and strike missions.

5.8 GHz - the band is mainly used for transmitting video and data from drone to ground as it has higher bandwidth and low latency, which allows transmitting video signals of high quality. With increasing distance, the attenuation of signals in this frequency range is faster than in other bands under consideration.

433 MHz and 900 MHz are low frequency bands used in control and telemetry signal transmission systems. Because of their interference properties, they are more effective in urban areas, forested areas, etc. However, it should be remembered that the use of *900 MHz* requires proper authorization and registration with the air navigation network.

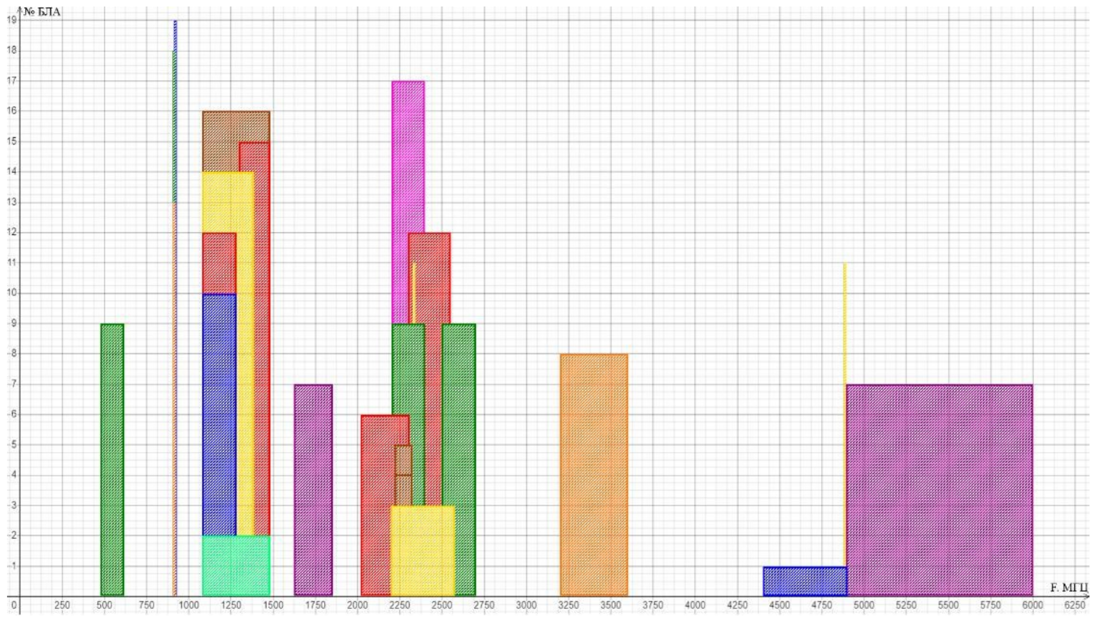


Figure 2.1 - Video channel frequency ranges of UAV UAS video channels

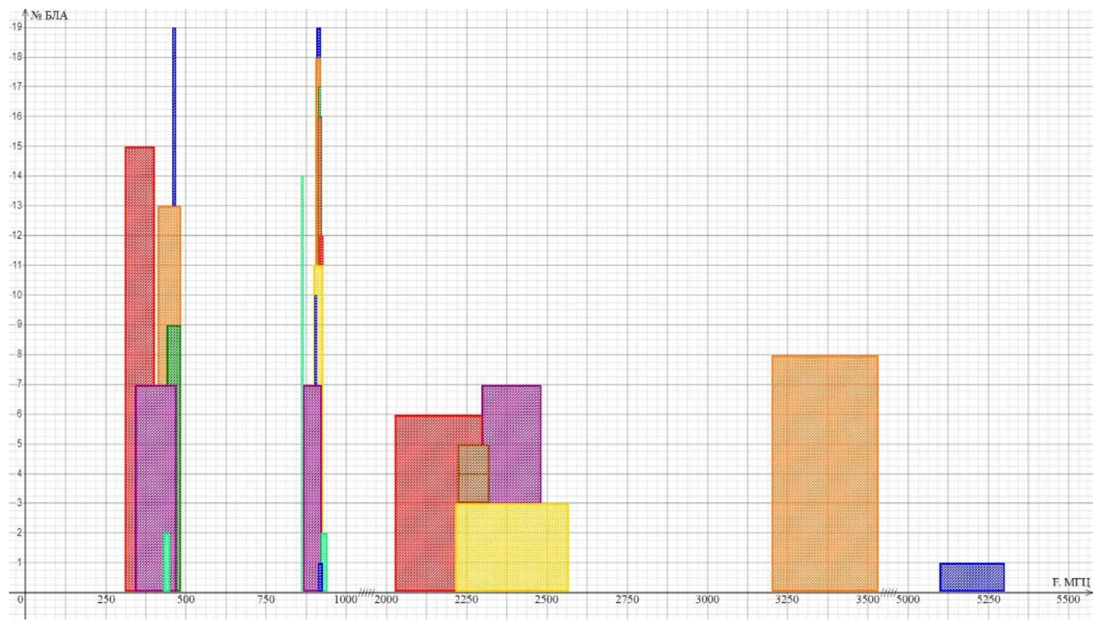


Figure 2.2 - Control and telemetry channel frequency ranges of UAV UAS control and telemetry channels

The choice of frequency range depends on the specific task and conditions of use of the drone. The choice should take into account local regulations, radio noise and environmental conditions.

Depending on the specific type of drone and its purpose, the frequency range may vary. However, controlling and transmitting data in these bands allows drones to function reliably and efficiently in different environments [1].

In general, different frequency bands allow drones to operate in different environments and perform different tasks. Developers and operators should select the appropriate band based on the requirements and specifics of the task to ensure safe and stable drone operation.

2.3 UAV control equipment

A radio transmitter (RTX) is a device that controls the flight of an FPV drone. It is often referred to as radio control equipment, remote control, etc. (Figure 2.3).

Figure 2.3 - Control panel, receivers and flight controller

Keep in mind that your choice of remote control (RC) determines the type of receiver (RX) you can use. If you purchase a remote control

In this case, you must purchase a receiver from the same manufacturer. Radio transmitters and receivers from different manufacturers will not work together. Recently, remotes with a multiprotocol module have been gaining popularity. Such control equipment can be connected to a huge number of different receivers of different brands, the operator only needs to select the brand name and type of receiver in the remote control settings.

The main features of the control panel are:

– Form factor (full-size and "gamepad");
– number of switches as well as their operating modes;
– the operating frequency of the radio transmitter;
– communication protocols;
– availability of a compartment for an external module;
– transmitter power;
– range;
– number of channels;
– software firmware;
– telemetry support;
– FPV simulator support;
– availability of Trainer .

Gamepad-style remotes are more compact but limited in function. They have a smaller screen, fewer switches, and smaller control sticks.

Full-size remotes have ergonomics to suit a wider range of users, standard-size sticks offer higher resolution and accuracy.

When choosing a remote control, in addition to dimensions, it is important to consider design and such factors as grip comfort, cord loop, location and types of switches. The weight of the remote control is also an important factor. Working with a heavy device can quickly cause fatigue.

The main elements of the control panel are two sticks (*gimbals*) used by the operator to control the UAV's movement along four channels (axes):

Throttle - Controls the thrust of the electric motors, used to move the aircraft up or down.

Pitch - Controls the UAV's rotation along the transverse axis, used to move the aircraft forward or backward.

Roll - Controls the rotation of the UAV along the longitudinal axis, used to move the aircraft to the left or right.

Yaw - Controls the UAV's rotation around the vertical axis, used to turn the aircraft to the left or right.

There are four different modes of remote control stick operation: Mode 1, Mode 2, Mode 3 and Mode 4. Selecting a remote control with the appropriate mode depends on the operator's personal preferences, but it is best to choose Mode 2, the mode most often used by drone pilots (Figure 2.4).

Figure 2.4 - Operation mode of the control panel MODE 2

In Mode 2, Throttle and Yaw commands are issued from the left stick, while Pitch and Roll commands are issued from the right stick [13].

There are two main types of sticks used in modern control units: potentiometer-based and Hall sensor-based. Potentiometer-based mechanisms have a lower cost, but they wear out faster, while Hall sensor controls have higher accuracy and are more durable.

Control panel switches are used to activate additional functions (launch, flight modes, horn, etc.). These switches can be two-position or three-position, and can also have sliders and rotary knobs.

When selecting a control panel, the number of channels should be considered - this is the number of aircraft functions that can be controlled. Manufacturers of radio equipment, as a rule, specify in the characteristics information about how many channels their devices support. This is due to the maximum number of controls and available switches, as each of them requires a dedicated channel to transmit data to the drone receiver [9].

The two sticks on the remote control use four channels because they are responsible for four commands: Throttle, Yaw, Pitch, and Roll. Additional channels (they are called AUX channels) are tied to switches responsible for starting the drone and other functions. Therefore, you need at least 5 channels to fly an FPV drone.

Many popular radio communication protocols, such as Crossfire and ExpressLRS, support up to 12 channels, and most transmitters have a

There are four to eight switches available, and that's more than enough for piloting.

The frequency of the radio transmitter is an important parameter consider when choosing a remote control for an FPV drone.

Having a compartment for an external module on the control panel can be useful if you plan to upgrade to a more advanced radio system in the future. There is no need to purchase a new device, but rather an external module with new features [10].

Most commonly, 2.4 GHz and 900 MHz transmitter frequencies are used to control FPV drone flight.

Currently, 2.4 GHz is the standard for radio control. In most countries this frequency is legal for amateur use. It requires smaller antennas and is therefore very popular with pilots.

The 900 MHz frequency is used for longer range flights because control signals are less adversely affected by radio propagation conditions. Larger antennas are required for signal transmission. However, many FPV drone owners prefer this lower frequency [5].

It is worth noting that the exact value of the operating frequency for the 900 megahertz band varies from region to region. In most countries of the world it is 915 MHz, in the European Union it is 868 MHz.

Sometimes other less common frequencies are used in radio control: 27 MHz, 72 MHz, 433 MHz and 1.2 GHz. For FPV drones, 2.4 GHz or 900 MHz are better suited.

All transmitter manufacturers use algorithms with pseudo-randomization of the operating frequency. The software-controlled transceiver constantly scans the airwaves to find the frequency least affected by interference and automatically switches to the free channels found. This process is carried out at a frequency at which the operator does not visually see pauses or control failures. In addition, the advantage of the algorithms is that they can be used to realize flight compatibility between different operators and aircraft.

An important parameter when choosing a control panel is the communication protocol used in the transmitter. Currently, FPV drone control equipment supports the following popular protocols:

– TBS Crossfire (868 MHz /915 MHz);
– ExpressLRS / ELRS (2.4 GHz and 868 MHz /915 MHz);
– TBS Tracer (2.4 GHz);
– Immersion Ghost (2.4 GHz);
– Frsky ACCST V1 /V2 (2.4 GHz);
– Frsky ACCESS (2.4 GHz);
– Flysky;

– Spektrum.

Protocol ExpressLRS is characterized by accessibility and versatility. In addition, it is based on open source code. In turn, the TBS Crossfire protocol offers high reliability and a user-friendly interface.

Some models have a built-in radio communication protocol, while other devices are equipped with bays for installation of additional radio frequency modules (Figure 2.5). The presence of such a compartment is a definite advantage, as it makes the system more flexible if it is necessary to switch to another protocol.

Figure 2.5 - Control panel switches and consoles with additional RF modules

Not all radio control systems offer the same range. Even if two connections have the same frequency and output power, their maximum range can vary significantly, as factors such as the technology used and the quality of the components play a role.

It is generally accepted that low-frequency systems perform better over long distances. Meanwhile, newer systems such as ExpressLRS
2.4 GHz with LoRa (Long Range) modulation, are excellent over longer distances, although they have a higher frequency.

It should be noted that obstructions between the transmitter and receiver adversely affect the range and can significantly reduce the area of confident communication. In addition, reception range is also affected by

The sensitivity of the receiver and the type of antennas. Some models are equipped with two separate antennas to reduce signal loss due to obstacles or interference. The position of the antennas is important - for example, a 90 degree angle between the antennas can significantly improve reception quality.

For example, older Frsky 2.4 GHz radio systems (ACCST V1 and V2) can operate confidently at distances of up to 1.5 kilometers. At the same time, the new ExpressLRS 2.4 GHz system, using a power of only 100 mW, is able to cover a range of tens of kilometers thanks to innovative technologies and high-quality hardware. If you need to work over longer distances, you should TBS Crossfire.

The software (firmware) serves as the interface that allows you to interact with the remote control and control the drone's flight. One of the recommended firmware is EdgeTX. It is open source and has an extensive user base. A significant portion of radio transmitters on the market support this firmware and come pre-installed with EdgeTX. This allows you to easily transfer the settings to a new device when upgrading the hardware.

EdgeTX offers many different customizations and supports different types of aircraft. For beginners, mastering the firmware may not be easy, but the knowledge gained from using EdgeTX will be invaluable in the long run.

OpenTX is also a popular firmware, but it lags behind EdgeTX in terms of features and performance. Other options include FreedomTX, which is based on OpenTX and is used in TBS Tango 2 and Mambo. There are also the latest Frsky models running ETHOS.

A remote control with EdgeTX or OpenTX firmware provides the user with the ability to connect to the FPV simulator via USB port. Telemetry - telemetry is feature, which allows you to receive в real-time data on important drone parameters, such as power signal, battery voltage, current consumption, and more.

This information can be extremely valuable during flight as it helps to make informed decisions and avoid potential problems [8].

Most modern communication protocols, including ExpressLRS and TBS Crossfire, support telemetry. The feature allows data to be displayed directly on the device screen, and the user is alerted with an audible alarm when certain thresholds are reached.

A trainer port is a connector on the control hardware that allows you to connect two remotes simultaneously to control the same drone. It is a very useful tool for training. For example, when an experienced pilot takes the drone to a specific location at a safe altitude, and then hands control to a novice, who can to practice piloting without the risk of crashing. Transmitters with these ports are highly recommended for hands-on training.

The radio *receiver* ***(receiver, receiver, RX)*** (Figure 2.6) is located on the UAV and is responsible for receiving operator commands from the control panel and transmitting data to the flight controller (Figure 2.7).

Figure 2.6 - Radio receivers

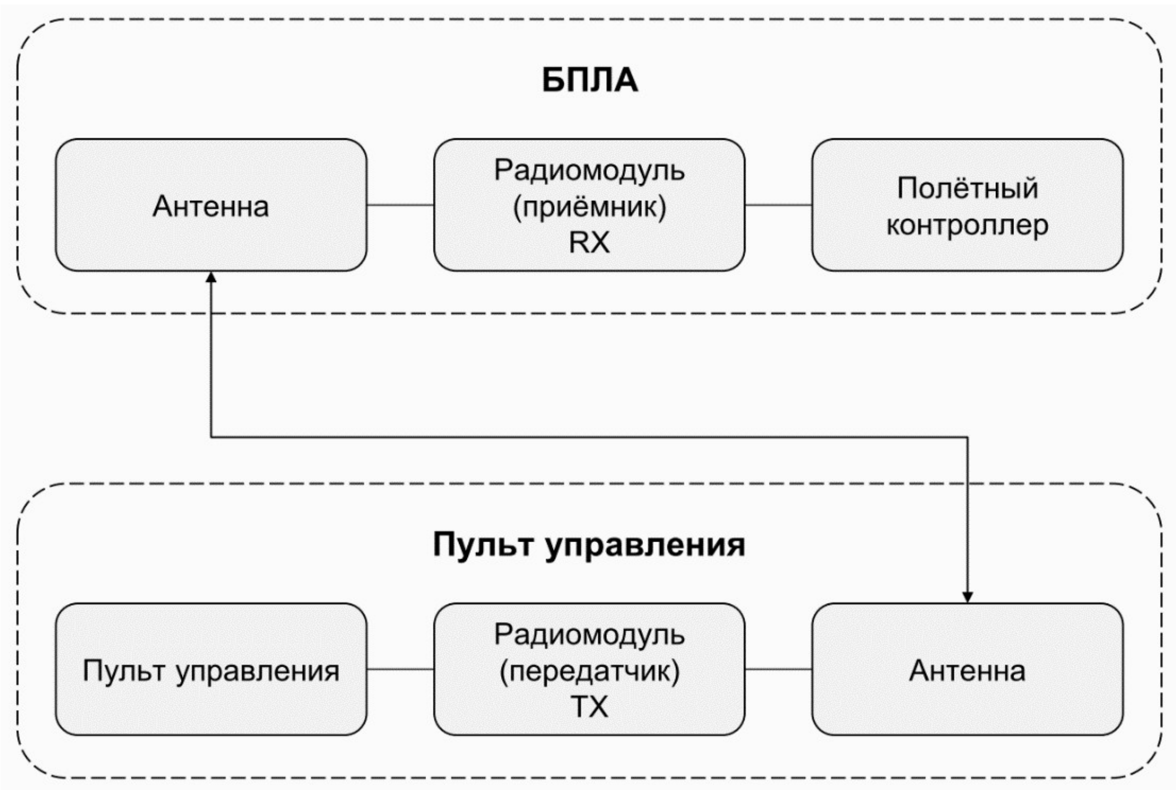


Figure 2.7 - Scheme of interaction between the control panel and radio receiver in UAVs

The main parameters of the radio receiver are: frequency, signal coding protocol and number of command channels. Only receivers compatible with the radio frequency of the control panel should be used. In other words, they must support the same communication protocol at the same frequency as the transmitter.

Signal encoding protocol means the way in which commands received from the console controls are encoded into the data stream traveling over the radio channel. When designing protocols, noise immunity and information flow density are the main considerations.

The most common types of protocols for data transmission between the control panel (TX-transmitter) and the receiver (RX-receiver):

– PMW (PWM) protocol is a protocol that uses pulse width modulation, i.e. an analog signal where the pulse width determines the effective value of the output voltage, and thus the servo deviation. PMW receivers use a single servo wire for a single channel. If a nine-channel transmitter or higher is chosen, 9 or more wires will have to be connected. Such complex and heavy wiring will result in increased aircraft weight;

– PPM protocol is a protocol that uses Pulse Position Modulation (PPM). In this protocol, several signals are sent over one wire in series. Up to 8 channels can be connected on one wire, which is sufficient for most users. PPM is still used in most multicopters.

Let us summarize the characteristics of the receive-transmit devices presented above.

Receiver Characteristics:

– sensitivity;
– A protocol for interacting with the data consumer;
– PU compatibility.

Transmitter Characteristics:

– power output;
– protocol for interacting with the data source.

General:

– operating frequency range;
– data rate;
– physical layer standard (radio exchange);
– voltage and power consumption;
– Mass;
– overall dimensions;
– delay (depends on the receiver and transmitter);
– operating temperature, moisture protection, etc.

2.4 FPV drone video transmission and reception system

The video signal transmission and reception system is designed to transmit video signals to the operator from the FPV drone video camera and consists of the following equipment:

- FPV goggles with video receiver;
- FPV drone video transmitter.

FPV goggles (Smart goggles) or ***FPV helmet*** is a device that receives a real-time video stream from a video transmitter located on the UAV and displays the received video information on the built-in display. The video receiver (video receiver/VRX) that receives the video signal from the UAV can either be built into the goggles or connected as an external module. The source of video information is a course video camera mounted on the UAV [3].

FPV helmets are usually rectangular and oblong in shape and are attached to the head with two straps. Inside there is a screen and a large lens (Figure 2.8).

Figure 2.8 - FPV helmet

FPV goggles are more compact than a helmet, containing two screens and two lenses inside (Figure 2.9).

Figure 2.9 - FPV goggles

The use of FPV goggles, helmets, allows you to create a realistic immersion in the flight "from the first person". In addition, it is possible to receive video signal on a separate FPV monitor (Figure 2.10).

FPV monitor (screen) is a display included in the video receiver with receiving antennas. The monitor is equipped with a visor to reduce the influence of extraneous light sources on the image quality. Separate screens are not used for FPV racing drones [8].

Figure 2.10 - FPV monitor

The main features of FPV helmets are:

– screen resolution (e.g. 1280×720, 800×400, 480×272, 500×300 - the higher the numbers specified, the better);

– FPV goggle field of view (FOV) is the angle that determines the size of the visible image;

– availability of a built-in video receiver;

– receiver frequency (number of supported channels) (e.g. 40 channels, 32 channels, 5.8GHz);

– function Diversity (the presence of two dispersed Diversity function (having two separate receivers receiving the signal and a system that selects the best one);

– Aspect ratio - the ratio of the width to the height of the screen (e.g. 16:9, 4:3);

– Having a DVR (video recorder for recording video);

– size and weight;

– battery life and availability;

– Interpupillary distance (IPD) (for eyeglasses);

– availability of additional lenses with dioptres (for eyeglasses);

– fan to prevent fogging of the screens and lenses of the goggles;

– The head tracking function available;

– audio output for connecting headphones;
– HDMI connector for connecting the glasses to a monitor;

– 3D video viewing support;

– video input - for connecting an external receiver.

If the helmet or goggles have spaced receivers, then the signal will be received separately by each antenna and synchronized, increasing the overall quality of the displayed picture. Different antennas are used with spaced receivers, usually patch (dipole) and mushroom (circular) polarization, much less often monopole or linear polarization [9].

An FPV drone video transmitter module is a device that receives the video signal from an FPV drone camera, converts it into a video signal of a certain frequency and transmits it to a video receiver, which is located, for example, in the helmet.

Main characteristics of the video transmitter module:

– output power (the range of stable video signal transmission (within line of sight) depends on it;

– operating frequency range (high frequencies: 5.725-5.85 GHz; low frequencies: 2.4; 1.2 GHz);

– channel support and channel switching mechanism;

– compatibility of the video transmitter with the equipment;

– dimensions and weight;

– signal type (analog or digital);

– antenna connector (SMA, uFL, MMCX);

– built-in microphone;

– body type;

– voltage (range from 7 to 24V);

– signal delay.

1. Video Transmitter Power Output is the amount of power per unit of time that the video transmitter emits during operation. The higher the transmitter power, the greater the radio coverage area and the greater the range of the FPV drone. But is a downside to this: the higher the power output of an FPV drone, the more interference it causes to other UAV operators.

The output power of video transmitters generally has three fixed values: 25 mW, 200 mW, and 600 mW.

25 mW is the standard for most racing quadcopters and, as a rule, this power does not interfere with other pilots. The range of UAV use in this case usually does not exceed 100 meters.

200 mW is the standard power for short-range flight, typically less than 500 meters.

600 mW is the power output for long distance flights. In this case, the video transmitter will get very warm and interfere with other pilots.

All modern video transmitters have the ability to adjust the output power of the signal, this allows you to conveniently use the drone indoors, setting it power 25 mW and outside indoor at the for long-distance flights - 200 or 400 mW. It should be remembered that the higher the power, the faster the battery is discharged, as the power consumption increases [12].

2. The main operating frequencies of the video transmitter:

- 5.8 GHz;
- 2.4 GHz;
- 1.2 GHz.

In practice, most modern video transmitters operate at 5.8 GHz, which increases the bandwidth of the channel. However, video transmitters operating at 1.2 GHz are gaining popularity due to greater noise immunity and range.

3. Video transmitter channel support is a part of the common frequency band within which autonomous frequencies are allocated for independent control of UAVs, to enable other UAV operators to use these frequencies. As a result, up to 40 or more pilots can operate simultaneously, each using its own operating frequency in the vicinity of the 5.8 GHz frequency in the common frequency band. The channel in most video transmitters is displayed on a small screen.

There are 4 mechanisms for switching between channels:

– DIP (mechanical);
– button with display;
– with an infrared remote;
– through the OSD.

DIP is already obsolete and is only used in older video transmitters.

Button with display - now the most popular option, you just press the button in a certain order and the display will change the channel, for example, 2-B, 3-A and so on.

An infrared remote control is a device that can be used to remotely turn on the desired channel without override.

OSD (SmartAudio, Tramp Telemetry) - A feature that allows you to select a channel via a menu on the goggle or helmet display.

4. The compatibility of a video transmitter with hardware is determined only by the availability of groups and channels (A-1, B-3, etc.).

5. Dimensions and weight (form factor) is the size of the transmitter board. As a rule, these are miniature devices of the same size as the receiver of the control equipment, mounted in the back of the quadrocopter. But now more and more often manufacturers have started making video transmitters 30x30mm in size. This is the standard flight controller size, so the PC and video transmitter are mounted in an assembly, one on top of the other.

The size and weight are written for each transmitter. The size determines whether the board will fit in the assembly and how much free space is left. Weight is very important for assembling mini- and microdrones.

6. By signal type, video transmitters can be analog or digital. Digital video transmitters transmit video with quality, significantly better than analog ones. However, they are therefore more expensive. Due to the image compression processes in digital FPV systems, there is a delay, which can be reduced by sharpening and degrading the video quality. The result of this is a loss of detail. An analog video transmitter signal eliminates delays in transmitting the signal to the receiving equipment. It will not lose frames or image segments when the signal is noisy.

7. The antenna connector for video transmitters exists with different connectors. The most popular connectors are SMA, uFL and MMCX.

SMA is a standard, large threaded connector, it has been used for many years in radio electronics as a reliable and simple connector. It is now one of the most popular connectors. It is manufactured in two versions: SMA and RP-SMA.

uFL - this connector is much smaller than SMA and is used in compact assemblies where it is not possible to install equipment with large mass-size characteristics. The connector is designed as a latch. If the antenna is unclipped during flight, the video transmitter may fail, provided that it is operated without the antenna for some time [5].

MMCX is one of the newest connectors. It is similar to uFL, but smaller in size. MMCX combines tradeoffs: from SMA durability, and from uFL weight and size. Its only drawback is that it is hard to find an antenna with the same connector.

For some video transmitters, a Direct Solder connector is available with the option of directly soldering the antenna to the connector. In addition, you can always use adapters from one connector to another, but this may lead to a drop in output power and, as a consequence, to a deterioration of video quality. Therefore, it is better to choose a video transmitter and antenna with the same type of connectors.

8. The built-in microphone (Internal Microphone) records sound and transmits it to the FPV helmet or goggles.

9. The housing of most video transmitters is either a heat shrink printed circuit board or an aluminum (plastic) housing. Usually video transmitters are placed inside the drone frame where they are well protected.

10. The *supply voltage of* the video transmitter has a strictly defined value specified in the technical description. Incorrectly selected supply voltage value can lead to significant video noise, artifacts and even video transmitter failure [6].

FPV drone video receiver is a device designed to receive a video signal from a video transmitter and transmit it to the display means of the UAV control operator (FPV helmet or FPV goggles).

2.5 FPV drone antennas

An FPV drone typically has two radio systems: a radio control system to control the drone and a video system to broadcast video through the FPV camera. Each system has an antenna, which is designed to convert oscillating electrical energy into electromagnetic radiation and vice versa. Antennas have different characteristics depending on their functional purpose.

Every FPV antenna, regardless of appearance, has the same set of components (Figure 2.11).

а) б)

Figure 2.11 - Structure of FPV drone antennas:
a) - pin antenna; b) - clover antenna

Figure 2.11 shows that FPV antennas consist of the following elements.

1. Conductive element - converts an oscillating electrical signal into electromagnetic wave energy radiated into the ether as radio waves. Every antenna has at least one conducting element. Some may have more than one conducting element, such as dipoles.

2. Ground/base (counterweight) - the component is made of metal, it is connected to the quadcopter by means of a connector, also, if positioned correctly, it amplifies the signal that is transmitted to/from the quadcopter. The base should be positioned so that it is parallel to the ground.

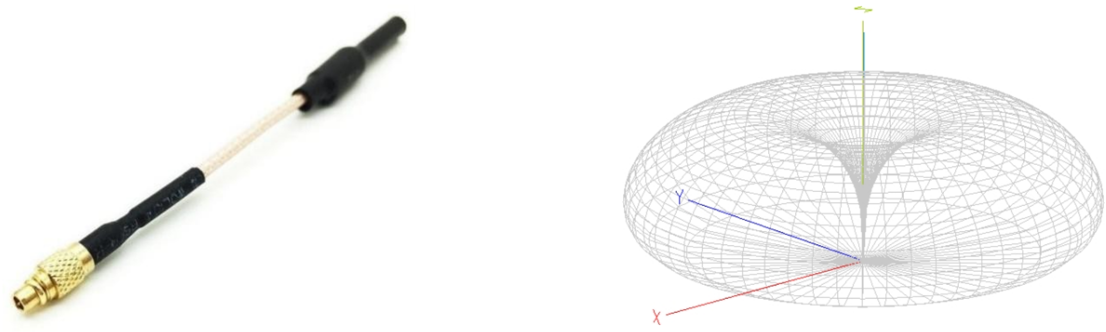
3. Structure - The antenna body material is usually dielectric, plastic or acrylic.

4. Coaxial is a cable that is a special type of protective wire that can transmit electrical signals from one point to another without emitting a radio signal.

5. Connector is a connector that connects the antenna to the transmitter on the drone. It serves as a conductive element.

FPV antennas come in the following types:
– pin (monopole) antenna;
– dipole antenna;
– clover (mushroom) antenna;
– spiral antenna;
– patch antenna.

A pin (monopole) antenna is omnidirectional and has a circular pattern (DN) in the horizontal plane and toroidal in the vertical plane (Figure 2.12), as well as linear polarization (vertical or horizontal, depending on the position of the antenna in space).

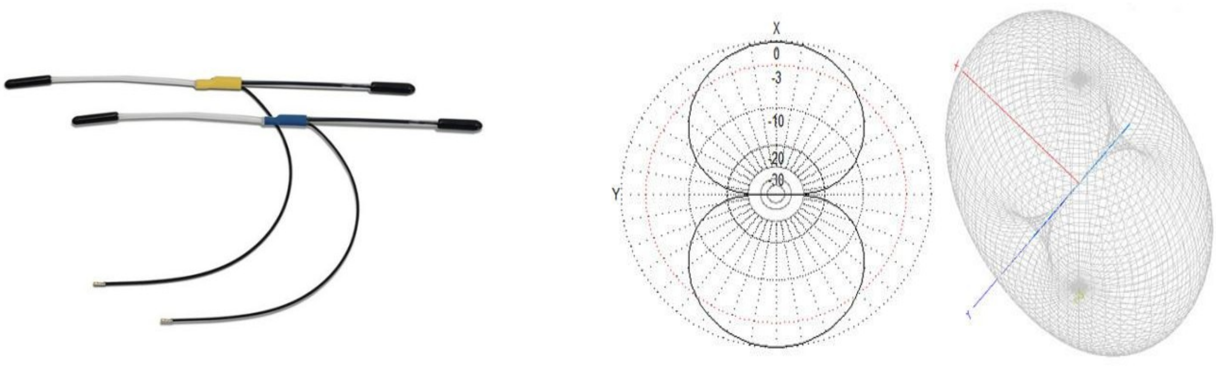


a) б)

Figure 2.12 - Pin (monopole) antenna: a) appearance; b) radiation pattern

The link quality using a monopole antenna will be best when the antennas are placed in the same plane. If such antennas (receiving and transmitting) are placed perpendicular to each other or point directly at each other, the link quality will be very poor [6].

A dipole antenna is omnidirectional and has a circular pattern in the horizontal plane and a toroidal pattern in the vertical plane (Figure 2.13), as well as linear polarization like a pin antenna.



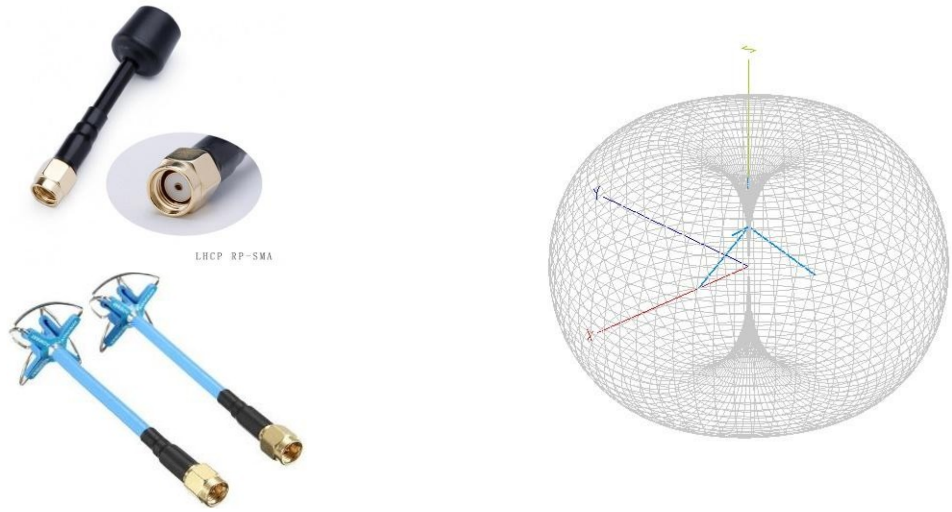
a) б)

Figure 2.13 - Dipole Antenna:
a) ; b) directional pattern

The difference between dipole and monopole antennas is that the dipole antenna has a larger main lobe width compared to the pattern of a monopole antenna, which gives the former better performance.

A clover (mushroom) antenna has a pattern like a pin antenna (Figure 2.14) and is circularly polarized, which provides excellent transmission and reception in almost any position.

The highest gain occurs in the horizontal plane and the lowest gain in the vertical plane. Such an antenna will work worse if its end is pointed at the quadrocopter, but the signal will still be there.



а) б)

Figure 2.14 - Clover Antenna:
a) - ; b) - directional diagram

A spiral antenna is a directional antenna with circular polarization (Figure 2.15). The more spiral turns an antenna has, the narrower its DN width. Spiral antennas with one or two turns of helix have a DN very similar to a patch antenna, which will be discussed next. However, adding turns (6 or more) can significantly narrow the DN and increase the directional properties of the antenna.

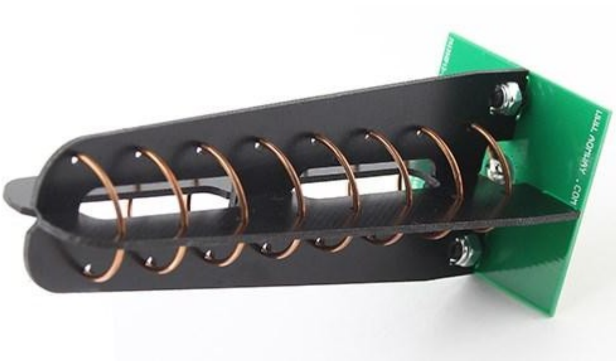
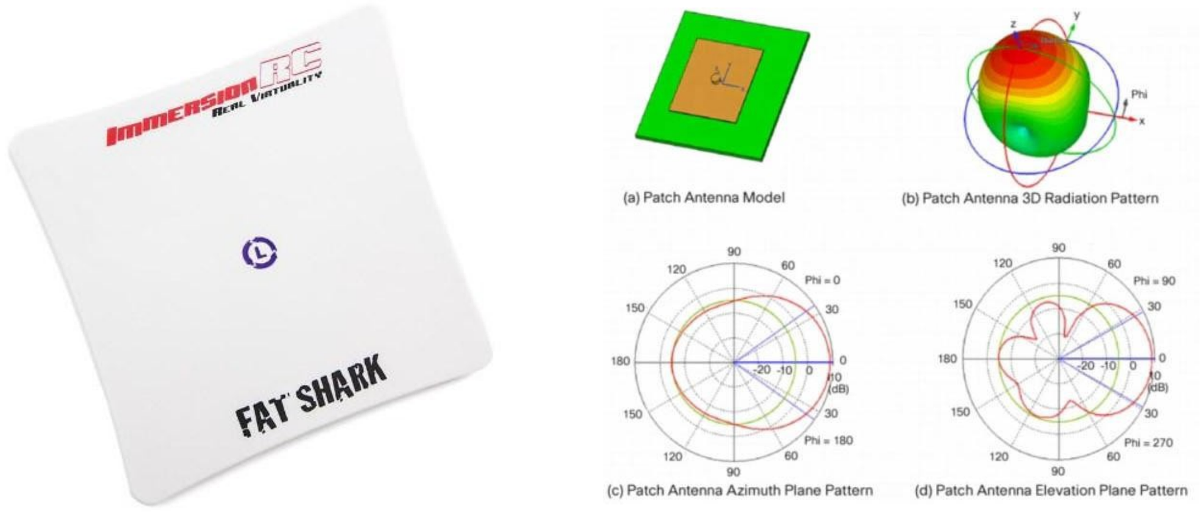


Figure 2.15 - Spiral antenna

A patch antenna has a three-dimensional drop-shaped radiation pattern in one direction, indicating its high directional properties. They are usually used as receiving antennas (Figure 2.16).



a) б)

Figure 2.16 - Patch Antenna:
a) - ; b) - directional diagrams

The most common antenna for FPV drones is the FoxeerLollipop 4 Plus 5.8 GHz (RHCP / LHCP) antenna shown in Figure 2.17which has the following characteristics:

– operating frequency range: 5.5-6 GHz;

– gain: 2.6 dB;

– directional pattern;

– polarization: RHCP for analog video and LHCP for DJI FPV digital system;

– the axial ratio is close to 1.0.

Figure 2.17 - FoxeerLollipop 4 Plus 5.8 GHz (RHCP / LHCP) antenna lineup

Antenna installation is of great importance because the quality of the communication channel and the FPV drone's application possibilities depend on it. It should be remembered that the carbon fiber of the frame reflects radio waves, so antennas should be placed so that they are shielded by the frame as little as possible [8].

2.6 Radiosecurity

When organizing UAV flights, it is recommended to observe additional radio safety measures. This is due to the fact that technical means of radio-technical reconnaissance can find the source of radio emission and direction finding the location of the radiating antenna, as well as determine the type of transmitter equipment.

The less the UAV uses radio sources, the more difficult it is for the enemy to locate where it is operating from. Also, do not unnecessarily conduct radio conversations or keep the control panel or modem of the UAV ground control station turned on. If there is a need to turn on these devices to adjust the operation of the complex with the UAV, their transmission path should be placed so that the antenna pattern is not directed toward the enemy or is behind a reliable shielding radio signal obstacles. In addition, you should not twist the directional antenna in different directions unnecessarily. Only the UAV itself is accompanied by the antenna during flight and nothing else.

It is also not a good idea to fly from the same launch pad all the time. Several different sites should be used fly in the same sector, and should be used in a non-systematic manner. Units the flight area should be warned of the intention to use UAVs just before entering the site to minimize the consequences of information leakage [9].

It should be understood that control, telemetry, and video transmitter signals may be inhibited by interference. The ***types of interference*** are active interference, which is interference that is intentionally generated radio signals of a particular type, and passive interference, which is interference that occurs when a useful radio signal is re-reflected, such as from corner reflectors.

There are also means of electromagnetic defeat, which work on the principle of magnetron, i.e. generation of induction currents in the circuits of electrical equipment of the object that is exposed to radiation. At the moment there are no serial means of functional defeat in service with the AFU. Therefore, let us consider the means available and used by the enemy.

The most common and available method is signal suppression. The essence of the process is that a stronger noise signal is fed at the frequency of the operating equipment that needs to be jammed, which clogs the useful information signal.

Complex effects are possible, i.e. a combination of several frequencies at once. For example, simultaneous suppression of the telemetry channel and GPS signal leads to interruption of communication with the UAV and its disorientation in space; in the absence of other navigation systems, this usually leads to the loss of the vehicle.

Video feed suppression is usually critical for an FPV drone and results in video loss. For a commercial reconnaissance UAV, video loss is harmless and may interfere with visual surveillance and artillery fire correction.

There are no active ways to counteract such interference, only recommendations on how to strengthen the signal of your ground station, how to get out of the zone of influence of REB means and how to reduce radio stealth.

GPS Spoofing is the substitution of a GPS signal broadcast by satellites with another, stronger signal broadcast from a ground station. The signal from the spoofing ground station corrects the receiver's own position, which leads to disorientation [14]. The crew can counteract this if they notice the change in time by guiding the UAV by magnetic compass and ground reference points to the home position. Some reduction of the UAV's altitude may be effective.

Control/telemetry channel spoofing is the interception of a control or telemetry channel. The electronic countermeasure station notices the signal from the remote control or from the modem, reads the key, determines the control protocol and intercepts the control by its own signal with the same key, on the same frequency. In case of such counteraction, the one whose signal from the control equipment will be stronger will win. As a countermeasure, UAV developers use all kinds of ways to encode the control signal [7].

Changes in the environment in which FPV drone tasks are performed may result in the need to *improve UAV performance*.

The process of FPV UAV performance improvement is related to software updates, as well as modernization of its components and implementation of improvements to increase the reliability of its application. It should be remembered that improvement of some characteristics may lead to deterioration of others. For example, increasing the battery capacity increases the weight of the UAV. Therefore, it is necessary to choose components that have the most optimal parameters and characteristics for the task at hand. It is also important to realize that each model has its own limitations that should not be exceeded.

Technical measures that improve the reliability of FPV UAV applications include the following procedures:

- the use of a reinforced frame;
- Use heat shrink tubing or duct tape to hold the wiring to the frame housing;

- using 3D printed camera, antenna or ESC mounts;
- using two battery straps or duct tape to secure the battery to the frame;
- Use of rubber or silicone bushings when attaching the board assembly to the frame to absorb vibration and shock;
- The use of bumpers at the ends of the beams;
- application of launching (landing) sites;
- application remote repeaters signal to to increase the flight range and maximize signal coverage;
- use of multiple radio transmitters/receivers operating on different frequencies;
- use of rotary directional antenna devices for UAV tracking.

Control questions

1. List ranges frequencies of FPV drones, their their features, advantages and disadvantages.
2. Name the basic equipment required for radio control and video streaming of FPV drones.
3. Name and characterize the main parameters of the device that transmits the video signal from the FPV camera of the UAV to the FPV goggles.
4. FPV receivers: types and characteristics.
5. FPV antennas: purpose and design.
6. List the main types of FPV antennas, their design features, directional patterns and polarization types, advantages and disadvantages.
7. FPV antennas application conditions.
8. What radio safety precautions are recommended when organizing UAV flights?

3 HOW TO PREPARE THE FPV DRONE OPERATOR FOR FLIGHT AND TAKE INTO ACCOUNT THE OPERATIONAL LIMITATIONS OF THE DRONE.

The foundations for the successful accomplishment of the flight and the task assigned to the UAV crew, as well as ensuring the safe use of the UAV, are laid during flight preparation. Mistakes made at this stage are difficult or impossible to correct during flight and may lead to failure of the combat mission and other serious consequences. When preparing for flight, the UAV operator must carefully check the correctness of the initial data and navigational calculations required for flight (track angles, distances, landmarks, flight times, terrain elevations, etc.) so that he or she will not have doubts about their validity in a difficult situation.

Accurate calculation of navigational elements before flight is necessary to perform the flight and combat missions in the most rational way, taking into account the technical capabilities of the UAV, actual weather conditions along the flight route and other constraints [15].

3.1 Flight task preparation and visual orientation

FPV drone operators are usually paired with an assistant. The FPV drone crew is assisted by a reconnaissance UAV crew searching for targets and guiding the kamikaze UAV on the final leg of the flight.

One of the basic rules of navigation in the use of UAVs of any type is the continuous preservation of orientation, which means that at any time of flight the operator must know the position of the aircraft and the nature of its movement relative to the line of guidance (LOB). Orientation can be accomplished visually or by technical means.

At present, the *main technical means of* UAV navigation are: satellite navigation systems; inertial navigation systems; accelerometers; gyroscopes; magnetometers; radio altimeters (sonars); barometers; and vision systems. These systems and means are used on board the UAV together, the information coming from them is integrated and helps the UAV operator to accurately maintain the specified flight parameters.

In the case of FPV drone application, due to the lack of possibility to install most of the technical navigation aids, the operator maintains *visual orientation*.

The FPV drone operator observes the environment with the help of a directional camera and determines the position of the UAV in space only with its help.

Visual orientation is the determination of the UAV's location from recognized landmarks by comparing the map with the terrain.

A landmark is a natural or artificial object, or an area of the Earth's surface, depicted on the map and visible to the control operator in flight. A landmark is considered recognized when the control operator recognizes it by coincidence with the image on the map.

Visual orientation is used to control the path, determine the navigational elements of the flight, find and reach the target. The main advantages of visual orientation are simplicity, reliability, high accuracy and high reliability of UAV position determination. The ability to conduct visual orientation in flight is one of the elements of flight control operator skill [16].

Landmarks can be natural (roads, settlements, forests, rivers, etc.) or artificial (beacons, searchlights, conditional signs, colored smoke bombs, signal-oriented bombs, etc.).

By configuration and size landmarks are subdivided into: linear, area and point landmarks.

Linear landmarks are landmarks that have a large length for a relatively small width (rivers, roads, canals, seashores, mountain ranges, etc.).

Area landmarks - occupy a relatively large area and stand out on the background of the terrain with their contours (large settlements, railway junctions, lakes, forest areas in steppe areas, etc.).

Point landmarks are road crossings, bridges, small settlements, small railroad stations, individual mountain tops. Point landmarks also include lighting equipment (beacons, searchlights, smoke bombs, etc.).

Landmarks are distinguished from each other by their *primary* and *secondary* features. The *main* features include the shape, size and color of the landmark. The basic attributes distinguish one type of landmark from another. For example, a settlement is distinguished from a patch of forest by its color; a road is distinguished from a river by its shape. *Additional* features are used to distinguish homogeneous landmarks, for example, two settlements. Additional features of main landmarks include other landmarks near them, such as roads, forest areas, rivers, and lakes.

Characteristic landmarks are used for visual orientation when approaching a ground target, these are landmarks that are clearly distinguishable and easily identifiable from a given flight altitude.

It is very important for the UAV operator to select characteristic landmarks on the map before the flight. These landmarks should be "raised" on the map, i.e., if it is a paper map or chart, mark them out with a pencil. A marker can be placed on an electronic map. The correct selection of characteristic landmarks makes visual orientation much easier.

Characteristic landmarks *when flying at medium and high altitudes* include large settlements, lakes, coastlines, large rivers. *When flying at low altitudes*, characteristic landmarks include those with vertical development: chimneys, elevators, mountain tops.

During flight, the UAV operator first detects a landmark without distinguishing its details at a range called the detection range. The recognition of a landmark (landmark details are considered) depends on the nature and number of its distinguishing features and the duration of the observation. The greater the detection range and the closer the landmark is to the actual track line, the more time the operator has to recognize it. The presence of at least one specific, unique feature allows to recognize a landmark at once [14].

The range of visibility of landmarks depends on the altitude of the UAV, the size of the landmark, the background of the terrain and meteorological conditions (air transparency, illumination, etc.), as well as (for FPV drone) the resolution of the camera, the goggle display and the quality of the received video signal.

Under average visibility conditions:

– landmark detection range is equal to 10 flight altitudes;

– identification range is equal to 3 - 5 flight altitudes.

When flying over poorly oriented terrain, not only large, but also small landmarks should be used for orientation: separate hills, ravines, gullies, gullies, roads, trails, etc.

In monotonous terrain, you should use those landmarks that stand out among other objects, create a "motley" terrain, as well as the mutual arrangement of landmarks. For visual orientation over the

"In mountainous terrain, landmarks should be used whose contours are not subject to change and are clearly visible against the general background of the terrain. In a mountainous area, characteristic peaks, ridge and gorge configurations, mountain cover and color are used for visual orientation.

At low and extremely low altitudes, visual orientation is difficult due to the short range of visibility of landmarks and high angular velocities of terrain movements. Landmarks, even close ones, are seen in perspective rather than in plan. Flight speed also affects the angular velocity of landmarks and their observation time. At low altitudes and high flight speeds, the time of landmark observation is sharply reduced [21].

Visual orientation is based on determining the UAV's position by comparing the map with the observed terrain. In FPV drone calculations, this function can be performed by an assistant operator. The following rules must be observed when conducting visual orientation:

– to stay on course;

– Before comparing the map with the terrain, it is necessary to orient it to the sides of the world;

– Each UAV location determination should, where possible, be preceded by a track calculation to enable the map to be compared with the terrain in the area of the UAV's intended location;

– Due to the limited time to recognize landmarks, especially when flying at high speeds, it is necessary to expect the appearance of landmarks within visibility, i.e. to know which landmark and from which direction it should appear;

– From the set of landmarks visible from a given flight altitude, first select the largest, most characteristic ones, recognize them, and then proceed to the identification of smaller ones;

– Identify landmarks by more than one distinctive feature, so as not to confuse landmarks that are similar to each other.

To maintain orientation during flight, the UAV's position must be determined periodically. The UAV's position can be determined by flying over a recognized landmark or by comparing the UAV's position relative to several recognized landmarks.

Map to terrain comparison is performed by moving from map to terrain. Before the flight it is necessary to select one or more characteristic landmarks on the map and then find them on the terrain. This allows you to study these landmarks on the map in advance, and then expect their appearance on the ground [15].

In unmanned aviation, based on the Methodological Recommendations for short-range and short-range UAV flights of the Ministry of Defense of the Russian Federation, before the flight, the UAV operator must understand the purpose, objectives and conditions of the flight, determine what technical means should be used for its performance, as well as what tactical techniques will be used, calculate the flight route, its parameters, and draw up a flight task diagram.

A flight path is the projection of the flight path onto the Earth's surface. The line along which the control operator must guide the UAV is called the *Line* of *Set Path (LSP)*, or *set route*. The line over which the UAV actually flew is called the *Line of Actual Path (LAP),* or *actual route*. The flight route is selected depending on the nature of the mission, taking into account:

– the location of the target at the time of approach and the best direction of approach;

– the reliability of orientation and target acquisition;

– the greatest concealment from the enemy;

– location of the enemy's electronic and fire countermeasures and the shortest flight duration in this area;

– terrain and weather conditions along the route;

– prohibited zones and areas with special flight regimes;

– the tactical and technical capabilities of the UAVs flying the mission.

Characteristic landmarks are chosen as waypoints.

Layout of the route on the flight map may include:

– marking the main points of the route;

– drawing the line of a given path;

– Determination and mapping of track angles, distances and doldrums time of flight along the route sections;

– marking of the set (estimated) time to reach the target;

– marking of characteristic terrain elevations along the route sections, target exceedances, calculation of safe flight altitudes;

– plotting the correction points of the navigation system.

Flight calculation is performed to ensure that the specified route is accurately maintained and that the target or reference point (boundary) is reached at the specified time, to ensure coordination of the actions of calculations in groups and to control their flight. Flight calculation is carried out simultaneously with route plotting. It includes:

– determining the length of the sections between the main points of the route (the length of the stages) and the total length of the route;

– determination of flight time by route sections and total flight duration;

– Determination of track angles along the route sections;

– determination of safe altitudes along the route sections;

– other data depending on the flight task. The data obtained are recorded in a workbook or notebook.

Flight calculation is divided into *preliminary* and *final*.

The preliminary calculation is performed without wind (based on true airspeed). It is performed during the flight preparation period. Its results are plotted on a map and recorded in a notebook.

The final calculation of the flight is made during the pre-flight preparation period, taking into account actual wind data received from the route weather scout or on the basis of meteorological data not more than 3 hours old.

A UAV *flight task diagram* should generally include:

– graphical flight model (order and sequence of flight task (exercise) execution, with indication of flight time and altitude, tactical techniques and parameters of their execution);

– necessary reference data and calculations in the form of text or tables;

– the procedure for interaction with other UAV operators or spotters;

– safety measures when performing a flight task (exercise).

As a rule, flight maps and flight task diagrams are not prepared for FPV drone flights. However, in one way or another, most of the listed elements of the flight task are thought out in advance [16].

The fulfillment of a flight task when using FPV drones has its own peculiarities.

1. When planning a flight, weather conditions should be taken into account if possible: air temperature, wind speed and direction.

2. The flight route should be based on the maximum FPV drone flight time minus 25% (if the flight time is 20 min, then the flight task completion time should not exceed 15 min). If the FPV drone is used for reconnaissance, the time of return to the landing point should be taken into account when calculating the time of task completion.

3. Study preliminary reconnaissance data on the location of enemy units. Select the route in such a way as to ensure the stealth of the UAV's entry into the target area (reconnaissance), exclude or reduce the effectiveness of the enemy's UAV countermeasures.

4. Tactical techniques should also be based on the use of UAV maneuvering capabilities, terrain camouflage, the actual state of enemy UAV countermeasures, and the current combat situation.

5. The flight altitude of the UAV must ensure stable communication, which is achieved by ensuring direct radio visibility. The choice of flight altitude is based on the following contradiction: the higher the flight altitude, the greater the line of sight, and the lower the flight altitude, the lower the probability of suppression by the enemy's REB.

6. When carrying out tasks of fire defeat of the enemy while flying along the route, it is necessary to conduct cross-country reconnaissance.

7. Special attention should be paid to the choice of launch and landing site, use of remote transmitters and repeaters.

Flight along a route to fulfill a flight task requires the UAV control operator to pay attention not only to piloting techniques, but also to control the movement of the UAV strictly along the planned trajectory, to be cautious, and to quickly solve computational and logical problems in his mind. Successful fulfillment of a flight task is possible only when the flight is fully prepared in advance on the ground.

3.2 Impact of weather conditions on FPV drone flights

FPV drones are designed to search for and engage enemy targets at a relatively short distance from the launch point. For this reason, and based on the technical characteristics of this type of UAV, operators of these vehicles should have some knowledge of the impact of weather conditions on their use. Since the flight time and range of the vehicle are limited and the altitude does not exceed three hundred meters, it can be considered that in most cases the vehicle design can assess the meteorological conditions in the area of its application visually. It should be understood that the following factors may affect the performance of the vehicle's task [17]:

– *wind speed* exceeding the maximum permissible values for this apparatus;

– *cloud height* and (or) *range of visibility*, complicating or excluding visual contact with the underlying surface, as well as the ability to find and hit a given object of the enemy;

– *hazardous weather phenomena* that affect flight safety and can be conditionally divided into three groups: those that impair visibility (fog, haze, rain, snow, drizzle, blizzard, dust storm), those that complicate wind conditions (squall, hurricane, blizzard, dust storm) and those that lead to some hazardous effects (spark discharges (lightning), turbulence, icing).

Let's take a closer look at the above elements.

Wind is the horizontal movement of air relative to the earth's surface. Wind has two parameters - *direction* and *speed*:

– *speed* **is** measured in meters per second, kilometers per hour, knots (nautical miles per hour), and Beaufort scale points;

– *direction* (from where the wind blows) is measured in degrees (relative to north) (0° to 359°) and rhumbas (16 rhumbas): S, SSV, SV, SV, VV, VV, VYV, VYUV, YUV, YUV, YU, YUUZ, YUZ, ZUZ, Z, ZSZ, SSZ, SSZ. (Figure 3.1).

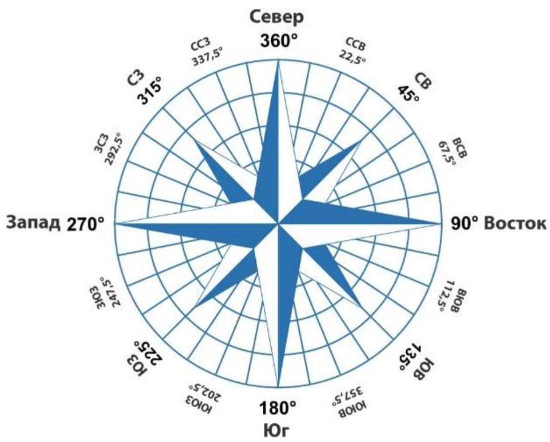


Figure 3.1 - Wind direction rhumbas and degrees

Wind speed is measured to the nearest 1 m/s and wind direction to the nearest 10°.

To measure wind parameters near the ground, cup and screw anemometers are used to measure wind speed, weathervanes to determine wind direction. Examples of such sensors are presented in Figure 3.2.

Figure 3.2 - Wind sensors of remote meteorological stations

In addition, since the FPV drone operator is usually paired with a reconnaissance UAV, the wind speed can be measured automatically by the reconnaissance UAV and transmitted to the FPV drone operator.

Clouds are visible aggregates of suspended water droplets and/or ice crystals at some height above the Earth's surface, which are products of condensation of water vapor. Cloudiness has three parameters to be determined:

– the number of clouds;
– cloud shape;
– height of the lower cloud boundary.

The *number of clouds* is determined visually in tenths of the visible sky coverage (one tenth is called a point). If the entire sky is closed, the clouds are 10 points, half of it is 5 points, etc.

The *shape of clouds* is determined according to a developed classification. It defines 10 main forms of clouds, of which 2 forms are dangerous in themselves - these are cumulonimbus and powerful cumulus clouds. The first of them are associated with heavy rainfall, thunderstorms, squalls, hail. Flying in such clouds is prohibited, as they cause strong upward and downward air movements, spark discharges, icing and turbulence. This may lead to loss of control of the vehicle and its destruction.

The cloud lower boundary altitude (*CLBA*) is the distance from the ground surface to the lower cloud base (measured in meters).

There are several methods for determining GNGOs:

– visual (the observer determines the altitude based on cloud properties);

– Pilot balloon (a rubber shell filled with hydrogen or helium is launched, and the time it reaches the ABO (at a known rate of ascent) is used to determine the altitude);

– instrumental (a special device (light locator) determines the CSO by the time of beam passage to clouds and back);

– (using an aircraft);

– Estimated (GNGO is estimated using special formulas). Ferrel's formula for estimating the GNGO:

$$H_{obl} = 122\left(T - T_d\right),) \tag{3.1}$$

where T is the air temperature in degrees Celsius, T_d is the dew point temperature in degrees Celsius.

Ippolitov's formula for the estimation of GNGOs:

$$H_{obl} = 22\left(100 - f\right),) \tag{3.2}$$

where f is relative air humidity in percent.

In the field, visual, airplane, and computational methods of determining the VNGO are available to BPLA calculators.

Visibility can be assessed by means of a system of visual landmarks, which are always identified at observation posts to support the employment of artillery. The distance to the furthest landmark visible at the time of observation is the range of visibility. Associated factors such as time of day and the contrast of the observed object with respect to the background must also be taken into account in determining visibility.

In relation to the *hazardous weather phenomena* listed above, *icing* should be emphasized. For icing to occur, two conditions must be simultaneously met:

– presence of clouds at flight altitude (fog near the ground - for FPV drone);

– The air temperature at flight altitude should be between 0 and -20 degrees Celsius. Temperature range in which icing is most likely to occur: -2 to -5 degrees Celsius [17].

It is possible to estimate the air temperature at flight altitude using information from high-altitude weather maps and/or aerological charts. However, this type of information is unlikely to be available in the field, and special training is required to work with such documents. Therefore, temperature can also be estimated using a calculation based on the vertical temperature gradient. It has a value of 0.65 degrees per 100 meters of altitude. Thus, to determine the temperature at the desired level, the height in hundreds of meters should be multiplied by 0.65 and the resulting value subtracted from the air temperature near the ground.

For example, the temperature at the ground is +2°C, the humidity at the ground is 90%, and the flight altitude is 400 meters. First, we use the vertical temperature gradient to determine the temperature change with altitude: ΔT= 0.= 2.6°C. Accordingly, the air temperature at the flight altitude $T_{(h.p.)}= \ T_h - \Delta T$ = 2 - 2.6 = -0.6°C. Further, using Ippolitov's formula we determine the height of the lower boundary of clouds: H_{obl} = 22(100-90) = 220 meters. Based on these calculations, the flight at the specified altitude will take place in clouds at negative temperature. Thus, we can expect icing at the flight altitude.

Since FPV drone flight takes place at low altitude and high speeds, along with the above factors, the aerology of the terrain over which the flight is performed should also be taken into account. At wind speeds of more than 5 - 7 m/s the influence of local obstacles (forest areas, buildings) can cause turbulent disturbances that interfere with the precise piloting of the UAV. The higher the wind speed, the stronger these disturbances. The UAV operator, while flying, must take into account the possibility of such phenomena [19]. These effects are most pronounced on the *leeward side of* obstacles. The *leeward* side is the side of the obstacle on which the wind is blowing, while the *leeward* side is on the other side of the obstacle, opposite to the windward side. On a diurnal course such effects are most often observed in the period from 12 to 18 hours local time and in the warm period of the year.

FPV drones can be used in conditions of high humidity and precipitation. Snow, rain and moisture condensation pose a certain danger to FPV drones - when moisture gets on the working electronics, malfunctions may occur in the form of damage to electronic circuits of the flight controller and other equipment, which leads to sudden engine failure, loss of communication, etc.

To protect the electronic components of the FPV drone from moisture, it is necessary to reliably insulate connectors, contacts, electronic circuit elements, boards and seal the housing in which they are located.

3.3 Technical capabilities and application limitations of UAVs

In addition to taking into account the weather conditions during the flight preparation process, the FPV drone operator needs to know the technical limitations of the UAV for flight time and range, as well as the range of the control and video transmission equipment [18].

Flight time is one of the most important parameters to consider before flight. The longer the UAV stays in the air, the more applications it can be used for. The flight time of a drone depends on the manufacturer, model and battery condition, as well as the UAV's weight and weather conditions. Most manufacturers provide flight times in their drone specifications, but they are not always accurate, as these times are calculated under standard load conditions in a laboratory. In practice, the UAV weight differs from the standard weight because additional equipment (protective covers, a larger battery, a larger camera, etc.) is attached to the UAV.

Let us consider one of the techniques for approximate doldrums calculation of quadrocopter flight time [17].

There are two parameters to be considered for the calculation:

1. The weight of the UAV and its ;
2. size and capacity.

Obviously, a heavy UAV with a smaller battery capacity will have a shorter flight time compared to a lighter drone with a relatively larger battery capacity.

Before we get to the formula for calculating flight time, several variables need to be defined.

Total flight weight (G_{TFL}), kg is the weight of the UAV just before takeoff. It includes the weight of the UAV itself, any optional accessories, payload and battery.

Average current consumption (I_{CP}), A is the average current consumed by all motors from the battery. The average value is used because the actual current consumption varies greatly during different phases of flight and depends on the mode of operation (flying at maximum speed draws more current than smooth flight). To account for variations, the average value is used.

Power density (P_{PD}), W/kg - the ratio of motor power to weight is used to describe how much electrical power is required by motors to lift one unit of weight. It is essentially a parameter that depends on the efficiency of the motor [18].

Brushless motors have a value of 80 to 120 watts per kg and brush motors have a higher value of about 150 to 180 watts per kg. The more efficient the motors are, the less power is required to lift 1 kg of weight. The following values can be used for calculation: *brushless motors* - 100 W/kg, *brush motors* - 170 W/kg.

The total voltage of the battery ($U_{battery}$) [V] is indicated by the markings on the battery case and depends on the configuration of the cells (cells) in the battery. The output voltage remains constant throughout most of the battery's operation (it drops dramatically when the battery discharges below a certain value).

Battery capacity (C), Ah is the capacity of the battery to store electrical charge. The battery capacity is indicated by the markings on the battery case and is expressed in milliampere hours (mAh).

Discharge limit battery (DPR), % - limit depth of discharge battery. The default value of 80% is used for the calculation, this means that only 80% of the total capacity will be used to calculate the flight time, with 20% left on the battery as a safety margin.

Calculation of flight time

1. Calculate the average current that the motors will draw from the battery to support the total flight weight:

$$I_{CR} = G_{POL} \cdot \left(O_{RE} / U_{ACB} \right). \tag{3.3}$$

2. Having obtained the average current, calculate the flight time of the UAV in hours.

$$T_{POL} = C \cdot D_{PR} / I_{CR}. \tag{3.4}$$

Calculating the range of the FPV drone***'s transceiver and transmitting equipment*** is as important as calculating the flight time and range. The following techniques can be used for both command radio and FPV video transmission.

The following formulas are used in radio communication to determine the direct radio visibility range *D*, km:

up to 1 GHz

$$D = 4{,}12\left(\sqrt{h_1} + \sqrt{h_2}\right), \tag{3.5}$$

for frequencies above 1 GHz

$$D = 3.57\left(\sqrt{h_1} + \sqrt{h_2}\right), \tag{3.6}$$

where h_1 is the height of the console antenna, m; h_2 is the height of the UAV antenna, m.

Formulas (3.5) and (3.6) can be used to roughly estimate the radio communication range, which is usually a sufficient condition for determining the communication range for telemetry.

Let's consider the technique of estimating *the range of video stream transmission* from FPV drone to the video receiver located at the operator. The methodology is based on determining the energy balance of the line. Usually, the maximum communication range is determined by the minimum signal level at the receiver input. Values of 7-13 dB are used in calculations.

The energy balance of the line is determined based on the following parameters:

– antenna gains of the receiver and transmitter antennas;
– the output power of the video transmitter;
– of the video receiver's sensitivity.

To perform calculations, these parameters should be converted into decibels [dB] beforehand.

Receiving antenna gain is a number indicating how many times the active power at the receiver input with a given antenna will be greater than the active power at its input if an undirected (isotropic) antenna is used.

Transmitting antenna gain is the ratio of the power at the input of a reference undirected (isotropic) antenna to the power supplied to the input of the antenna under consideration, provided that both antennas create in a given direction at the same distance equal values of field strength, i.e. it characterizes the ability of the antenna to concentrate the signal energy in a certain direction.

The gain coefficients of FPV drone antenna systems depend on their design and are measured in isotropic decibels [dBi].

The output power of a video transmitter is the average power of the radio signal delivered to the transmitting antenna, usually stated in milliwatts - [mW (mW)], but this value can be converted to decibel-milliwatts [dBm (dBm)] using the following expressions:

$$P_{((dBi)} = 10 \cdot \lg(P_{(((\,)(mW)(\,))} / 1mV) \,(,) \tag{3.7}$$

$$P(mW) = 1mV \cdot 10^{P(dBm)/10}. \tag{3.8}$$

Table 3.1 can be used to convert mW to dBm.

Table 3.1 - Conversion of absolute signal power (mW) to relative units (dBm)

mW	dBm
0.01	-20
0.1	-10
1	0
1.2589	1
1.5849	2
1.9953	3
3.1628	5
10	10
100	20
1000 (1W)	30
1500 (1.5W)	31.76
2000 (2W)	33.01

Video receiver sensitivity - determines the minimum RF power that can be detected by the receiver. The more sensitive it is, the larger the negative number (see Table 3.1). -85dB is a good value for a goggle or helmet receiver.

With these four values, you can roughly calculate the FPV range to know how far the video communication will be.

Ideally, the maximum range will be when the signal power drops to 0 dBm, but video receivers (in goggles or helmet) at this point stop receiving anything and there is strong noise.

To ensure a reliable connection, usually adopt a minimum signal level Typically L_{CB} 10 - 12 dB. *(The receiving boundary is LM Link Margin)*.

The energy balance of a line L_{Σ} or FSPL (Free Space Path Loss) is defined in dBm as:

$$L_{\Sigma dop} = G_{aPRM} + G_{a\,PDP} + PDP - P_{PRM}, \qquad (3.9)$$

where G_{APRM} - gain gain receiving antenna,dBi; $G_{a\,PRD}$ - gain gain transmitting antenna dBi; P_{PDP} - power (energy potential) of the transmitter, dBm; $_{RPM}$ - sensitivity of the receiving path, dBm.

Propagation losses in free space:

$$L_{CB} = 20\lg(d) + 20\lg(f)\ ,) \qquad (3.10)$$

where *f is* the frequency, MHz; *d* is the length of the radio line, m.

An expression for determining the communication range in km:

$$d_{CB} = 10^{\left[\frac{(L_{\Sigma extra} - L_{(CB)} - 32.44)}{20} - \lg(f)\right]}, \qquad (3.11)$$

The following is *an example of calculating* the *communication range* for an FPV system.

Let's set the following parameters of receiving and transmitting devices:
video transmitter power - 25 mV (14 dBm);
gain of the video transmitter antenna - Lollipop V2 (2.5 dBm); sensitivity of the glasses (helmet) receiver - True-D (5 μV ≈ -93 dBm);
the gain of the eyewear receiver antenna is Lollipop V2 (2.5 dBi);
loss in free space (reception boundary) $(L)_{CB}$ - 10 dBm.

Substituting the values in (3.9) and (3.11) we calculate the communication range (Table 3.2).

Table 3.2 - Example of calculation of communication range

L_{CV}, dBm	f, MHz	G_{APRM}, dBi	G_{APRD}, dBi	R_{PDR}, dBm	R_{RRM}, dBm	d_{CB}, km
10	5800	2,5	2,5	14	-93	0,518289

If the receiver sensitivity is specified in microvolts, μV, you need to convert them to decibel-milliwatts dBm using the formula:

$$_{RPRM}= U^2 / R \quad , \qquad (3.12)$$

where $_{RPM}$ - level, dBm; U - voltage, μV; R - wave impedance, Ohm (taken as 50 ohms in our calculations).

In order to increase the transmission range, individual line parameters must be changed. You can increase transmitter power or receiver sensitivity, or use a higher gain antenna for the receiver. Doing any or more of these items will, in theory, increase the range of signal reception. You can also use lower frequency video transmitters and receivers, such as 1.3 GHz instead of 5.8 GHz, to increase range.

The calculations given in the manual are suitable for ideal conditions (open terrain). In real life, due to the influence of external factors and signal attenuation, the range will be less than the calculated range.

The main reasons that cause signal attenuation:

- interference and noise in the environment or from other pilots;
- the video transmitter's power drops as it heats up;
- dependence on antenna orientation:
- at 45 degrees= -3 dB;
- at 90 degrees= -20dB;
- two linear antennas pointing at each other= -30 dB; antenna polarization dependence:
- linear to circular= -3 dB;
- RHCP to LHCP= -20dB;
- losses in coaxial cable and SMA, MMCX, UFL adapters - 0.1-0.3 dB.

Another way to increase the range of signal reception is to use antennas with a narrow radiation pattern instead of omnidirectional antennas, but outside the narrow sector the signal power drops significantly. That is It is necessary to point the receiver antenna at the UAV at all times.

Thus, in addition to increasing the output power of the video transmitter, it is possible to increase the range of FPV reception by changing other parameters of the system [1].

The main indicator of the state of the radio channel and the quality of radio reception is the signal-to-noise ratio (SNR) at the receiver input. The higher this value is, the higher the probability of correct reception, the lower the probability of errors, the higher the quality and stability of communication.

The following factors affect the ROSS score:

– the transmitter power of the remote control and the quadcopter;

– sensitivity of the remote control and quadcopter receivers;

– consistency of antennas with transmitters;

– polarization;

– directional coefficient (DC) of antennas;

– capacity.

In order to improve the OSR and hence increase the communication stability of FPV drones, it is necessary to:

1. Increase transmitter power as much as possible based on the mass characteristics of the equipment.

2. Use receivers with higher sensitivity or use Diversity FPV by using a receiver with two HF paths (Diversity FPV), two antennas and one video output. Switching between the paths is automatic - based on higher signal strength.

3. Matching the receiver antenna to the transmitter so that all the energy of the RF oscillations at the output of the transmitter is maximized into the energy of the electromagnetic waves radiated into space.

OEM antennas are very often not matched to the transmitter.

You can check in the field the consistency of antennas with the transmitter using a special device, a radio signal power level meter - immersionRC-meter.

Measurement of the radio signal level is performed as follows:

– the reference antenna is connected to the transmitter, the antenna under test connected to the RC-meter;

– measure the relative receive level at the RC-meter input;

– choose the antenna that provides maximum RC-meter readings.

Power losses in the antenna can be estimated by the standing ***wave*** ratio (SWR). This is an indicator characterizing the quality of matching the load (antenna) with the transmission line (feeder), through which the radio frequency signal energy is brought from the radio transmitter to the antenna. The smaller it is, the better. The ideal value is 1, but in practice it is not achievable due to signal losses in the cable and connectors. The working value is considered to be 1.1 - 1.5. If the value of VSWR will be too high, it reduces the range of communication and overheating of the transmitter, which is dangerous to its failure. The VSWR value depends on many factors, in particular:

– from the relationship between the wave impedance of the transmission line and the load impedance;

– from the presence of inhomogeneities in the transmission line, such as connections, faults, small radius bends;

– from the quality of cable termination in the high-frequency coupler (connector) of the transmission line on the load side.

You can measure the VSWR using a VSWR meter.

4. Flight operations require that the receiving and transmitting antennas operate in the same polarization.

Polarization characterizes the location of the electric field strength vector in space during the propagation of an electromagnetic wave. To control FPV drones, as a rule, either pin antennas or clover antennas are used. That is, if the flight is planned to be carried out in one plane, then it is possible to use pin antennas, if the task provides for flight in different planes, then it is more appropriate to use the "clover" type antenna.

5. When performing flights, it is necessary to take into account the directivity factor of antennas. The directivity factor characterizes the directional properties of the antenna and is determined by its directivity pattern. If the flight is planned to be performed around the takeoff point, it is necessary to use either an omnidirectional antenna (pin, clover) or a narrow directional antenna (detector, spiral, patch antenna). In the latter case it is necessary to monitor the spatial position of the drone and in accordance with it to make the antenna pointing at the drone in azimuth and altitude. If the flight is planned to be conducted in one sector, it is more appropriate to use a narrow antenna [21].

Using quality receivers and transmitters, good antennas, proper polarization, antenna directivity factor and antenna orientation can significantly increase the range of video reception from an FPV drone.

Control questions

1. Explain the principles of the quadcopter control system and the operator's actions (moving controls) when tilting and moving forward(backward).
2. Explain the principles of the quadcopter control system and the operator's actions (moving the controls) when tilting and moving left(right).
3. Explain the principles of the quadcopter control system and the operator's actions (moving the controls) when gaining altitude (descending).
4. Explain the principles of the quadcopter control system and the operator's actions (moving the controls) when turning left (right).
5. What weather factors can affect a quadcopter's task performance?
6. What parameters does cloudiness have?

7. Necessary conditions for icing to occur.
8. What is visual orientation?
9. How do altitude and airspeed affect visual orientation?
10. What are characteristic landmarks and how is visual orientation accomplished in their absence?
11. What parameters does the flight time of a quadcopter depend on?
12. What parameters determine the maximum range of radio communication in FPV system?
13. What is the signal-to-noise ratio (SNR) at the receiver input?
14. What factors affect the signal-to-noise ratio (SNR)?
15. Name ways to improve the resilience of communications.

4 PREPARATION FPV DRONE К OPERATION И EQUIPMENT SETUP

UAV assembly and configuration is a technical task that requires knowledge and skills in electronics, specialized software and radio assembly. The assembly process is performed by selecting components with consideration of their hardware and software compatibility. A typical layout of FPV drone components and the order of their connection are presented in Figure 4.1 [19].

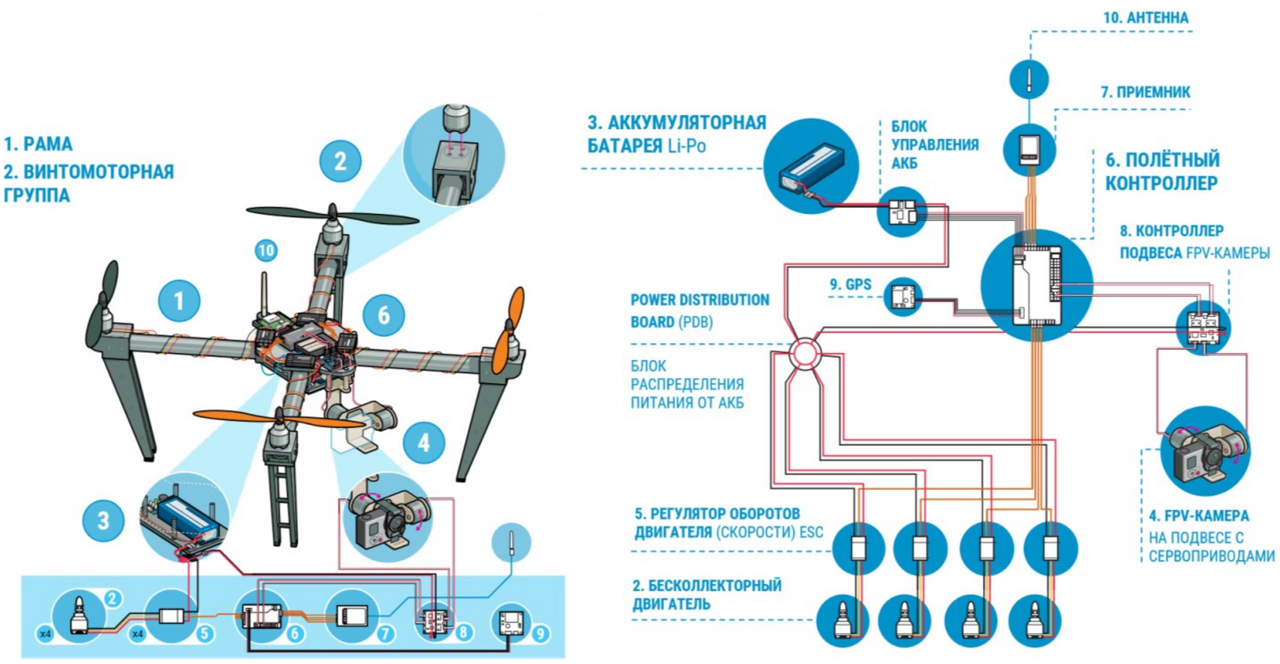


Figure 4.1 - Typical layout of UAV components and their connection

4.1 FPV drone assembly and flight preparation

The FPV drone assembly process depends on the design solutions and components used. However, the sequence of basic assembly operations is generally the same for most drones of this type.

In general, the FPV drone is assembled in the following sequence:

1. Frame Assembly.
2. Installation of motors and electronic speed controllers.
3. Installation of electrical wiring and connection of PDB.
4. Installing the flight controller.
5. Install and connect the receiver.
6. Setting up the control panel.
7. Pairing the control panel transmitter with the receiver.

8. Installation of camera, video transmitter, signaling device and other peripheral equipment.

9. Final assembly of the frame and securing the wiring and components of the drone.

10. Connecting the pack. Let's consider the assembly steps in more detail.

1. *Frame assembly* starts with *frame* preparation. It is recommended to prepare the frame before assembly. Sand the sharp edges of the carbon fiber parts, especially on the outside of the beams and plates. Sharp edges can damage wires and cut the battery strap in a crash. The machined edges can also help reduce the chance of the carbon fiber sheet delaminating in crashes. After sanding, you should wash all carbon fiber parts in soapy water to remove carbon dust residue from cutting, drilling, and sanding (be aware that carbon fiber conducts current). The parts must then be thoroughly dried.

Frame assembly should begin by placing the beams and beam retainer on top of the front bottom plate. The lower part with the beams is assembled first (the struts are left aside so as not to complicate soldering). To tighten the lower elements, hexagonal keys and sets of heads to them are required [20]. The plastic struts are fixed for attaching the flight controller assembly, power distribution board, electronic engine speed controller, and other components.

2. *The motors are installed* by bolting them to the frame. The length of bolts should be selected so as not to damage the motor winding (Figure 4.2). Connections are treated with thread locker to minimize the risk of unscrewing.

In case the *electronic speed controllers* are not integrated into the PDB board but are supplied separately for each motor, they are installed and fixed on the beams.

Figure 4.2 - Carbon frame of FPV drone with collectorless motors

3. The UAV structural elements are connected to each other by loops and wires. The FPV drone components are connected by wires at all subsequent stages of assembly. *The assembly of the electrical wiring* begins with measuring and adjusting the length of wires (taking into account the bends) necessary for ease of installation. The wires should be a few centimeters longer than the frame.

The wiring diagram may look as follows (Figure 4.3):

– PDB board is powered by a battery;

– electric motors are supplied from ESC through three wires;

– The flight controller is powered (+5V) from the PDB via the corresponding outputs;

– receiver is powered (+5B) from flight controller and is connected via UART2 to the flight controller;

– The video transmitter is powered by the PDB and video reception for transmission is from the flight controller;

– power supply camera (+5V) is supplied from video transmitter or flight controller.

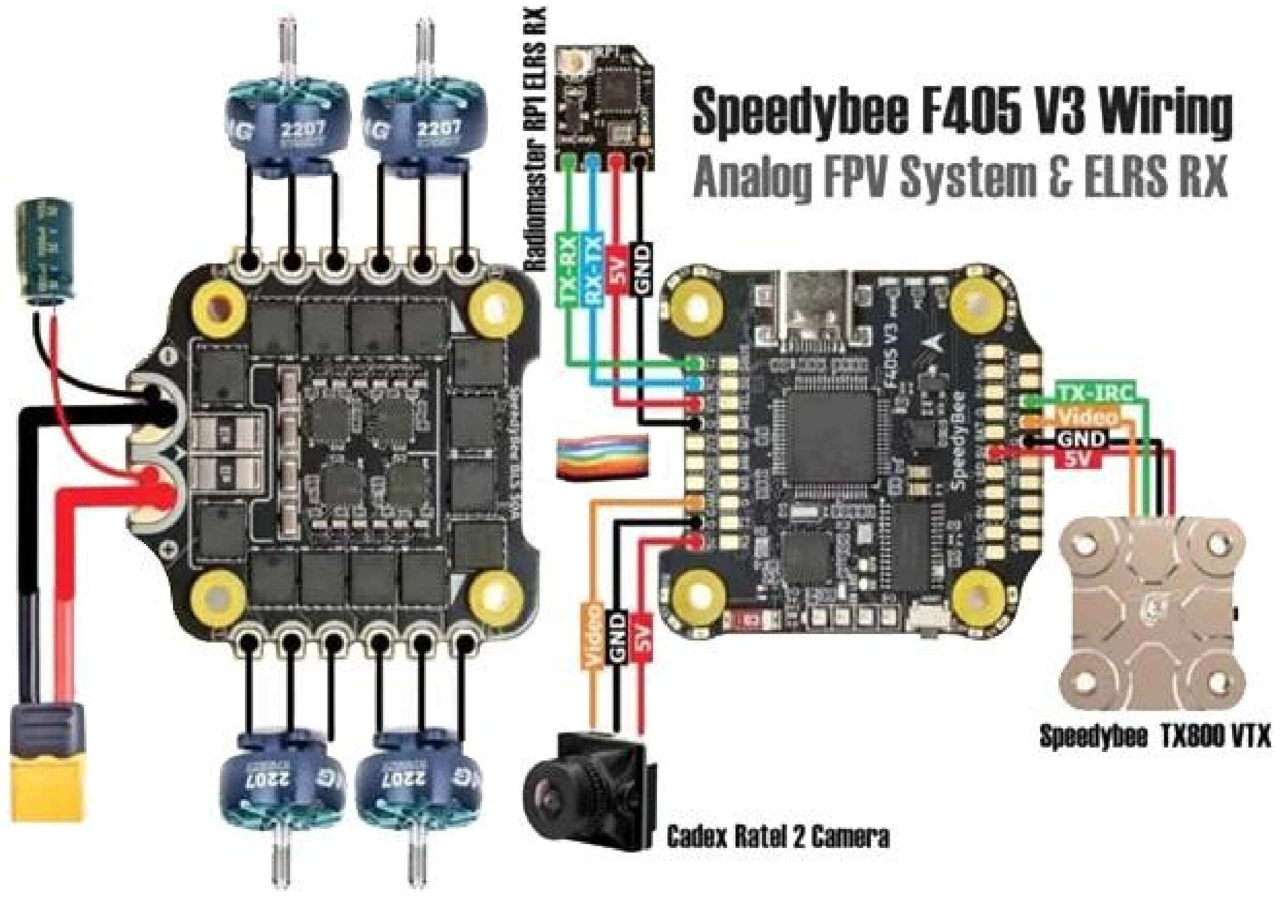


Figure 4.3 - Connection diagram of UAV components to the flight controller

It is necessary to observe the order and polarity of connection of electric motors to ESC according to their location on the frame (Figure 4.4). If the order or polarity is changed, the motor will rotate in the opposite direction.

Soldering points must be insulated with heat shrink tubing. Before soldering, a heat shrink tube of the required size is prepared and put on the wires. And only after that the work with the soldering iron begins. Next it is necessary to heat up the heat shrink tube to insulate the spots connections. After soldering, it is advisable to coat all boards with insulating varnish in several layers.

Figure 4.4 - Places of electric motors fastening on frame beams and place of soldering of electric motors to ESC

Do not allow the wires to protrude beyond the frame during installation. Carefully select their length and secure them with cable ties.

Next, it is necessary to solder the battery wire (XT60 connector) and the 1500 μF capacitor supplied with the PDB to the PDB power contact pads, observing correct polarity (Figure 4.5). The capacitor is used to reduce voltage surges and electrical noise generated by electronic regulators and motors.

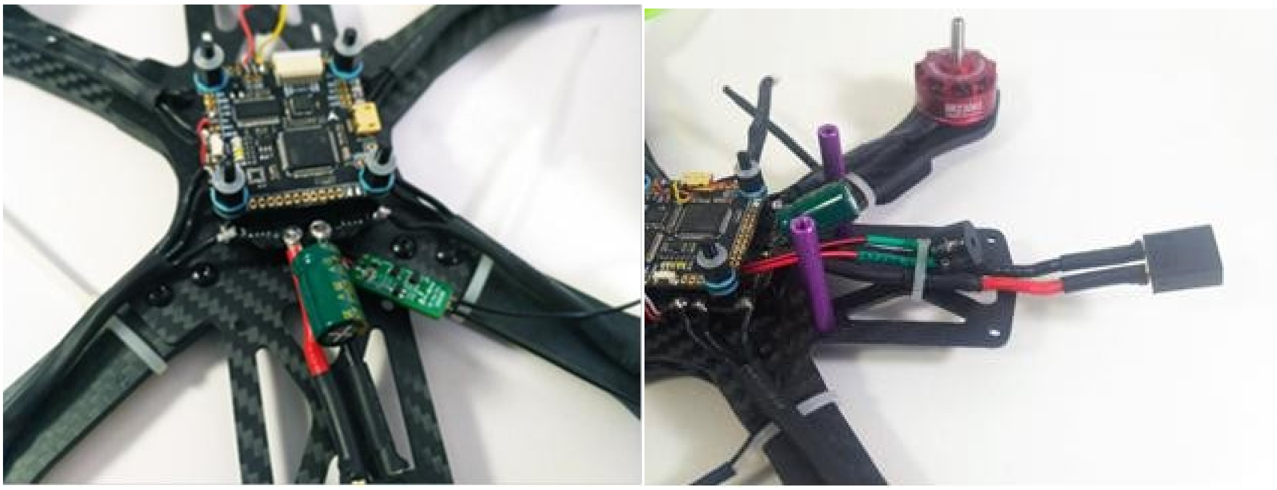


Figure 4.5 - Mounting the BPLA power wire and capacitor to the PDB board

4. *Installation of the flight controller* begins by securing it to the frame. In flight, the PC experiences vibrations and noise. These effects negatively affect the readings of some sensors. Therefore, during installation it is necessary to use softening cushioning materials in the places of fixing to the frame [6]. The flight controller should be equipped with shock absorbers to minimize the negative influence of vibrations and

vibrations. The flight controller is connected to the PDB by means of a loop (Figure 4.6).

Figure 4.6 - Mounting the flight controller to the PDB

5. *Installation and connection of the receiver* to the flight controller (Figure 4.7). To connect the receiver it is necessary to solder three wires to the appropriate contact area on the PC: white - signal, red - +5 V power supply and black - ground. The receiver should be placed in a heat shrink sleeve.

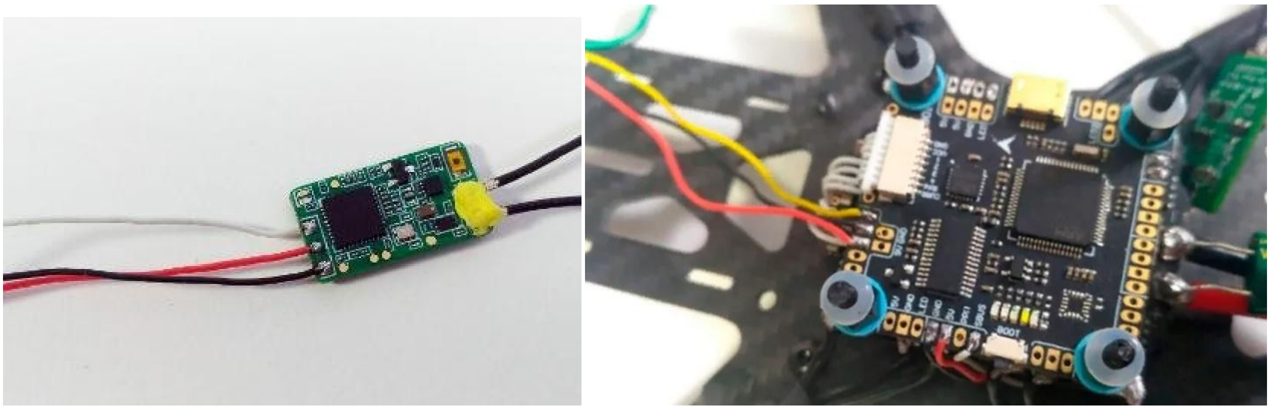


Figure 4.7 - Connecting the receiver to the flight controller

The receiver is mounted so that the antenna is outside the frame to avoid shielding of the radio signal by UAV structural elements. Most 2.4 GHz receivers use two dipole antennas. Antennas of this design should be mounted at right angles to each other.

6. The *control panel is set up* after the receiver has been installed. First of all, for correct data transmission between the remote control and the receiver, it is necessary to set the communication protocol in the transmitter settings of the control panel. The protocol is set in the SETUP menu for External RF or Internal RF module of the transmitter of the control panel (Figure 4.8). To

of the selected transmitter module to communicate with ExpressLRS or TBS receivers - set the MODE setting to CRSF.

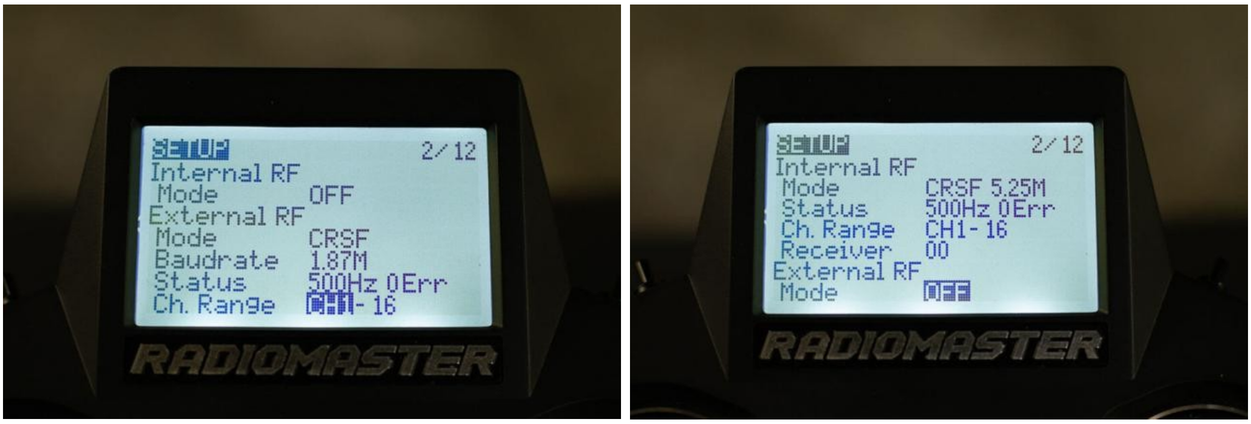


Figure 4.8 - Transmitter external and internal communication module settings

The toggle switches on the control panel are configured for each UAV according to the number of control channels involved and the operator's preferences. The settings are stored in the control panel memory. Several settings - models (according to the number of UAV models or control options) can be stored in one control panel. Preset control settings (model) have no assigned toggle switches except for the four stick control channels. Therefore, if the toggle switches do not work when checking the signals on the channels in Betaflight Configurator, you must assign them in the Mixes tab of the hardware model settings. To reassign a toggle switch, select the desired channel, press the select button and click Edit. Then select Source and assign the toggle switch to this channel (Figure 4.9).

It is important to remember that only AUX1 (channel 5) and no other channel should be used to enable or disable the Parking Mode (APM) in ELRS and TBS protocols.

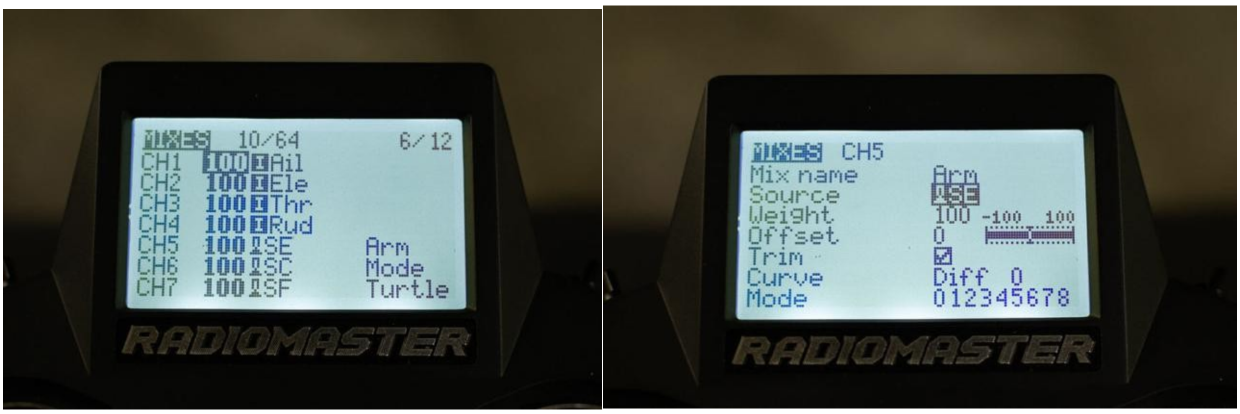


Figure 4.9 - Assignment of toggle switches to control channels

7. *Pairing the control panel transmitter with the receiver.* To perform this operation, press the SYS button on the remote control, go to the system settings section and select the ExpressLRS Lite or TBS Agent Lite menu item. Then in the script settings (Lua Script) you need to select WiFi Connectivity and then select Enable WiFi. Press OK again to enable WiFi signal distribution on the transmitter (Figure 4.10).

Figure 4.10 - Configuring Wi-Fi signal distribution from the transmitter

Next, it is necessary to connect to the ExpressLRS TX wireless network with the default password expresslrs (Figure 4.11).

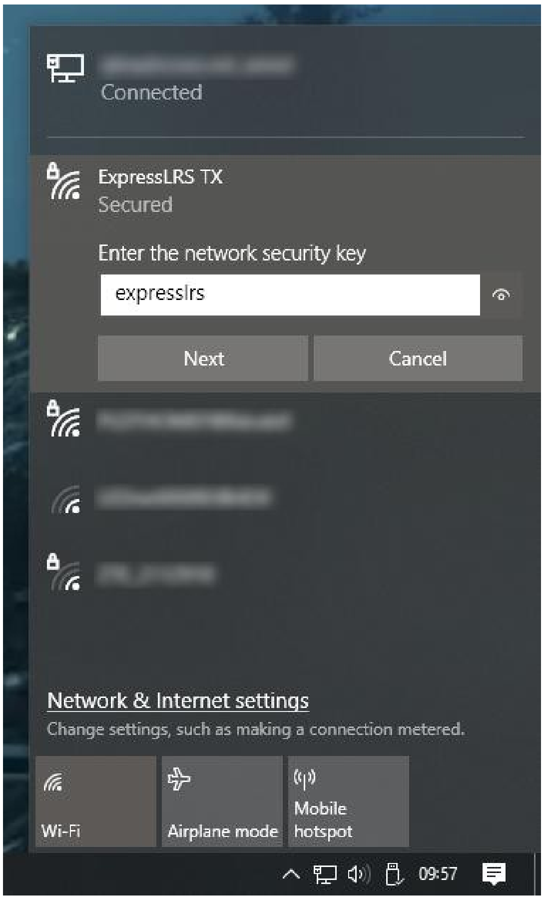


Figure 4.11 - Connecting to Wi-Fi signal from the transmitter

Particular attention should be paid to the software configuration, which consists in linking the transmitter with the receiver via Wi-Fi. For this purpose, it is necessary to configure the same

Binding Phrase on both devices. This word will be used by the receiver to find the transmitter, therefore a unique character-numeric sequence must be used to prevent another UAV from connecting to one transmitter. The code word is entered in the transmitter settings menu (Figure 4.12), which should be displayed in the computer browser when the equipment is successfully connected to the Wi-Fi network. After entering code word it is necessary to press button.
"preserve". [10].

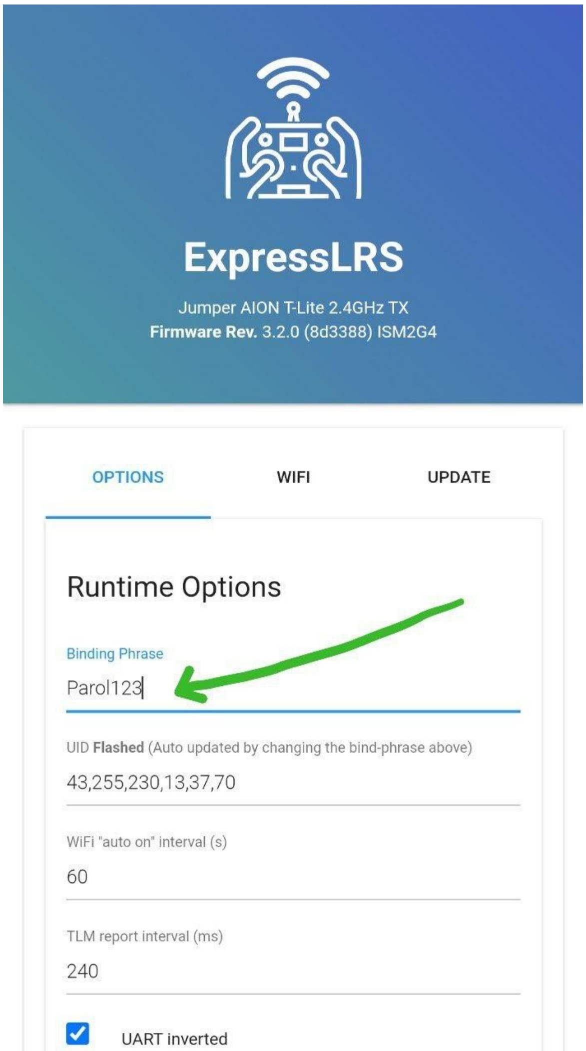


Figure 4.12 - Transmitter codeword settings menu

To assign a codeword to the receiver firmware, power on the receiver. If the receiver does not connect to the transmitter within 60 seconds after powering up, the receiver will automatically enter the Wi-Fi signal distribution mode. The green LED on the receiver will blink green rapidly. The process of entering a codeword on the receiver is the same as entering a codeword on the transmitter.

No further additional procedures are required for binding, pairing will be performed automatically if the code words on the transmitter and receiver match.

8. Installation of the camera, video transmitter and signaling device. The video transmitter is connected to the flight controller by soldering. To solder the wires of the video transmitter the scheme shown in Figure 4.3 is used.

It is best to power the FPV camera from either a distribution board (PDB) or a video transmitter.

Figure 4.13 - Mounting the video transmitter and camera on the UAV

The video transmitter antennas are attached to the frame with plastic ties at right angles to each other as shown (Figure 4.14 a) or by mounting the antennas on a V-shaped mount (Figure 4.14 b).

a) б)

Figure 4.14 - Methods of attaching antennas to an FPV drone:
a) - with the use of plastic ties; b) - with the use of special fastening for antennas

The signaling device is attached to the corresponding contacts of the flight controller. This element is supposed to produce an audible signal, which makes it easier to find it in case of a fall.

9. *The final assembly of the frame and securing the wiring and components of the drone* is the final stage of the assembly and consists of installing the top plate and the battery mounting strap. The capacitor, wiring and other loose components of the UAV should be attached to the fixed frame elements using nylon ties or tape.

10. The battery is connected to the XT60 connector and secured to the frame with a strap. The battery can be attached to the UAV body either from the bottom or from the top (Figure 4.15).

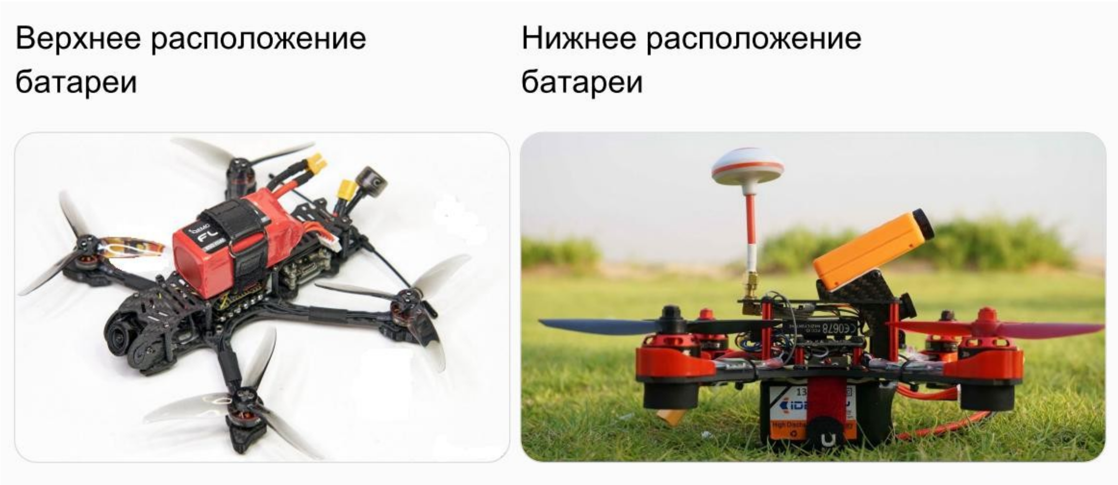


Figure 4.15 - Top and bottom location of the battery pack

Note that blade assembly is not performed until the flight controller is set up.

4.2 Preparing the FPV drone for operation and setting up the control and data channels

After assembling all the quadrocopter components, the software (firmware) is installed (updated) and configured on the PC. This procedure is performed using a special program - configurator. There are several types of configurator programs designed to configure the PC, each of them supports hardware from different manufacturers and different models of the same . The most popular one for FPV drone PC configuration is Betaflight Configurator - it is a program that allows you to get access to the PC and all its sensors, load software (firmware) into it, and set up its configuration. Let's look at the process of configuring the PC using Betaflight Configurator version 10.9.0.

The following hardware is required to install the software on the quadcopter [19]:

– A quadcopter with a flight controller that supports Betaflight Configurator version 10.9.0;

– MicroUSB cable;

– a computer with Internet access.

Configuration of the quadrocopter PC starts with launching the Betaflight Configurator program (the flight controller is not connected). On the first tab of the program (Figure 4.16) there is list of drivers, which must be Install. Installed all suggested drivers suggested by the program [1].

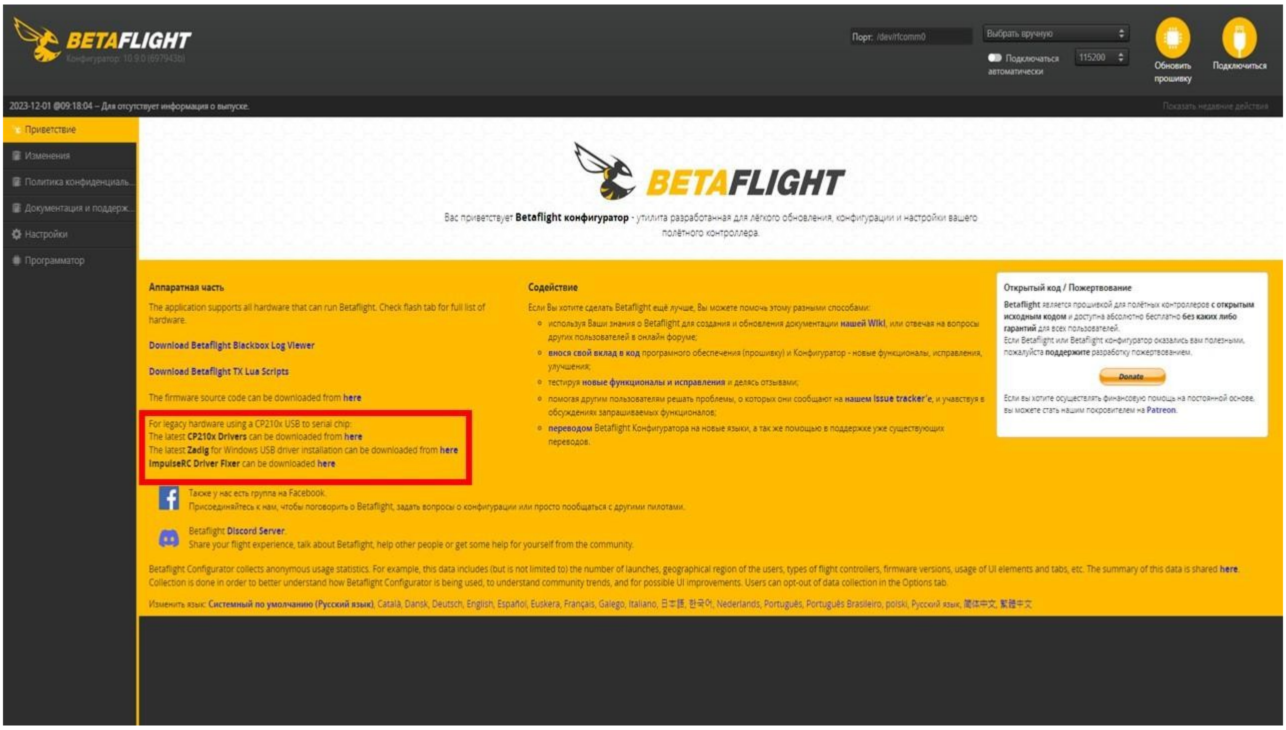


Figure 4.16 - Betaflight program interface with list of drivers

In order to update the firmware (firmware), it is necessary to press and hold the "Boot" button on the PC board and at the same moment connect the PC to the computer. Pressing the button starts the "Bootloader" mode, i.e. the PC is put into the software update mode. Once the USB cable is connected to the PC and the flight controller, only one blue LED should be on continuously. If the second LED is blinking, there is an error in the settings.

First of all, make sure that the DFU firmware upgrade mode is set (marker 1 in Figure 4.17). If it is not, repeat the previous steps. Also problems may occur due to incorrectly installed drivers.

Go to the "Programmer" tab (marker 2 in Figure 4.17). From the drop-down list select the available flight controller (marker 3 in Figure 4.17). In the next drop-down list select the latest stable firmware version (marker 4 in Figure 4.17).

Press the "Full chip erase" switch (marker 5 in Figure 4.17). When connected internet press button "Download firmware (Online)" button (marker 6 and 7 in Figure 4.17). Wait until the current firmware is downloaded firmware. After that the "Download firmware" button will become active.

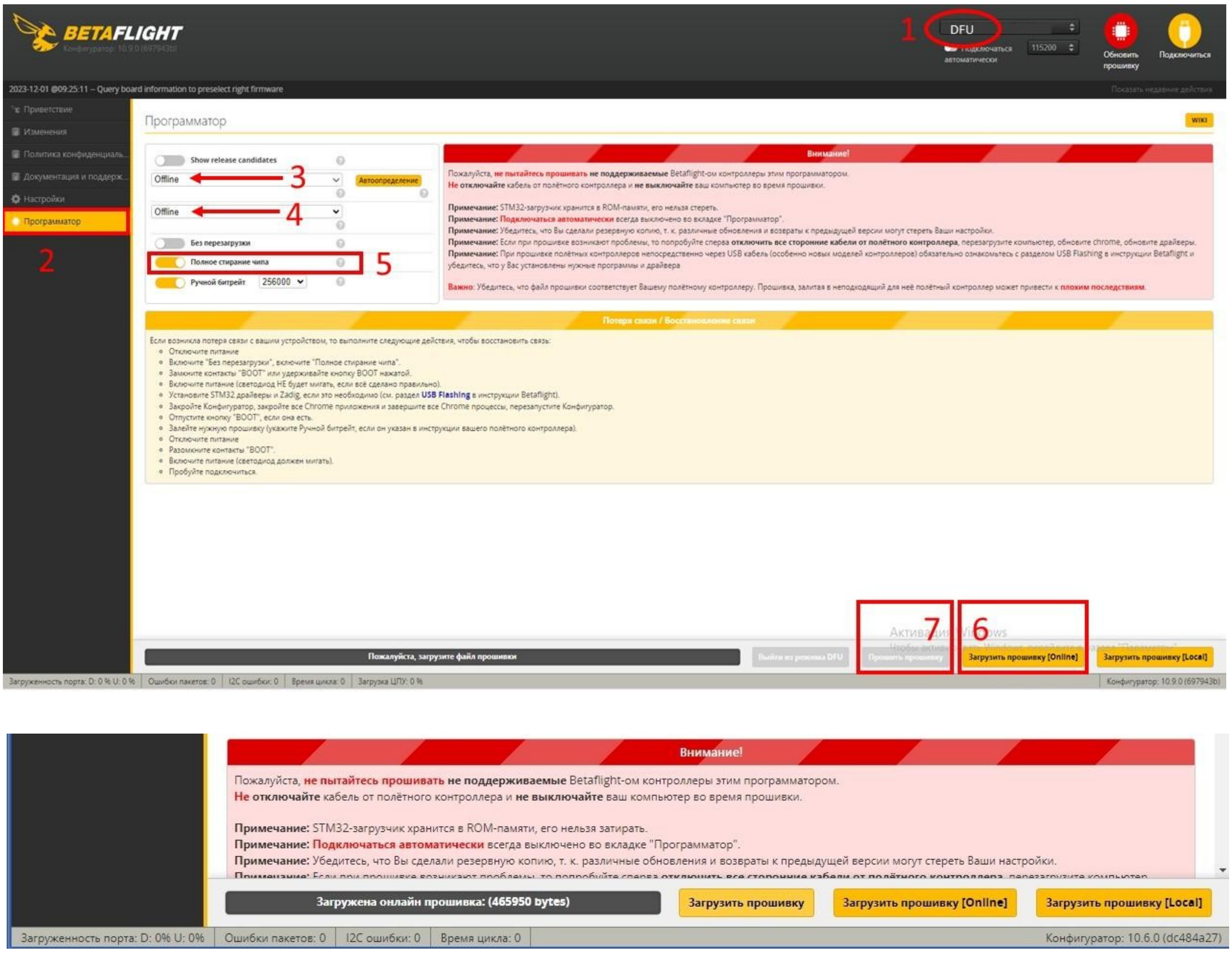


Figure 4.17 - Flight controller firmware update mode

Press the "Download firmware" button and wait until the firmware is downloaded to the PC. Then disconnect and reconnect the PC, but without the boot button pressed. The PC should blink with multicolored LEDs.

Press the "Connect" button. The Expert mode will be enabled at the top of the window.

Go to the "System" tab and calibrate the gyroscope/accelerometer (Figure 4.18). To do this, place the UAV on a flat surface and click "Calibrate Accelerometer" [1] [1]. As a result of calibration, the arrow on the flight controller indicating the direction of motion should coincide with the direction of the drone model in the position display window. The correct position of the calibrated accelerometer is shown in Figure 4.19.

If you failed to calibrate the gyroscope/accelerometer, go to the "configuration" tab and programmatically rotate the gyroscope until the arrow aligns with the direction of the drone model (Figure 4.19), and check that the accelerometer is enabled (Figure 4.20).

Then go to the "Configuration" tab and enable the Dynamic_Filter parameter to filter the data output from the gyroscope to the speed controller. Figure 4.21 shows the order of enabling the Dynamic_Filter parameter.

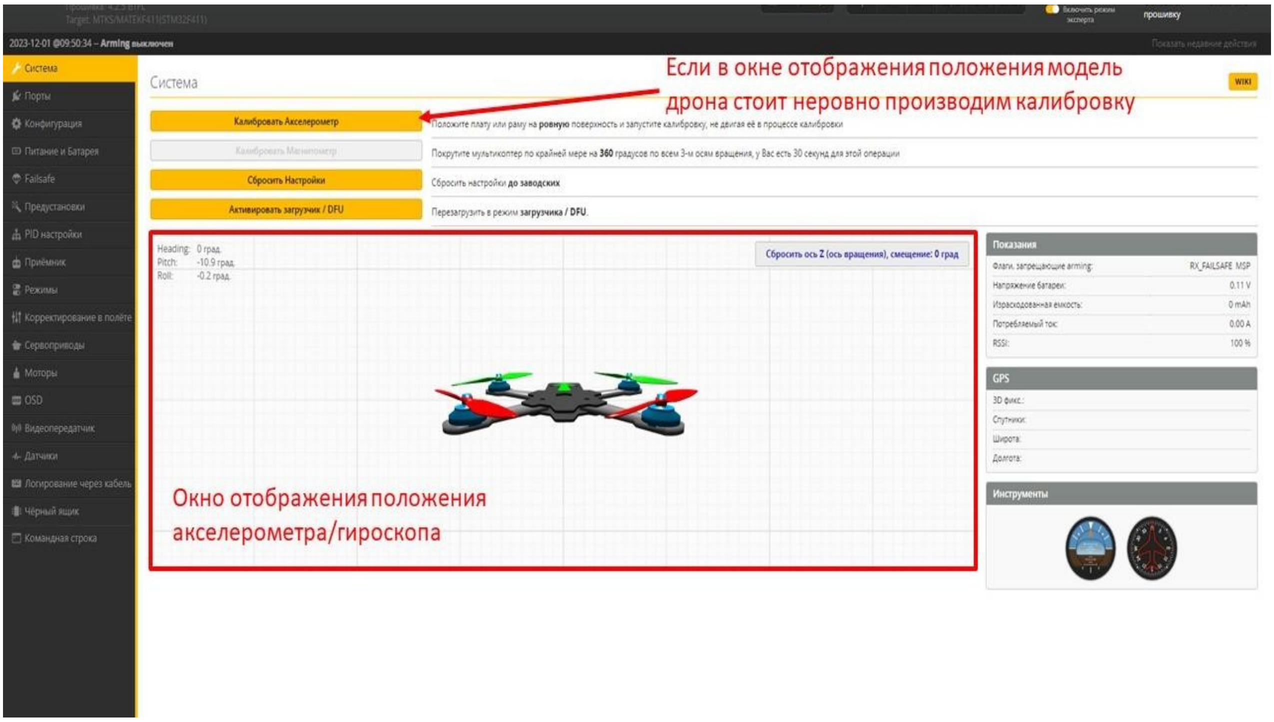


Figure 4.18 - Gyroscope/accelerometer calibration mode

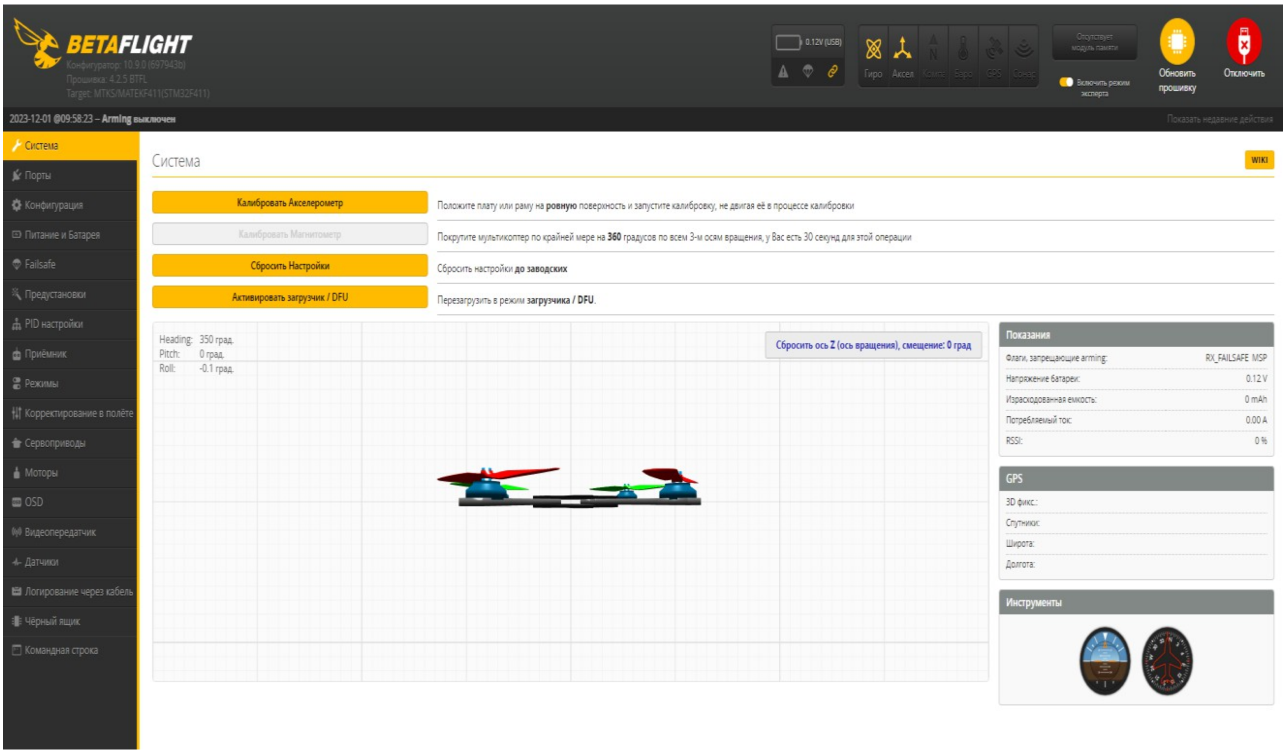


Figure 4.19 - Gyroscope/accelerometer calibration mode

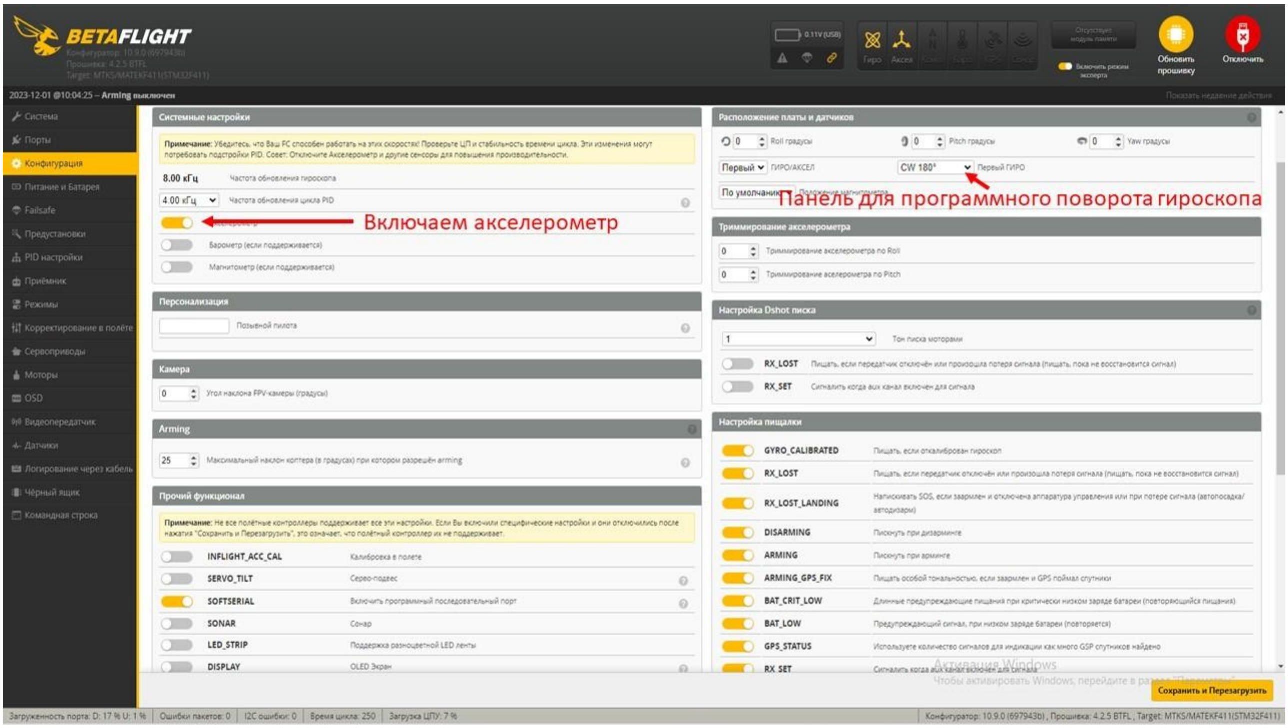


Figure 4.20 - Accelerometer On/Off Mode

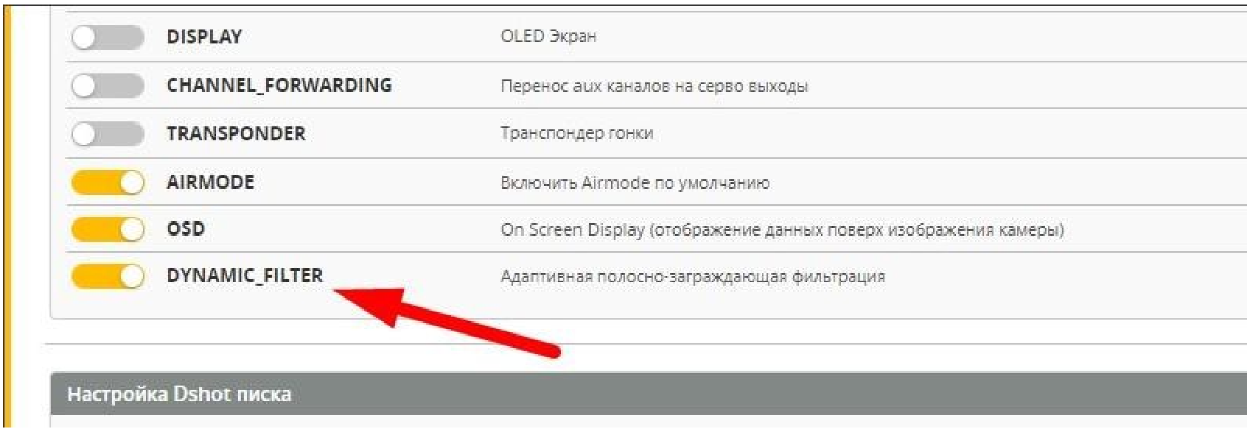


Figure 4.21 - Dynamic_Filter on/off mode

The Ports tab contains settings for the UART ports, i.e. the serial ports that are used to communicate with various components such as receiver, video transmitter, GPS module, etc. The USB VCP setting should always be enabled. The USB VCP parameter must always be enabled.

In this section it is required to enable the port, which is used to exchange information with the receiver (Figure 4.22). It may be different for different flight controllers.

It is necessary to configure the port inputs. A UART is a group of RX and TX pins. The number next to it indicates the UART number. According to how the receiver pins are soldered, it is necessary to enable Serial RX on the UART port (where the receiver is soldered) and select VTX on the UART port (where the video transmitter is soldered).

(IRC Tramp) to switch channels from the flight controller (optional) [8].

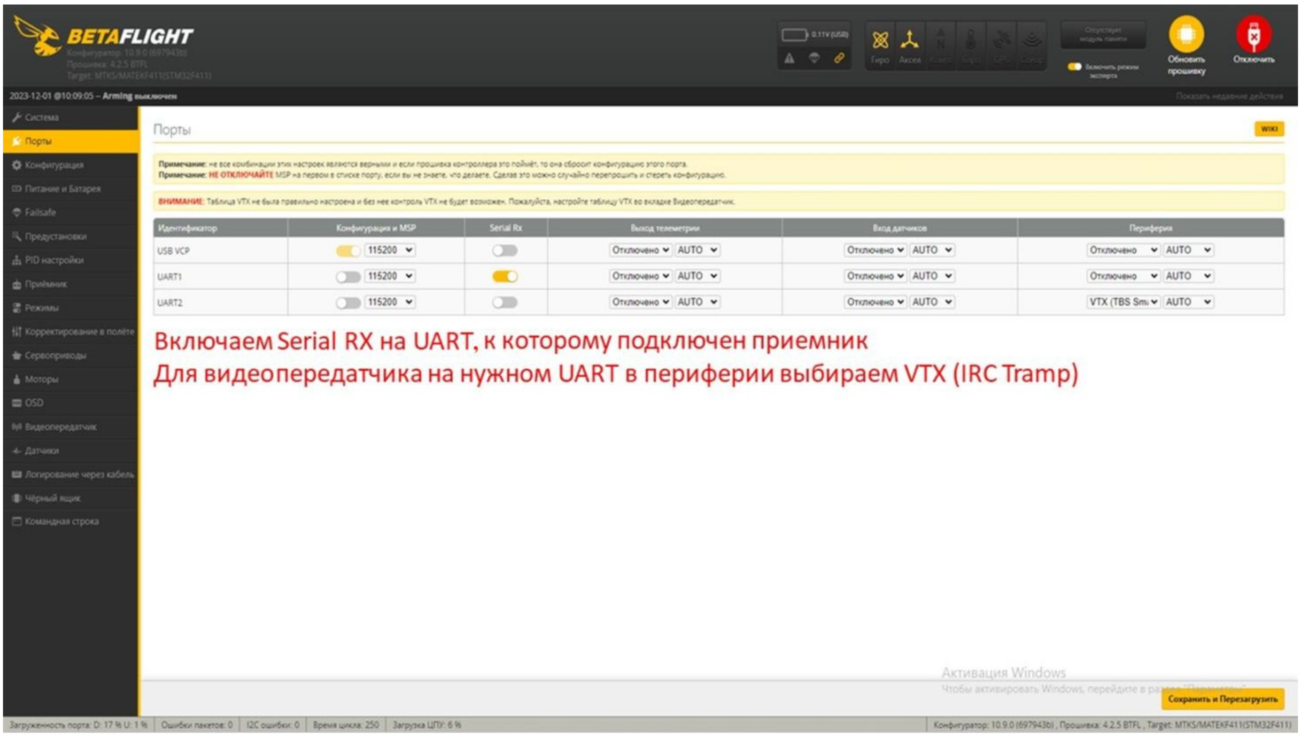


Figure 4.22 - Port inputs setup mode

Then *on the "Receiver" tab* you need to configure the reception mode, i.e. *the* port and communication protocol between the receiver and the flight controller.

Connect to Betaflight and go to the "Receiver" tab. Then connect the battery, turn on the remote control.

Check that all channels respond to the operator's actions. When he moves the sticks and switches, the colored bars should also move.

If the bars do not move, check to see if the receiver and remote are turned on and if the receiver is connected correctly . Also check that is in the tab.
"Configuration" whether the correct receiver type is selected (IBus, SBus, etc.) whether the correct operating protocol is selected (MultiSHOT, DSHOT, etc.).

Select "Serial port (via UART)" in the drop-down list and put "CRSF" in the communication protocol selection.

If the bars are moving, but not in the right order, you should try changing the markup map from AETR1234 to TEAR1234 in the "receiver" tab.

The threshold setting is used to calibrate the position of the sticks on the hardware. This is where the numerical value of the sticks in the extreme bottom position and in the extreme top position, as well as in the center. The default values usually do not need to be changed [9].

When you turn on the remote control and move the stick in different directions, the multi-colored bars (Figure 4.23) will run from 1000 to 2000, the average position when you release the stick should be at 1500 ± 1-2 units, but it is better to be exactly 1500. Because these 2 degrees will make adjustments in flight.

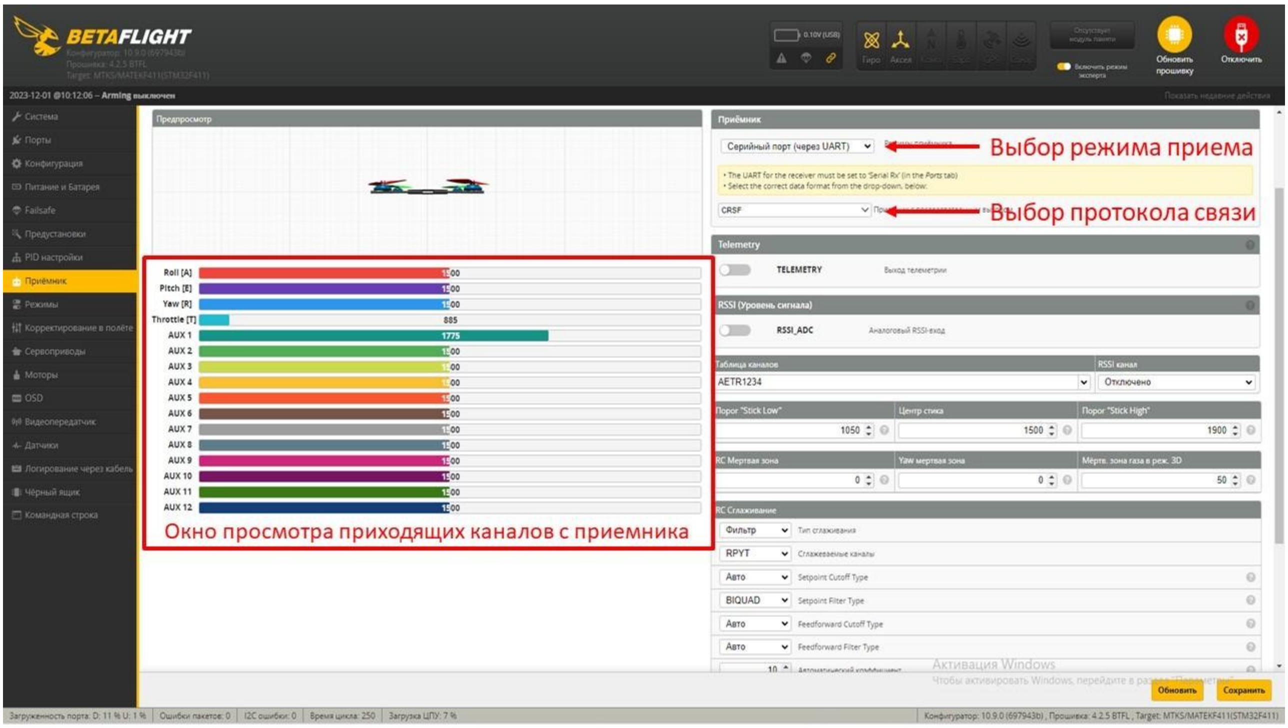


Figure 4.23 - Configuring the "Receiver" section

The values can be corrected using the trim buttons on the remote control (Figure 4.24) or by making adjustments via the CLI.

Figure 4.24 - Trim buttons on the control panel

Incorrect averages will cause the UAV to drift and fly in different directions.

Next, select the *"Motors" tab.* Before making settings on this tab, it is required:

1. Remove the propellers, if fitted. It is recommended to make all adjustments in this condition. Installed propellers are a risk of injury!

2. Connect the battery to the quadcopter.

3. Go to the Motors tab of the Betaflight configurator and turn on the slider under marker 2 in Figure 4.25. The box under marker 3 shows the correct direction of rotation for each of the motors.

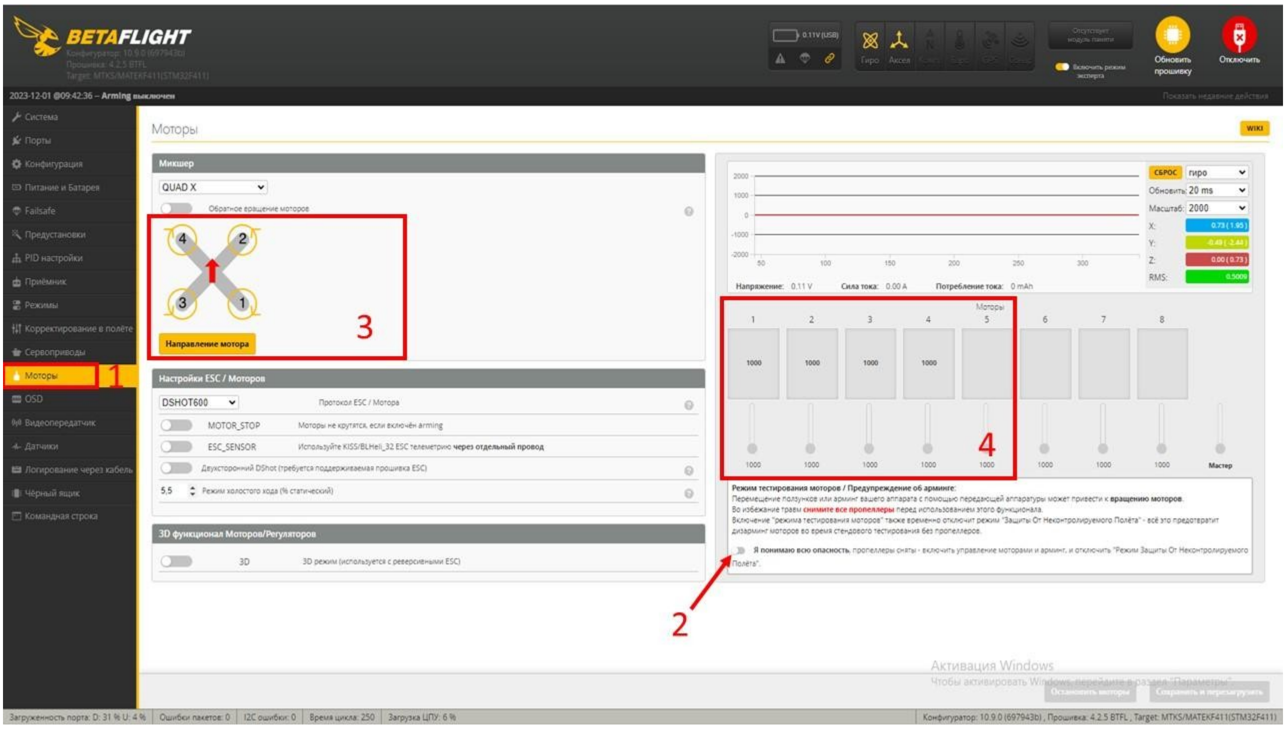


Figure 4.25 - Customizing the "Motors" section

4. Go to block 4 of figure 4.25. Slowly raise the slider near motor #1 and check the direction of rotation. If the rotation is clockwise, then move the slider down. Check all other motors in the same way, taking into account their direction of rotation. If the rotation of the motors does not coincide with block No. 3, it is necessary to adjust the rotation of each motor individually, for this purpose press: motor direction - individual and by pressing and holding down adjust the rotation of each motor individually [9]. If the UAV turns upside down during a test flight, it is necessary to reassign the channels of the tabs
"Reassign motors" (Figure 4.26).

Calibration of the revolutions controllers (ESC).

The protocols and parameters of the motors are configured in this block.

DSHOT600 is a communication protocol between ESCs and PCs. All modern ESCs and PCs support DSHOT300, DSHOT600 and DSHOT1000 protocols. You should select the protocol recommended by the manufacturer.

MOTOR-STOP - used to stop the motors when turned on.
The function is not normally used.

ESC_SENSOR - used to enable telemetry, if the regulators use a separate signal wire for this purpose.

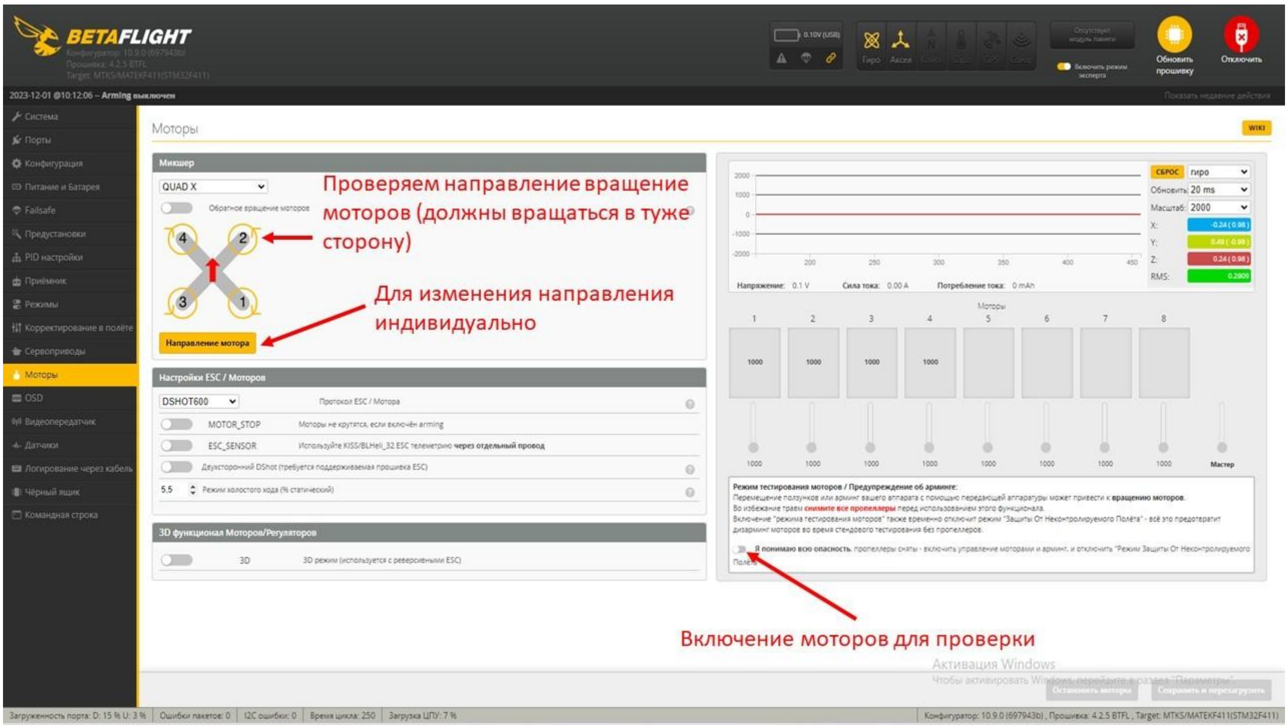


Figure 4.26 - Customizing the "Motors" section

Two-way Dshot is a new feature in Betaflight 4.x that allows the PC to receive engine RPM information via the ESC signal channel without the need for additional wires and channels.

Motor poles - a window where you enter the number of magnets in the motor.

Idle - a window in which you set the speed at which the propellers will rotate after turning on (Arming). Usually 2-4% is sufficient. There is no need to calibrate the controls if the DShot protocol is used, including DShot150, DShot300, DShot600, DShot1200 и DShot2400. However, they must be calibrated if the regulators have PWM protocol, Oneshot125, Oneshot42, and Multishot.

The process of calibration under OneShot is no different from calibration under any other protocol [8].

To calibrate the OneShot protocol:

– disconnect the FPV drone from power and remove the propellers from the motors;

– connect the flight controller to the computer, start Cleanflight or Betaflight and go to the Motor tab;

– select "Test motor", in Betaflight there will be a slider on the right side that allows you to raise the rotation speed to the maximum of all motors at once;

– raise the sliders of all motors up, connect power (battery connected) and sharply lower all sliders down. An audible alarm will indicate that all sliders are calibrated.

Next, disconnect and reconnect the battery and smoothly add a little bit of engine speed with the slider, make sure that all engines rotate simultaneously.

The "Modes" tab allows you to customize the different toggle switches on the remote control. In this mode, two toggle switches are mainly configured:

Arming - and disarming the quadrocopter (ARM - arming / DISARM - disarming electric motors);

Activation of stabilization mode (HORIZONT, ANGLE) and ACRO mode - manual control mode.

To configure the toggle switches it is necessary to select the required mode and press "Add Range". Then the range is adjusted so that the position of the toggle switch, where it is on, corresponds to the range (Figure 4.27).

Select a channel, e.g. AUX1, or leave "AUTO" and toggle any convenient toggle switch on the remote control that will be used for this function. The channel that is linked to this toggle switch will be automatically selected. Once AUX is selected, the toggle switch must be toggled several times, and the yellow marker corresponding to the toggle switch position will move on the indicator. If you move the yellow bars to the area where the yellow dot will be, the quadcopter will start reacting to this position, in this case it is Arming or .

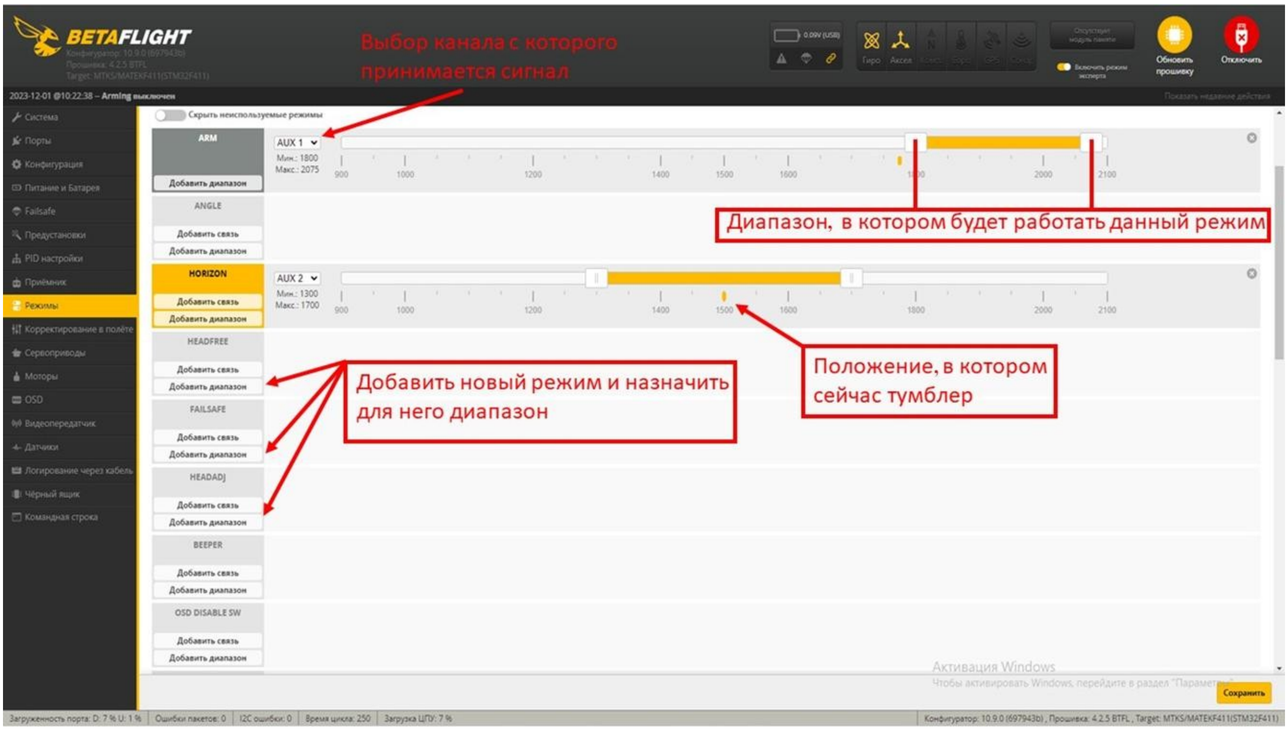


Figure 4.27 - Customizing the "Modes" section

The result shown in Figure 4.28 should be obtained.

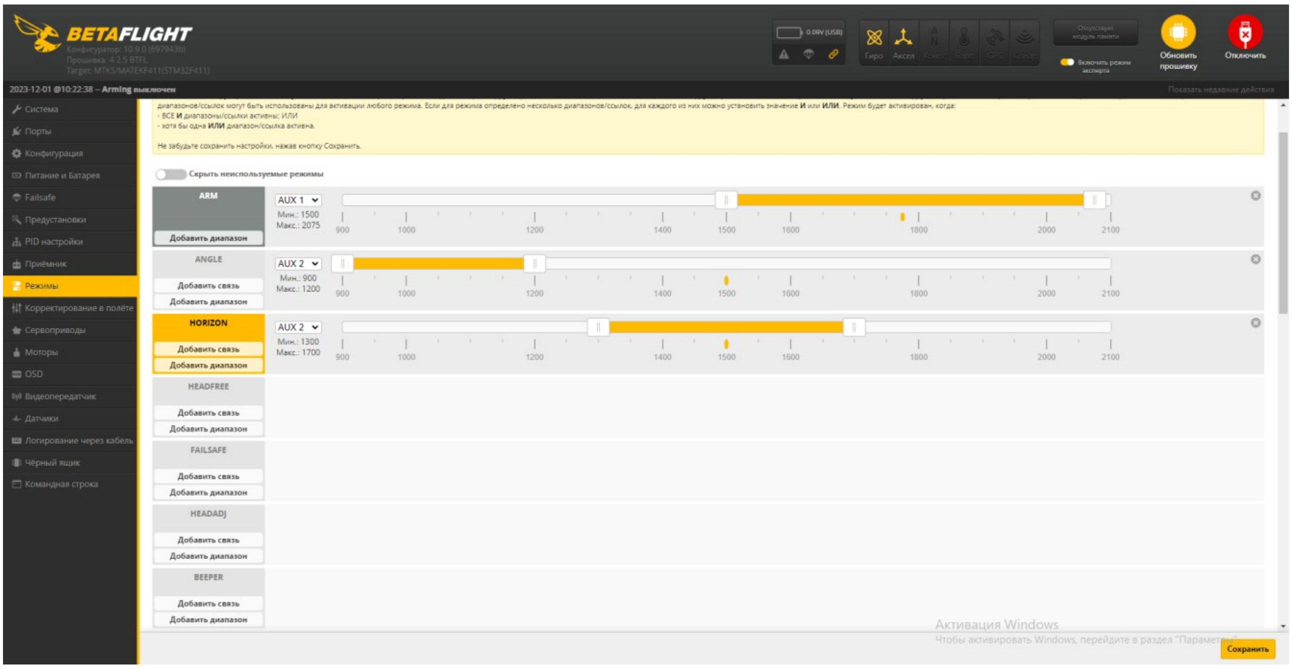


Figure 4.28 - Correct setting of the "Modes" section

The "Failsafe" tab allows you to configure the save mode, i.e. actions that the quadcopter will do when losing communication with the control panel (Figure 4.29).

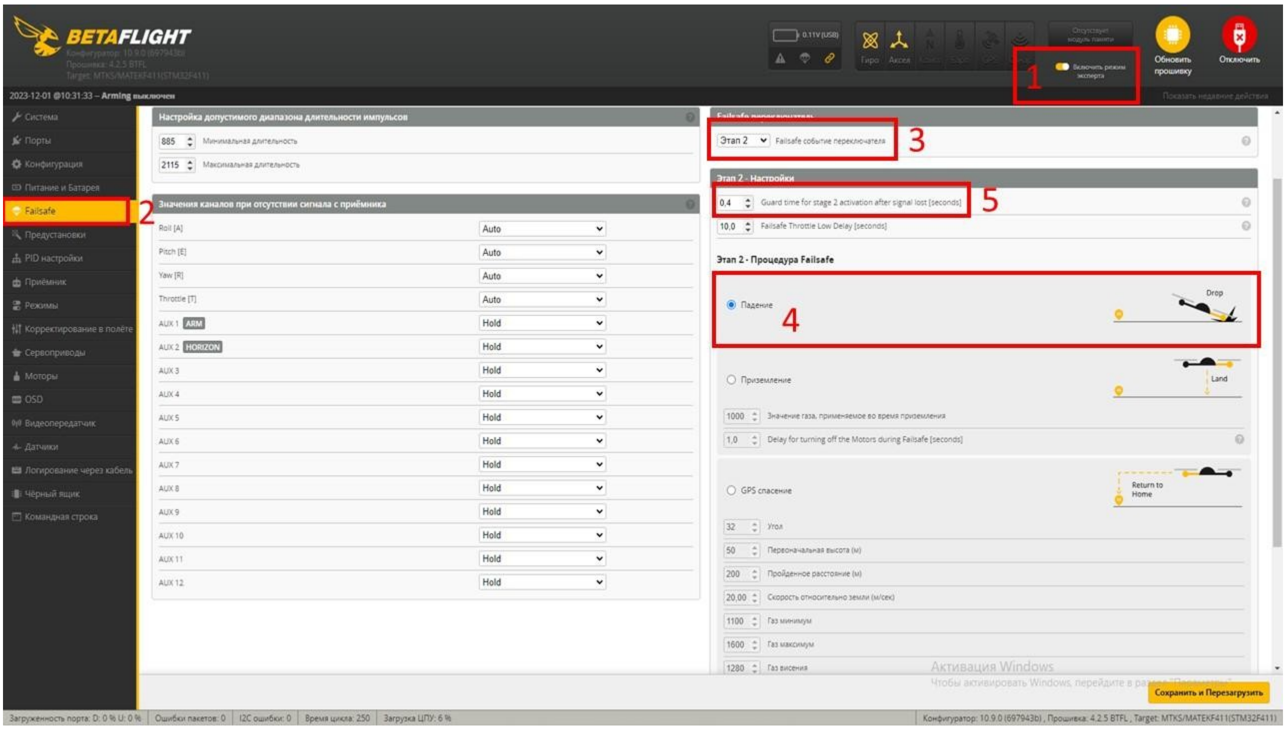


Figure 4.29 - Configuring the "Failsafe" section

Failsafe is a function that performs certain actions after the radio communication between the quadcopter and the control equipment is lost. Activating this function means that if the control equipment fails, the quadcopter will not fly further, but will make an emergency landing.

Failsafe is triggered in cases where:

– the quadcopter flew out of range of the control equipment signal;

– there is an obstacle between the quadcopter and the remote control, through which the signal does not pass;

– lost the power в remote control or receiver (the equipment is turned off/unplugged);

– the receiver disconnected from the flight controller.

When setting this Failsafe, 3 modes can be selected (Figure 4.29):

– Drop - The quadcopter shuts down its motors, causing it to fall;

– Landing (Land) - The UAV reduces throttle to 20% and slowly lands.

GPS rescue (Return to Home). If the quadcopter is equipped with a GPS module, you can use it to set the return of the quadcopter. In case of loss of communication, the GPS Rescue function is activated, the UAV will climb to a certain altitude and fly to the approximate takeoff point. The GPS Rescue function is an emergency function designed to regain control of the quadcopter, but not to land it. The function will be triggered if the UAV flies at least 50 meters away. It is not recommended to land the UAV using the GPS module, as it may hit the ground (no other sensors).

The "OSD" tab customizes the parameters of displaying various information on the screen of glasses or helmet (Figure 4.30).

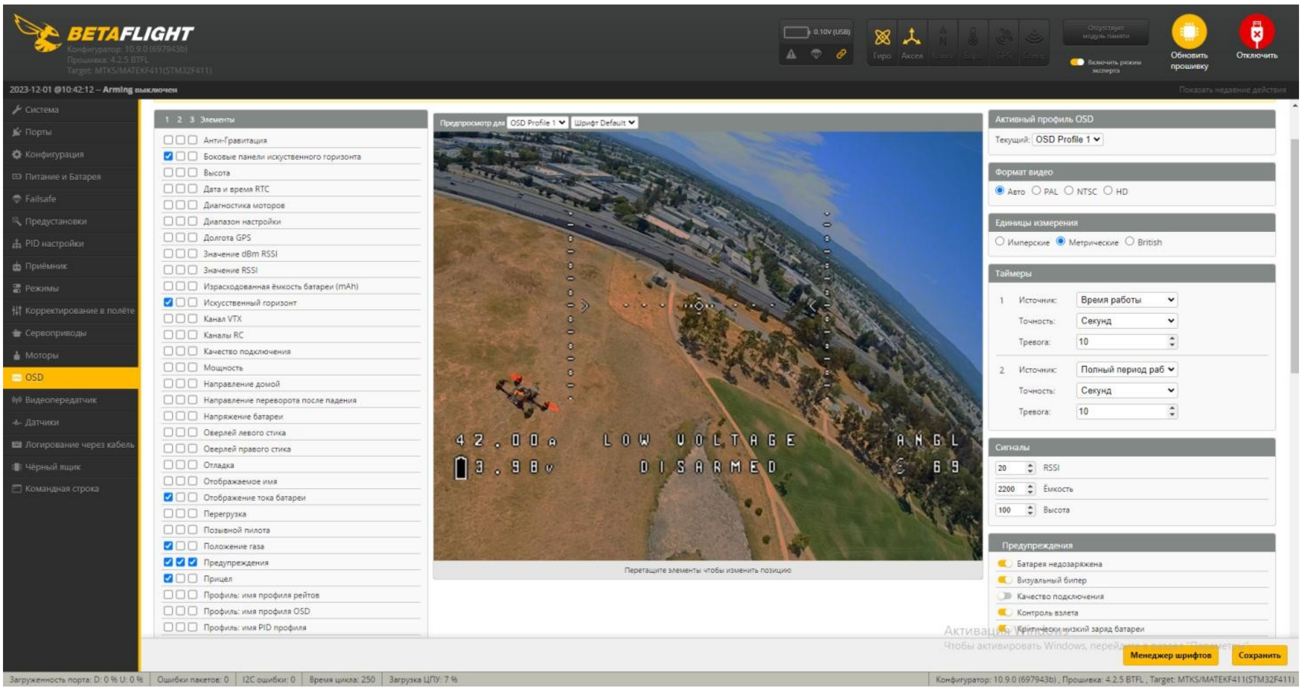


Figure 4.30 - Setting up the "OSD" section

In the center is the screen simulation. On the left side you should check the required parameters, then they will appear on the window. In order to to find out what a parameter means, you should put the mouse cursor over it - a tooltip will appear.

It is recommended to set the most necessary to avoid overloading the screen with information (Figure 4.31). When setting up it is necessary to tick the checkboxes and move the information on the screen to the necessary place.

Figure 4.31 - Result of setting the "OSD" section

Parameters that are monitored by the UAV operator in flight:

1) Optimal flip direction when falling upside ;
2) "Sighting" - the direction of the longitudinal axis of the quadcopter relative to the artificial horizon line;
3) Artificial horizon (aerial horizon) - shows the position of the horizon relative to the quadrocopter axis;
4) Current consumption current (instantaneous value);
5) Used battery capacity;
6) Voltage of one battery cell (average value);
7) Flight time;
8) General Mode Index;
9) Malfunction warning;
10) Quadcopter microcontroller temperature;
11) Control signal level;
12) Flight mode indicator.

The *"PID" tab is a* 3-word abbreviation:

1. P - Proportional;

2. I - Integral;

3. D - Deriative.

PID is a function in the flight controller that allows you to process information from sensors (typically a gyroscope and accelerometer) and produces control signals and then sends commands to the electric motor speed controllers (ESC).

The proportional component linearly changes the control signal (provides control sensitivity).

The integral component ensures minimization of static error (provides maximum control accuracy).

Differential component reduces The differential component reduces the amplitude of overshoot, which reduces sway.

After assembly and setup, the FPV system is tested by checking the quality of the video image in the helmet/goggles.

4.3 FPV drone maintenance and repair in the field. Tools and spare parts

Operator of the FPV drone must be able to independently perform maintenance, which includes the following steps:

– initial maintenance (external inspection of the product, cleaning of dust and dirt, inspection of cable and screw connections);

– maintenance maintenance c using spare parts Parts, tools and accessories (PTO);

– replacing broken beams;

– replacement of faulty screws;

– replacement of faulty motors;

– charging;

– soldering of mini-class BPLA elements.

Piloting FPV drones can be accompanied by accidents, which requires the operator's skills to carry out repairs. The greatest complexity is caused by repair in the field. Let's consider a set of equipment and spare parts for maintenance and repair of FPV-drones in the field, formed on the basis of experience of their operation:

– tool kit (knife, pliers, screwdriver set, tweezers, wire cutters);

– hexagonal heads -1.5, 2, 2.5 and 3 mm;

– soldering iron and ;

– heat gun (from USB);

– shrink tubing;

– PVC duct tape;

– retaining strap;

– a set of plastic clamps;

– hydrophobic (water repellent) for the camcorder.

BPLA spare parts:

- batteries;
- rays;
- a set of electric motors;
- propellers;
- electronic components;
- antennas.

The number of components for UAV repair should be selected in accordance with the intensity of flights, remoteness of permanent deployment points, terrain, etc. However, propeller blades, antennas, motors, frame beams and wiring are most often damaged as a result of operation; therefore, such components should be included in the spare parts and accessories kit.

4.4 Safety precautions for assembly and maintenance

When carrying out maintenance and repair work on the UAV, the requirements of the operating instructions must be observed.

Charge batteries only in specially designated places, observing the safety requirements for the operation of batteries of this class and sure that there are no people unrelated to this work at a distance of at least 5 meters.

It is forbidden to operate the batteries in case of mechanical damage of the protective film, swelling of the plates, appearance of characteristic odor of chemical reaction.

If a malfunction or emergency situation is detected during assembly, stop the process immediately and carry out a set of measures to eliminate it.

Upon completion of work, roll up the set according to the operating instructions, remove the battery pack from the UAV, charge the battery pack and place it in a container. It is forbidden to store the battery pack in free access.

If uncontrolled processes occur in the batteries during connection or charging (temperature rise, bloating, open chemical reaction), immediately disconnect it from the circuit and isolate the battery by placing it in a container or metal container, e.g. bucket, pan, etc. It is better to extinguish the fire with a powder fire extinguisher for class D fires (metal burning), carbon dioxide fire extinguisher, fire blanket (tarpaulin), earth or sand. Inhalation of combustion products should be avoided as they are toxic.

In case of injury, provide first aid and call a doctor. Until the doctor arrives, provide assistance based on the condition of the injured person.

4.5 Ensuring safety when working with means of destruction

Personnel who have mastered the safety requirements for handling live grenades are allowed to work with RGD-5, F-1, RGO live grenades from a mini-UAV.

Personnel who have successfully completed training for use and firing of the RPG-7 grenade launcher and who have mastered the safety requirements for handling the head part of the PG-7B round are allowed to work with PG-7B rounds fixed on UAVs.

Note: Grenades, shot and other explosive devices should be protected from strong shocks, impacts, fire, dirt, dampness.

When conducting classes:

– Before loading, inspect the grenades and fuses, and if any malfunctions are found, immediately report to the drill leader (commander);

– insert the fuse only before loading the grenade into the dump system;

– load the grenade into the ejection system, check that the bottom cover is closed and held in place by the servo clamp;

– through the holes in the discharge system, unclench your hands and pull the pin. Do not:

– disassemble live grenades and repair malfunctions in them, carry grenades out of their bags (hooked on the ring, safety pin), as well as approach without command and touch unexploded grenades;

– to use grenades that have external damage;

– be on the launch pad during the launch of the armed UAV;

– to launch an armed UAV by hand.

If a loaded grenade has not been dropped from the drop system, the UAV's airspeed must be increased to increase the grenade's descent inertia.

In case of mine-explosive injuries it is necessary to immediately provide first aid and call a doctor. Until the doctor arrives, provide assistance based on the condition of the victim.

Control questions

1. What components are required to assemble a mini-class UAV?
2. FPV drone assembly procedure.
3. The purpose of the OSD board.
4. Why is carbon fiber the recommended material for mini-class UAV frames?
5. What are the main tabs for UAV configuration in the BetaFlight program menu, their purpose?
6. What is the purpose of the Failsafe mode?
7. Which channel is the parking mode (ARM) tuned to?

8. What are the procedures for tethering the drone to the control panel?
9. Where are the safety requirements for handling an FPV drone covered?
10. Rules for handling batteries during assembly and preparation for flight.
11. What is prohibited when working with defeat devices?

5 PILOTING FPV DRONES IN A SIMULATOR

Simulator programs are used for FPV drone operator training. They allow you to gain piloting skills without the risk of losing the UAV and wasting its flight life. At the same time, they help operators learn how to work with the UAV controls without the presence of the UAV itself. A flight on a simulator can be made in any weather, there is no need to obtain permission to use the airspace, and there are no restrictions on the flight time on the battery. Simulators are used by both beginners and professionals to maintain and improve their skills.

The best programs for FPV drone operator training are such simulators as: LiftOff, Velocidrone, FPV Freerider, DRL 3.0, FPV Air 2, Uncrashed: FPV Drone Simulator, DJI Flight Simulator, Zephyr Drone Simulator. The simulators differ from each other by realization of flight model, which takes into account aerodynamics and dynamics of UAV flight, presence of multiplayer (possibility to fly on one map of several participants) and map editor, type of supported operating systems. The most popular simulator is LiftOff, which stands out for its realistic graphics and flight model, a large number of tracks and UAV models, as well as the ability to change their components and settings [18].

5.1 Software interface and features

You will need the following equipment to work on the simulator:

– ground equipment of FPV system - remote control, helmet (optional), wires for connecting the remote control to the computer (USB, micro USB, Ture-C);

– computer (laptop) with software (simulator). Let's use the LiftOff simulator as an example.

There are two options for connecting the control equipment to the computer:

– directly by cable (USB, micro USB, Ture-C) or through a special adapter (Figure 5.1);

– by connecting the control equipment transmitter to the simulator via PC and receiver (Figure 5.2).

Modern FPV helmets or goggles are connected to a computer via HDMI cable. The image from the computer monitor is duplicated on the FPV helmet screen.

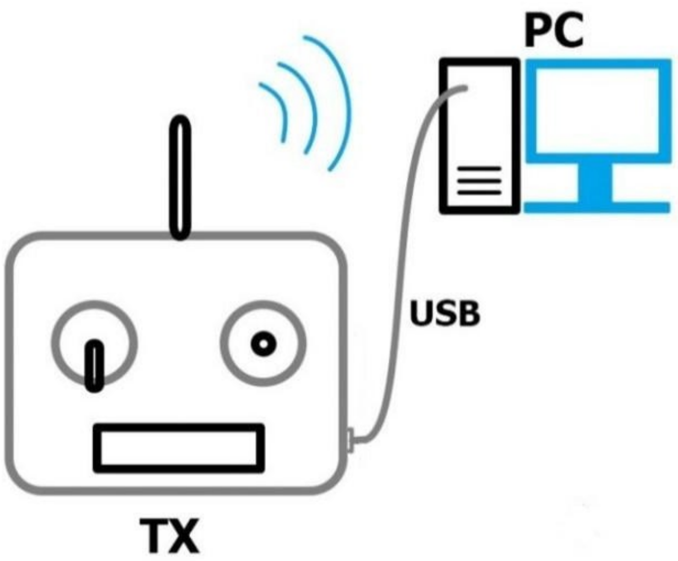


Figure 5.1 - Connection diagram of FPV drone operator training equipment via cable

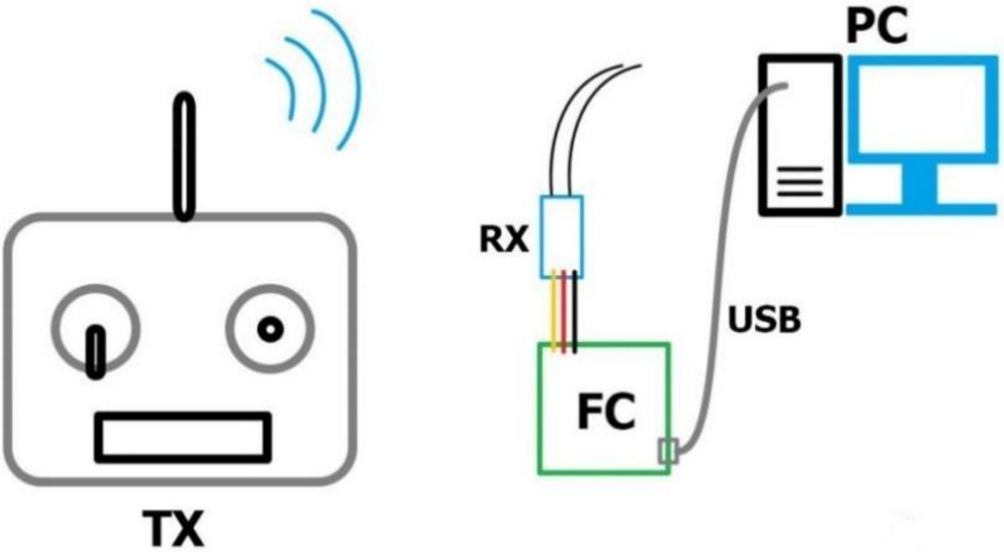


Figure 5.2 - Connection diagram for FPV drone operator training via flight controller

For training on simulator need perform the following steps:

1. Install the LiftOff simulator from the included distribution (if not installed).
2. Turn on the control panel (equipment).
3. Connect the USB Type-C cable first to the computer, then to the remote control connector.
4. Select "USB Joystick (HID)" mode in the remote control menu.
5. Launch the simulator by the shortcut.
6. B menu simulator select OPTIONS → CONTROLS → CONTROLLER (Figure 5.3).

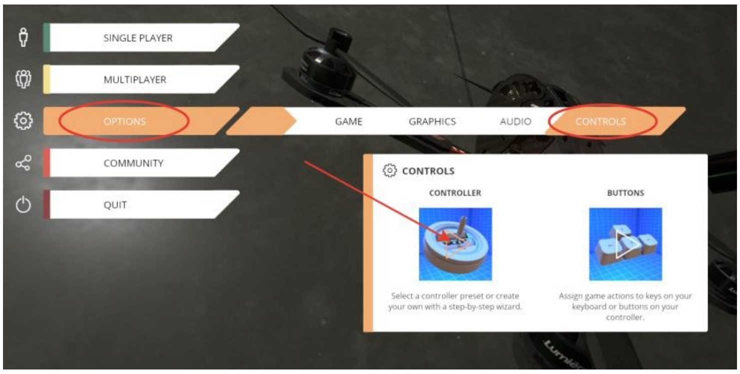


Figure 5.3 - CONTROLS menu of the LiftOff simulator

7. In the menu that opens, select SELECT →Select the model of the remote control connected to the PC (for example, Radiomaster TX12 Joystick model) → Save (Figure 5.4).

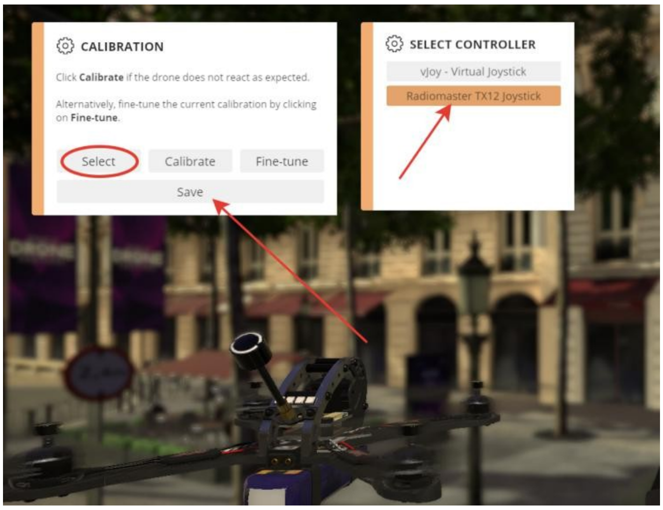


Figure 5.4 - SELECT CONTROLLER menu of the LiftOff simulator

8. Then press Calibrate → Start calibration, follow the prompts on the screen (move the control sticks according to the prompts on the screen) → Save (Figure 5.5).

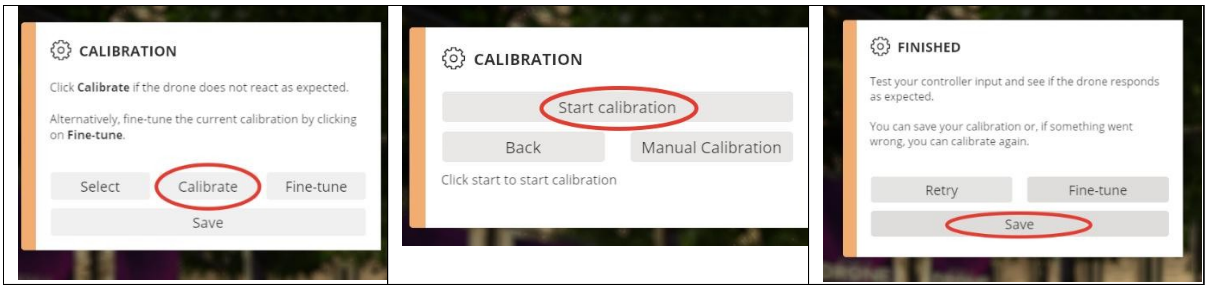


Figure 5.5 - Menu "CALIBRATION" of the LiftOff simulator

9. Return to the main menu.
10. Select Single Player → WORKBENCH and click on the opened picture with a copter (Figure 5.6).

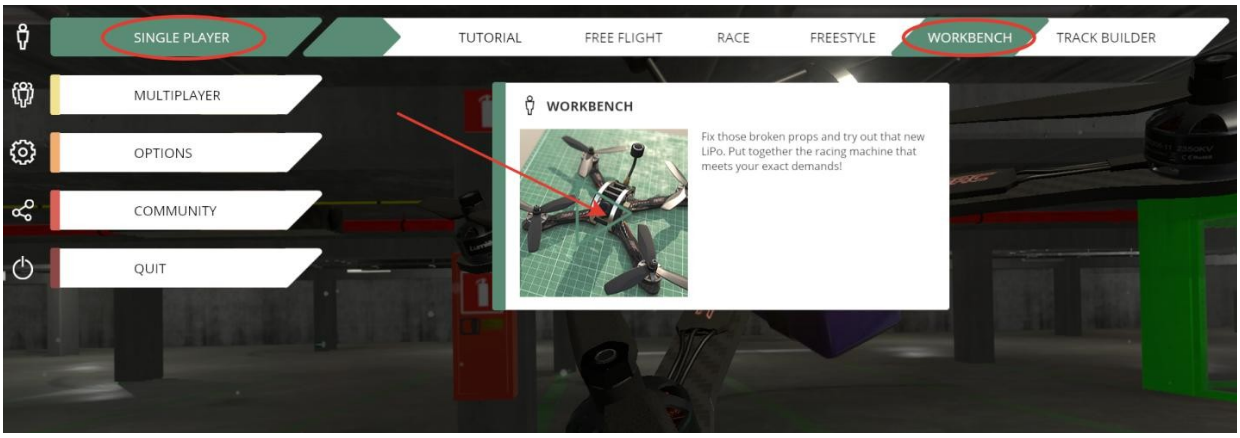


Figure 5.6 - WORKBENCH menu of LiftOff simulator

11. Select the BLUEPRINTS item (Figure 5.7).

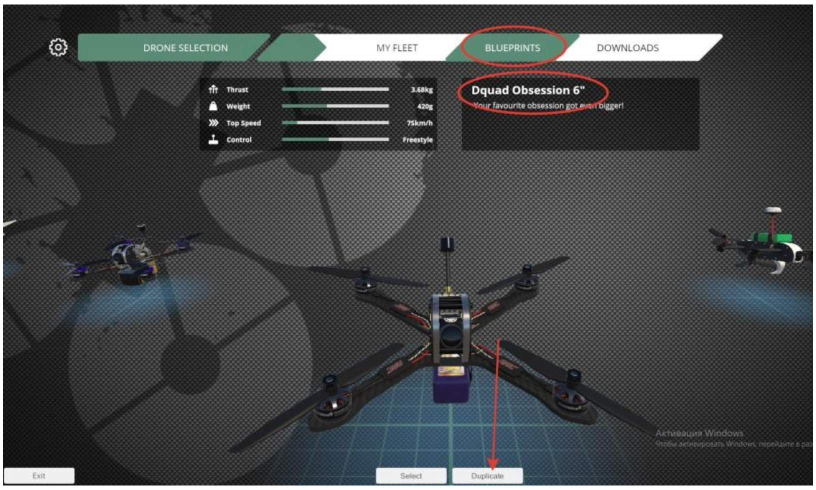


Figure 5.7 - Menu "BLUEPRINTS" of the LiftOff simulator

12. Arrows keyboard arrows select model of the quadcopter "Dquad Obsession 6"."
13. Click Duplicate→ OK at the bottom.
14. Press Select at the bottom (Figure 5.8).

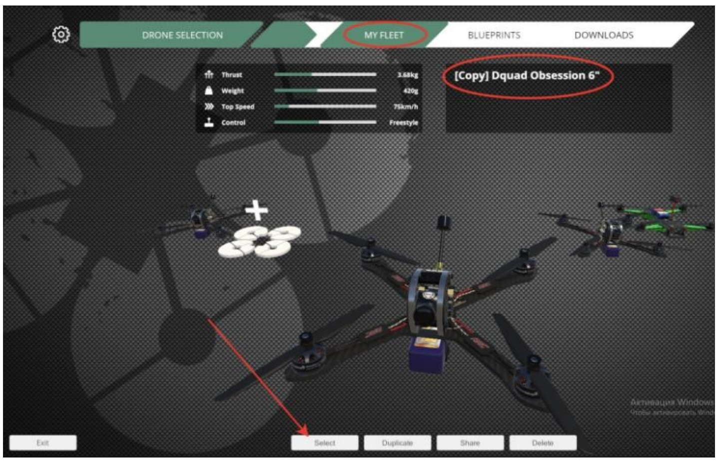


Figure 5.8 - MY FLEET menu of the LiftOff simulator

15. In the window that opens, click Edit Flight Controller Settings at the bottom right (Figure 5.9).

Figure 5.9 - EDIT DRONE menu of LiftOff simulator

16. Set the RC Rate and Super values as 1.00 and 0.60 for all three lines (Figure 5.10).

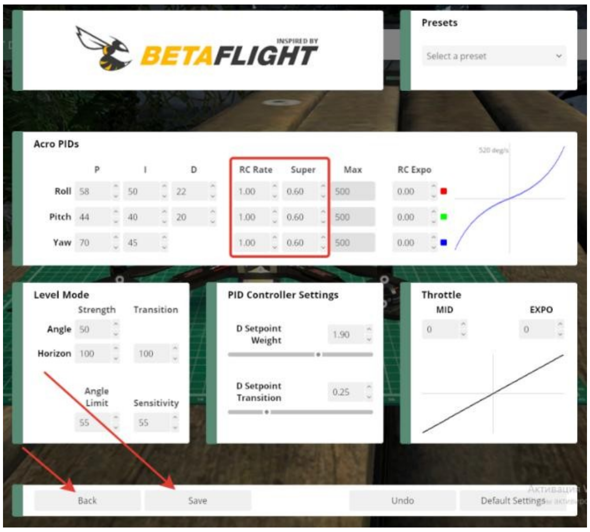


Figure 5.10 - Edit Flight Controller Settings menu of LiftOff simulator

17. Click Save→ Back.
18. On the right side of the Drone Name line write "Main" (Figure 5.11).

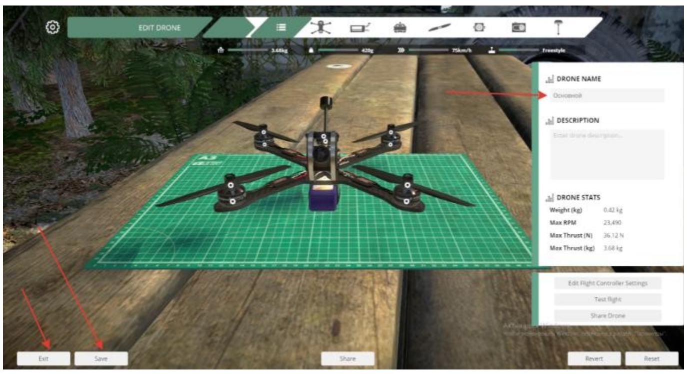


Figure 5.11 - EDIT DRONE menu of LiftOff simulator

19. Click Save→ OK→ Exit.

The modes in which the FPV drone can be in:

– power's off;

– parking mode (DISARMED): power is connected, motors are off, video is broadcast, UAV does not respond to control signals (no control output to motors, flight controller sees the signal);

– Flight mode (ARMED): motors are on and the UAV is responding to control signals.

UAV control modes:

– ANGLE mode: the copter automatically returns to the horizontal position in the absence of deflection signals, the maximum tilt angle of the copter is limited. This mode is usually called "STABILAZE" in simulators;

– HORIZON mode (HOR): the copter automatically returns to the horizontal position in the absence of deflection signals, but the angle of inclination of the copter is not limited, the copter can flip;

– ACRO (AIR) mode: the copter maintains its tilt in the absence of deflection signals [7].

To *control the FPV drone model in the simulator*, you use the remote control for 3 axes and throttle, and use the keyboard for everything else.

Main buttons involved (English layout): R - restart flight;

A - switch flight modes; T - rewind
time;

F - switches the video mode;

C - enable/disable simulation of video communication quality (FPV goggles simulation);

V - switch the view to third-person view; B -
switch the view to operator view;

↑ and↓ - changing the camera angle;

← and→ - change camera focal length (angle of view); ESC - call
the menu.

The UAV control screen in the simulator is shown in Figure 5.12:

Figure 5.12 - UAV control screen in LiftOff simulator

The following information is displayed on the UAV's control screen:

– flight mode;

– compass;

– aerial horizon;

– "Sighting" - the direction of the longitudinal axis of the copter relative to the artificial aerial horizon line;

– altitude relative to the takeoff point;

– traveling speed (relative to the ground).

By as refinement piloting skills piloting skills It is possible to increase the complexity of the flight task by changing the map.

Approximate increase in difficulty by map:

- map 8 "hannover" (Hannover) track 1;
- map 1 "field" (Straw Bale) track 1;
- map 2 "forest" Pine Valley) tracks 1, 2;
- map 4 "garden" (Autumn Fields) track 1;
- map 1 "field" (Straw Bale) track 2, 3;
- Map 10 "The Pit";
- card 11 "golf" (The Green);
- map 8 "hannover" track 2;
- card 12 "hall" (Hall 26);
- map 5 "hangar" (Hangar C03);

Medium difficulty maps: LiftOff Arena tracks 3, 2; Dubai Legends; Bardwells Yard

. More difficult maps: 4 "garden" (Autumn Fields) track 2; LiftOff Arena track 1. The most difficult maps: Paris Drone Festival tracks 1 and 2; Minus two tracks 1 and 2. ***General recommendations for FPV drone operator on piloting:*** Keep hands hands relaxed, tension в hands only reduces stick positioning accuracy and, as a result, makes flying less predictable.

It is forbidden to make sharp stick movements. The more sharply and forcefully you move the stick, the faster the engine speed and rotation speed of the drone in one or another axis will change. At the beginning of training, you should move the sticks constantly, but do it very slowly and smoothly. This way the trainee will learn to feel the copter itself faster, and further its behavior will be more predictable. You should be especially careful when moving the throttle stick.

The main thrust of the copter is on the vertical axis, so the main influence on the change of the velocity vector is the change of the vertical axis direction and the movement of the throttle stick.

Rotating the copter along the yaw axis slightly affects the direction of its movement. To turn the copter correctly, it is necessary to deflect the stick not only along the yaw axis, but also along the roll axis. The stick movement is performed *simultaneously* and smoothly.

Fixed radius turning maneuver in ACRO mode requires *to* use both sticks *at the same time.* To turn left: roll to the left, pitch to self, yaw to the left, throttle away. To turn right: roll to the right, pitch to self, yaw to the right, throttle off.

As the copter tilts, the vertical thrust vector decreases and the horizontal thrust vector increases, so you need to add throttle to maintain altitude when maneuvering.

When flying in open terrain, in most cases, flying sharply upward is sufficient to avoid a collision and subsequently regain equilibrium [14].

To brake, you do not remove the throttle, but tilt the copter in pitch to brake The stick is moved "toward you" and the throttle is added, then the throttle is reduced and the horizontal position is returned. Move both sticks in a coordinated manner.

To gain FPV drone control skills, you need to practice your control skills in a simulator.

5.2 Execution exercises "Takeoff. Holding Altitude. Straight-line flight. Turns. Landing."

The purpose of the exercises "Takeoff and altitude hold. Straight-line flight. Turn. Landing" are to acquire and improve the following skills:

1) Smooth Landing;
2) Altitude Retention;
3) Turn with altitude hold;
4) Maintaining a straight flight path.

Exercise #1 "Maintaining altitude in HORIZON or STAB mode".

To perform this exercise, we recommend Map #1 "field" (Straw Bale) without a track (Free Flight), in HORIZON or STAB mode, make a climb, descend to one meter and, holding the altitude, keep the drone at one point, not allowing a shift in the sides of more than 2 meters and changes in altitude of more than fifty centimeters for 10 seconds.

The objective of this exercise is to develop the student's ability to hold the UAV position at a given point for ten seconds, in HORIZON or STAB mode.

The criterion for exercise #1 is a successfully completed mission with no contact with the underlying surface and no damage to the UAV.

Exercise No. 2 "Flying straight sections with turns in HORIZON or STAB mode".

The following map is recommended for the exercise (Map 1 "Field" (Straw Bale) without a track (Free Flight), in HORIZON or STAB mode fly around the field along the fence at any height clockwise or counterclockwise, deviating from the straight line direction of the fence by no more than 3 meters.

The task of exercise No. 2 is to develop the operator's skills in changing the flight direction, as well as in maintaining a straight flight path of the UAV [19].

The criterion for Exercise #2 is a successfully completed mission in which the operator did not make contact with the underlying surface or damage the UAV.

Exercise #3 "Maintaining altitude in ACRO mode".

To perform this exercise, we recommend Map 1 "Field" (Straw Bale) without track (Free Flight), in ACRO mode, make a climb, descend to 1 meter and, holding the altitude, fix the drone at one point, not allowing a shift in the side more than 2 meters and change in altitude more than 50 centimeters within 10 seconds.

The objective of this exercise is to develop the trainee's ability to hold the UAV position at a given point for 10 seconds in ACRO mode.

The criterion for exercise #3 is a successfully completed mission with no contact with the underlying surface and no damage to the UAV.

Exercise No. 4 "Flying straight sections with turns in ACRO mode".

For this exercise we recommend Map 1 "Field" (Straw Bale) without track (Free Flight), in ACRO mode fly the field along the fence at any height clockwise or counterclockwise, deviating from the straight line direction of the fence by no more than 3 meters.

The objective of exercise #4 is to develop the operator's skill in operating the UAV in ACRO mode.

The criterion for Exercise #4 is a successfully completed mission in which the operator did not make contact with the underlying surface or damage the UAV.

Exercise No. 5 "Flight along straight sections with turns with altitude control in ACRO mode".

To perform this exercise it is recommended that Map 1 "Field" (Straw Bale) without track (Free Flight), in ACRO mode, fly around the field along the fence (deviating from the straight line direction of the fence by no more than 3 meters) with maintaining a constant altitude (raising the UAV no higher than 20-15- 10-5 meters above the fence) clockwise or counterclockwise, without exceeding a speed of 20 km/h.

The objective of exercise #5 is to develop the operator's skills to change flight direction and to fly the UAV in a stable and controlled manner.

The criterion for Exercise #5 is a successfully completed mission in which the operator did not make contact with the underlying surface, exceed the speed limit, or damage the UAV.

After the above exercises, when the UAV control skill is developed, the landing is practiced (low-speed approach to the launch point and smooth descent to touchdown) [19].

5.3 Execution of exercises "Overcoming an obstacle course. Flight in a confined space. Funnel. Landing inside the house."

The objectives of the exercises are:
- improving piloting skills;
- acquiring skills of flying in confined spaces;
- obstacle course.

The obstacle course exercises are performed in ACRO mode after acquiring primary UAV piloting skills.

Exercise No. 6 "Overcoming an obstacle course".

For this exercise we recommend map 2 "Forest" (Pine Valley) track #1, passing the track in "Race" mode.

The task of exercise No. 6 is to fly along an optimal trajectory with overflight of small obstacles.

The criterion for completing the exercise is that the mission is successfully completed without touching the underlying surface or damaging the UAV. During the pass, it is allowed to gain altitude to avoid collision with obstacles and then return to the trajectory.

Exercise No. 7 "Flight in a confined space".

For this exercise we recommend the map "Minus two" track 1, in ACRO mode perform takeoff, fly around the map boundary, land at the takeoff point.

The objective of Exercise 7 is to develop the operator's skill in closed-loop control.

The criterion for completing the exercise is the absence of operator confusion when controlling the UAV in confined spaces, as well as the absence of UAV damage and contact with the underlying surface.

Exercise #8 "Funnel."

Circumnavigate the tree in the center of the field on the Autumn Fields map
The objective of exercise #8 is to keep the tree in sight for several turns.

Exercise #9, "Planting Inside the House."

task is to land inside the house through a window on the Autumn Fields map and then take off and fly back through the same window.

Control of the acquired skills takes place in the presence of the instructor, the trainee is obliged to perform independently:
- connection of the operator control panel to the "LiftOff" simulator;
- perform exercise No. 3 "Maintaining altitude in ACRO mode";

– perform exercise No. 5 "Straight-line flight with altitude control in ACRO mode";
– perform exercise No. 6 "Overcoming the obstacle course";
– performing exercise No. 7 "Flight in a confined space".

It is recommended to select "Race" from the top menu bar to improve your skills and further training.

6 FPV DRONE PILOTING

6.1 General recommendations on control FPV drone. FPV drone flight under the control of an instructor

The flight on a real FPV drone is allowed to persons who have passed the operator training course and successfully passed the test for knowledge of the theory of UAV design and equipment, as well as confirmed the presence of stable practical skills of FPV drone control on the simulator.

Before starting the flight, the operator must:

– Visually inspect the equipment for damage;
– Charge the batteries of the FPV drone, goggles and remote control;
– install the remote control antenna;
– install the eyeglass antenna;
– turn on the remote;
– to turn on the glasses;
– install the battery in the copter and it in;
– to wear glasses;
– set the desired flight mode.

To perform a flight, the following steps must be performed:

– check the position of the left stick (throttle to minimum);
– switch parking mode to ARMED;
– gently push the left stick away from you until the UAV is off the ground;
– try to avoid sharp jerks of the sticks;
– try to keep your hands relaxed;
– to land the UAV at the desired point and smoothly reducing altitude and speed, near the ground, enter the parking mode (DISARMED).

Advice to the FPV drone operator in case of battery discharge, accidents and collisions with obstacles:

– if in during flight in center of the screen the following message is displayed "LANDING NOW" is required to land the UAV immediately, as the battery will spontaneously shut down after a few seconds due to discharge;

– If the drone cannot be kept in the air after a collision, the UAV should be switched to the parking mode (DISARMED) as quickly as possible to preserve the equipment;

– if the end point of the copter's fall allows you to take off, then follow the "flight" algorithm;

– If the UAV has fallen in upside down position, check throttle position, switch mode to (DISARMED), after which turn on mode. When the copter is in "turtle" mode (ground flip mode), return the mode (ARMED) and use the right stick to give a control signal to flip the copter. After

The flip is switched back to the DISARMED mode, then to the ARMED mode, and then proceed according to the "flight" algorithm;

– if it is impossible or undesirable to turn the copter over by yourself, place the copter in a convenient place for takeoff and follow the "flight" algorithm;

– If it is not possible to visually locate the place where the copter was dropped, the "beeper" mode should be activated to facilitate the search for the UAV;

– If the copter is disabled after a fall, you should review the recording from the goggles and try to reconstruct the copter's flight path to make it easier to find it;

– If after the crash, the image disappears and reappears and the copter does not respond to control signals, you should turn off and on the power to the copter. It is also possible that the battery is discharged and you need to connect another one.

For the novice FPV drone control operator, it is essential to understand the difference between the two most commonly used flight modes:

Angle (STAB) is a stabilized flight mode, which is most often used during initial learning to fly a quadcopter. In this mode, the stick deflection (roll/pitch) controls the roll and pitch angle values. In this mode, you cannot flip the quadcopter 360 degrees in the pitch or roll axis as in ACRO mode. In Angle mode, you can release the pitch/roll stick and the copter will automatically return to a horizontal position. This mode does not affect the yaw rotation of the drone.

ARCO - this is a flight mode in which the stick deflection (roll/pitch) is determined by the copter rotation speed along the selected axis. If you release the stick in this mode, the copter will not return to the horizontal position as in Angle (the copter will continue moving with the previously selected parameters) [10].

In addition to the recommendations for FPV drone piloting in the simulator, the following features should additionally be taken into account for real flights.

The behavior of the copter in reality and in the simulator is different. The simulator gives a general understanding of how the copter is controlled and how it reacts, while when flying in reality, all physical laws that are not realized or not perfectly realized in the simulator apply to the copter [12].

There is no wind in the simulator, which makes controlling the copter much more difficult. However, the heavier the copter is, the weaker it is affected by the wind. Sophisticated heavy copters can compensate for the effect of wind in some limits, but have their own limit of use by weather conditions.

When flying in open terrain, flying sharply upwards is usually sufficient to avoid hitting an obstacle.

Braking requires you to tilt the copter in pitch rather than retracting the throttle

"If you are using the sticks, you can use both sticks in a coordinated manner. Move both sticks in a coordinated manner.

The tilt of the camera affects the "comfort" of flying at different speeds. The smaller the angle, the easier it is to fly at low speed, the larger the angle, the easier it is to fly at high speed. In most copters the camera is set at 30-45°, but for initial training and skill development you can set it at 15°. There are copters where the camera is set at 60-70° to maximize flight speed. It should be noted that the higher the camera angle, the more difficult it is to land/take off as visibility in the lower hemisphere is limited.

Flying a copter in small enclosed spaces (indoors) requires smoother handling of the sticks, sudden movements may cause a collision.

When the copter approaches a vertical wall, a sticking effect is created and the copter is "pulled" by the front of the copter to the wall, and the efficiency of the motors drops.

The behavior of a copter with a suspended payload differs significantly from that of a copter without payload due to the increased inertia and the higher level of thrust required to maintain altitude. The weighted copter accelerates and decelerates less, and the amount of thrust available is inversely proportional to the increased total weight of the copter.

Flying a copter over long distances in open terrain requires the ability to navigate visually.

When flying over terrain, it is necessary to consider not only the distance to the object you are flying to, but also the terrain. Tall houses and buildings, trees and other objects can weaken the video and control signal. Power lines and other infrastructure may not be visible to the camera and collision with them may result in a crash.

Always study the terrain on the map before the flight, memorize large objects that will be easy to see from the air, this will help to orient yourself in space. After takeoff you should look around and fix some reference objects (landmarks), relative to which you will move, for example, a water tower or a large distance among trees in a forest area. This is necessary in order not to get lost when flying to the object or returning "home".

If you approach a large object or terrain, you may lose the video signal but retain control. In such a situation, you should switch the copter to ANGLE mode and gain altitude to improve communication conditions. To avoid such situations, you should try to maintain altitude to achieve a reliable reception signal. Remember: the farther the operator is from the copter and the lower the copter is flying relative to the copter, the easier it is to lose the video and control signals, so you should always choose the most direct flight path to the object so that the loss of signal does not prevent you from completing the task.

6.2 Self-control of FPV drone. Performing the exercise "Takeoff. Flight along the route. Landing". Flight analysis

The FPV drone self-piloting lesson is conducted in the following sequence:

– Checking the functionality and pre-flight preparation of the UAV, console and FPV goggles (helmet);

– performing various exercises, namely: takeoff; keeping the UAV at altitude; turning in place; forward, backward, right, left movements; landing;

– Initial flights on a 3-inch mini-class UAV.

Preparing for independent operation on an FPV drone involves performing the following activities:

1. UAV equipment inspection.
2. Turning on the FPV goggles of the UAV.
3. Turning on the UAV control panel.
4. Enabling the BPLA.
5. Pairing the remote and goggles with the UAV.
6. Removing the lock on the helmet and on the UAV.
7. Perform basic UAV settings in the Betaflight Configurator program (in accordance with Section 4.2).

Before the flight, allocate video and radio channels to the trainees if multiple drones are used. Set the frequency of the video signal in helmets and UAVs.

In the course of training, the operator is required to acquire the skills to set up the equipment independently.

The first flights are conducted visually without the use of goggles (helmet) in order to visually observe the quadrocopter to fix the lift-off point from the ground and control roll, pitch and yaw angles. Exercises performed after the operator has adapted to the control: turns around its axis, forward/backward movements/landing;

After the operator has acquired the necessary visual piloting skills, the operator will begin a goggle exercise in a 3-inch mini-class UAV. The exercise is conducted to gain first person control skills.

Piloting exercises are conducted until the trainees achieve the following indicators: smooth movement of the UAV in space without bouncing, confident holding of the UAV at altitude, smooth landing, holding the mini-class UAV at minimum altitude before landing.

Piloting on rough terrain with terrain envelopment.

Cross-country piloting is initially conducted on a 5-inch mini-class UAV. After acquiring the skills to fly a 5-inch mini-UAV and the trainees have achieved the established indicators are flown on a 7-inch mini-class UAV with a drop system.

Note: TNT, RGD-5, F-1, VOG-17, etc. are used as payloads for mini-class UAVs.

During cross-country piloting, trainees perform the following exercises:

Figure *8* - takeoff from the starting point, flight along a pre-designated route around obstacles with turns in the figure "figure eight", return to the starting point (3-4 circles), landing (Figure 6.1).

Figure 6.1 - Exercise "Eight"

Obstacle avoidance - take-off, flight along the route with rounding and coming behind natural obstacles (trees, bushes) from the left and right sides, return to the starting place and repeated flight (3-4 circles), landing at the starting point (Figure 6.2).

Figure 6.2 - Terrain obstacle avoidance exercise

Flight along the trajectory with height retention - takeoff, flight through the frames (set one after another at a distance of three or four meters from each other with different height and width of the aperture) with retention, turn on an open area and return to the starting place with a repeated spanning through frames. To to complicate exercises frames can can be arranged in random order (Figure 6.3).

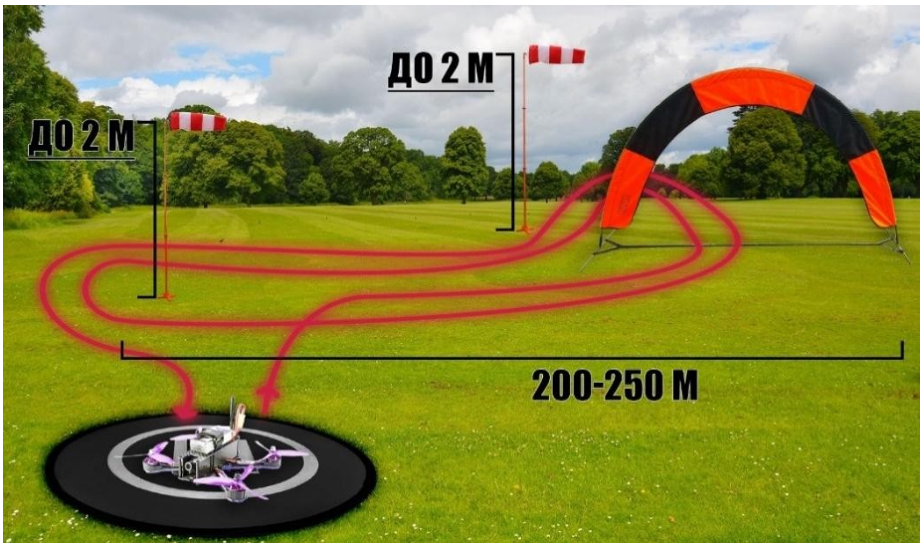


Figure 6.3 - Exercise "Flight along the trajectory with altitude hold"

Flight into a building or enclosed space - takeoff, flight to a building, flight into a building through an opening, turn inside an enclosed space, departure. During the exercise inside the building, the instructor must demonstrate the possibility of radio wave propagation and re-reflection effects, for this purpose the trainees set the video transmitter power (VTX) to minimum (Figure 6.4).

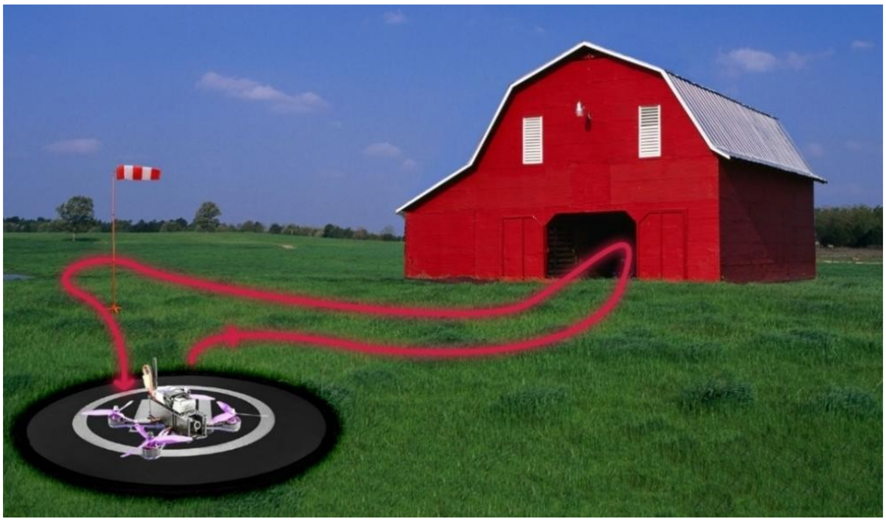


Figure 6.4 - Exercise "Flight with a turn in a confined space"

6.3 Final control of training

In order to check and evaluate the level of theoretical knowledge and practical skills in the field of FPV-drones and rules of their operation, students pass tests.

The credit is a complex lesson divided into two stages. The first stage is the entrance control of theoretical knowledge, the second stage is the control of practical skills. It is recommended to conduct the test on the target situation equipped with target situation (trenches, shields, obstacles, target designation circles).

The second stage includes a test of readiness to fly, which consists of ensuring that the trainees are not stiff or confused when operating the UAV, especially when faced with a complex situation.

Initial control skills are monitored by three exercises:

Exercise No. 1 - Keeping the UAV at altitude; Exercise No.

2 - Straight-line flight at low altitude Exercise No. 3 - Flight

for combat use.

Exercises are performed in simple meteorological conditions from a prepared site. The flight route must pass through characteristic landmarks.

Exercise #1: Keeping the UAV aloft.

Number of directorates - 1.

The time to perform the exercise is 1 minute.

Flight task:

The UAV ready for operation is positioned at a distance of 5 meters from the control operator on the launch pad. The control operator in visual mode (without FPV goggles) should take off and hold the UAV at a height of 2 meters for 1 minute.

The criterion for this exercise is to hold the UAV at a point with a deviation of no more than 0.5 meters. The quality control of the exercise is performed by two training instructors and the control time is timed using a stopwatch.

If the student successfully completes exercise #1, he/she is allowed to perform exercise #2.

Figure 6.5 - Exercise #1

Exercise No. 2: Straight-line flight at low altitude.

Number of directorates - 1.

The time to perform the exercise is 5 minutes. Flight task:

The UAV ready for operation is positioned at a distance of 5 meters from the control operator on the launch pad. The control operator performs the flight on a rectilinear trajectory at a height of no more than 1.5 meters from the ground with a deviation of no more than one meter horizontally for the time being. The flight is to be performed along the route, along the predetermined landmarks (trench, road, stretched tape) with a 180 degree turn at a given point and landing at the take-off point.

The criterion for this exercise is a successfully completed flight that eliminates contact between the UAV and the underlying surface and maintains a straight trajectory within the specified time.

The exercise is controlled visually by two training instructors.

If the student successfully completes exercise No. 2, he/she is allowed to perform exercise No. 3.

Figure 6.6 - Execution of exercise #2

Exercise No. 3: UAV combat mission flight

Number of directorates - 1.

The time to perform the exercise is 10 minutes. Flight task:

A UAV ready for operation, equipped with a payload (e.g., a life-size mock-up of an inertial munition) is positioned at a distance of 5 meters from the control operator on the launch pad. The control operator receives a mission to engage a ground object at a distance of about 500 meters, analyzes the capabilities of the UAV, assesses the current air (ground) situation, and, at the instructor's command, begins to perform the mission. Performs takeoff, flies to the target, identifies landmarks near the target, raises the UAV to altitude 50 - 100 meters with simultaneous departure from the target at 350-400 meters. At the instructor's first command, perform a dive to the target, then, on at the second command, takes the vehicle out of dive and lands (Figure 6.5).

The criterion for this exercise is a successfully completed flight, target approach and landing of the UAV, excluding collision with the ground surface, loss of control, operator confusion and loss of the UAV. Quality control of the exercise is performed by two training instructors using a second set of FPV goggles; the control operator completes the exercise (approach to the target) at the instructor's command "Take out".

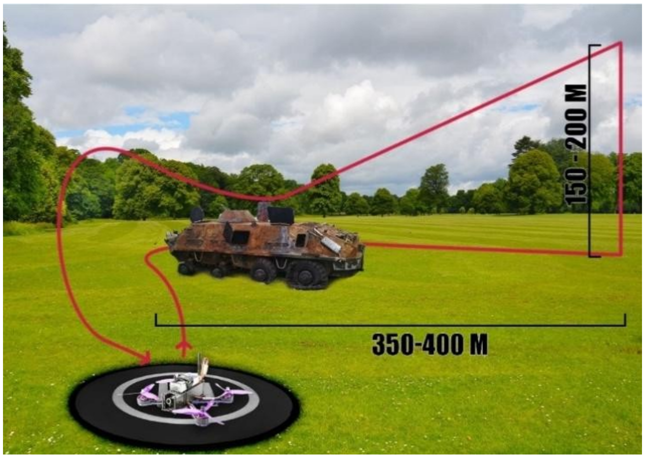


Figure 6.7 - Execution of exercise #3

The instructor, based on the results of passing the test and performing the exercises, decides on the completion of training and admission to independent driving in the calculation.

6.4 Safety precautions in preparation for flight, before takeoff and after landing

A large open space, preferably grassed, shall be selected by the course leader for the training flights. At the time of training, the piloting area should be away from buildings, power lines, cell towers, crowded places, railroads and highways, any sources of signal or electromagnetic radiation. A level area at least three meters away from obstacles should be selected for takeoff.

The trainees are obliged to follow the commands and requirements of the instructors.

The head of the class has the right to suspend students for health reasons in case of indisposition (dizziness, nausea, fever, profuse sweating).

All work on the UAV must be carried out with the battery disconnected. Connect immediately before flight.

Before you fly, you must:

– check the quadcopter for malfunctions, integrity hull, correct blade installation and integrity of propellers, engines, fastening of all assemblies, equipment and battery;

– check the charge of the UAV battery: it must be fully charged. Do not use a battery with damage, altered geometry (bloating) or bare wires;

– check the charge of the control panel;

– When connecting the battery pack, make sure that your fingers are out of the propeller rotation area;

– check that there are no error notifications (if self-diagnostic system is available);

– check the operation of the telemetry system;

– If necessary, calibrate the compass and gyroscope;

– When using GPS, make sure there are satellites available;

– Before takeoff, memorize or record the estimated flight time;

– move to a safe distance, but not less than three meters;

– perform the power-on procedure according to the drone's manual.

The UAV may take off only with the permission of the instructor (commander).

Before the UAV takes off after the launch command is given, make sure that there are no extraneous sounds on the propellers.

After liftoff from the ground, it is necessary to perform a control hover - fix the UAV at the liftoff point, stationary, at a low altitude, make sure that the engines are stable and the stick is working properly, and then you can start flying.

The UAV should be landed under the guidance of an instructor.

After landing, at the instructor's command "stop", immediately shut down the UAV using the appropriate button on the console and disconnect the battery pack.

After landing, check engines and speed regulators for overheating. If the engine or controller is hot, you should correct the fault. If the engines are hot on one side of the drone, it means that the weight is not properly distributed on the frame and the quadcopter compensates for this by increasing RPM [20].

You should also check the frame, motors, mounts for backlash. Visually inspect the board and electrical wiring.

6.5 Flight safety. FPV drone operator's actions in special cases in flight

When flying FPV drones, the operator must have an assistant "navigator" next to him, who will help to adjust the flight route if necessary, to warn about danger: the appearance of foreign objects in the flight zone, the approach of birds, animals, people, cars, the approach of the enemy and other dangers.

The following rules must be observed *when performing training flights*:

– follow all instructions of the teacher (instructor);

– fly only in the designated aerobatic zone and do not fly outside it, do not fly behind your own back;

– When performing training exercises, fly at a level below your own height;

– fly within line of sight, at a distance that allows the lesson leader (assistant) to ensure that there is no danger of collision with surrounding objects. In case of difficulty in locating and orienting the UAV, immediately land on the spot;

– When controlling the UAV, all stick movements should be performed carefully and smoothly, avoid sudden movements. If it is necessary to quickly change the direction of flight, move the sticks vigorously, but not abruptly;

– fly cautiously and perform only those aerobatic elements specified in the lesson plan. It is forbidden to perform maneuvers that may cause harm to people, animals, surrounding objects and property;

– Observe the speed limit. Keep the speed of the copter within the limits set by the exercise;

– return the UAV to the landing site by the estimated time, do not allow the battery to be completely discharged in flight. Land on a flat open area away from obstacles.

– due to peculiarities of FPV camera optics, angles and distances to objects can be perceived in a distorted form when flying with FPV goggles, so the operator should get used to the copter dynamics and peculiarities of determining the distance to objects. When learning to fly in FPV mode, it is necessary to fly cautiously at a low speed (5 - 7 km/h) at first;

– When flying at high speeds, take into account the inertia and drag of the copter to avoid collision with the ground or surrounding objects.

When flying FPV drones, situations may arise in which the UAV cannot be used for its intended purpose or is likely to be lost. These situations are referred to as special flight cases.

In difficult meteorological flight conditions for which the UAV is not adapted, it is necessary to take all possible measures to withdraw the UAV from them and make a decision to continue or terminate the flight task, taking into account the air situation, meteorological conditions and remaining battery power [18].

Propwash (propwash) is a critical flight mode, similar to the vortex ring mode in a helicopter, which develops during a sharp 180-degree turn, or during an attempt to sharply reduce vertical speed during a rapid descent of the quadrocopter with low translational speed. The mode is characterized by "thrust failures", the drone starts to vibrate and "kick" with a "low speed".

with a distinctive sound - not enough engine thrust to avoid a fall.

In order to avoid turbulence phenomena, it is not recommended to bring the UAV sharply out of a dive and perform turns with extreme overloads. When descending vertically at high vertical velocity, the throttle should be increased smoothly [6].

The following recommendations are more relevant for training UAVs, since a combat drone is more likely to be triggered by its payload if it crashes or hits an obstacle.

If a fire occurs in flight, if control is still possible, land the drone in a safe place, away from the crew, on a non-combustible surface. If the fire has occurred on the ground, allow the battery to burn out, if necessary, prevent the flames from spreading with a fire extinguisher, fire blanket and other improvised means.

If the communication system fails, the position of the vehicle at the time of loss of communication, its speed, altitude, flight direction, residual battery charge and flight time should be recorded. If communication with the vehicle is not restored after the estimated remaining flight time, measures should be taken to search for the vehicle [19].

In case of a sudden voltage drop on the flight controller, engine power reduction, failure of other equipment, take all measures for emergency landing of the UAV, excluding free fall of the vehicle [20].

In the event of a fall, immediately disconnect the battery from the UAV's onboard power supply and inspect it for damage, swelling, or fire. If there is heat, smoke or flame from the battery, do not touch the UAV with your hands without flame retardant gloves.

Control questions

1. What is prohibited during training flights?
2. Name action operator when hit FPV drone in meteorological conditions in which the UAV is not intended to operate.
3. What is the phenomenon of turbulence?
4. What actions should an FPV drone operator take when the drone loses power?
5. What actions should an FPV drone operator take when the communication system fails?
6. What actions should an FPV drone operator take in the event of an aerial fire if control is possible?
7. What actions should an FPV drone operator take in the event of a ground fire?

7 REGULATORY REGULATION B UNMANNED AIRCRAFT SYSTEMS

The main normative legal acts in the field of ABC:

The main document defining the norms of air legislation of the Russian Federation is the Air Code of the Russian Federation, which is adopted by the State Duma. In accordance with this document, federal rules for the use of airspace and federal aviation rules are developed and approved in accordance with the procedure established by the Government of the Russian Federation.

All regulatory legal acts applied in the Unified System must ensure a unified authorization procedure for airspace use, a system of state priorities, unified rules, standards, and procedures.

Federal Rules for the Use of Airspace, approved by Decree of the Government of the Russian Federation No. 138 of March 11, 2010, are developed in accordance with the Air Code of the Russian Federation and establish the procedure for the use of airspace of the Russian Federation in the interests of the economy and national defense, in order to meet the needs of airspace users and to ensure the safety of airspace use.

Russian Government Decree No. 1016 of June 21, 2023 amended the Federal Rules for the Use of Airspace in the part concerning the establishment of prohibited zones, flight restriction zones and flight zones for unmanned aircraft. The Federal Aviation Rules for State Aviation Flight Operations approved by Order No. 275 of the Minister of Defense of the Russian Federation dated September 24, 2004, developed in accordance with the current air legislation of the Russian Federation and regulatory legal acts, determine the procedure for state aviation flight operations and are mandatory for all aviation formations (aviation and aviation-technical units and units, centers, etc.).

The procedure for flight operations of unmanned aerial vehicles of the Ministry of Defense of the Russian Federation is defined by the temporary rules for flight operations of UAVs approved by the Chief of General Staff of the Armed Forces of the Russian Federation - First Deputy Minister of Defense of the Russian Federation on April 18, 2013.

7.1 Fundamentals organization air traffic air traffic в Russian Federation

In order to effectively conduct practical training sessions with FPV drone operators, the instructor staff must ensure timely registration of UAVs used in the training process.

The Government of the Russian Federation of March 19, 2022 №415 amended the Rules of registration of unmanned civil aircraft with a maximum take-off weight of 0.25 kilograms to 30 kilograms, imported into the Russian Federation or manufactured in the Russian Federation, (Resolution of the Government of the Russian Federation 25.05.2019 №658), namely: "aircraft with a take-off weight of more than 0.15 kilograms are subject to registration (accounting)".

An application for registration of an unmanned aircraft as provided for in paragraph 8 of the Rules for Registration (Registration) of Unmanned Civil Aircraft with a maximum take-off weight of 0.15 kilograms to 30 kilograms imported into the Russian Federation or manufactured in the Russian Federation shall be submitted to the Federal Air Transport Agency within the following time limits:

if the unmanned aircraft was purchased on the territory of the Russian Federation - within 10 working days from the date of purchase;

in case of importation of an unmanned aircraft into the Russian Federation - within 10 working days from the date of importation;

if the unmanned aircraft is manufactured independently, before it is used to perform flights in the airspace above the territory of the Russian Federation, as well as beyond its borders, where the Russian Federation is responsible for air traffic control.

7.2 Obtaining a flight permit and flight operations

The permissive airspace use procedure is the procedure under which airspace users carry out their activities based on plans (schedules, timetables) for the use of airspace, subject to airspace use authorization.

Therefore, when flying UAVs at altitudes above the authorized altitudes, and with a mass of more than 30 kg, an airspace authorization must be obtained.

Obtaining a flight permit.

In accordance with the structure and classification of the airspace of the Russian Federation's FP IVP airspace, an authorization or notification procedure for the use of airspace is established.

The authorization procedure for the use of airspace shall be established:

a) for airspace users whose activities are not related to aircraft flight operations and are carried out on the basis of airspace utilization plans throughout the airspace of the Russian Federation;

b) for airspace users performing flights (except for activities specified in paragraph 114 of the IVP FP), as well as in

Class G airspace - for flights of unmanned aerial vehicles.

In Class G airspace, a notification procedure for the use of airspace shall be established.

In Class G - flights performed according to instrument flight rules and visual flight rules are allowed. No aircraft echeloning is performed. All flights are provided with flight information services upon request. All flights at altitudes below 3050 m are subject to a speed limit of no more than 450 km/h. Aircraft flying under instrument flight rules must have constant two-way radio communication with the air traffic service (flight control) authority. Aircraft flying under visual flight rules are not required to have permanent two-way radio communication with the air traffic service (flight control) authority.

The boundaries of airspace structure elements shall be established by geographic coordinates and altitudes. The boundaries and conditions of use of airspace structure elements shall be published in aeronautical information documents.

The organization of airspace use in the Unified System zones (areas) shall be carried out by the Unified Air Traffic Control System authorities.

The list of operational bodies of the Unified Air Traffic Management System RF approved by Order of the Ministry of Transport RF dated September 28, 2020 №1224-P with amendments as of September 27, 2021.

Airspace users flying in Class G airspace shall notify the relevant air traffic service (flight control) authorities of their activities in order to receive flight information services and emergency notification.

When planning flights in Class G airspace, airspace users must have aeronautical and meteorological information.

The use of airspace by unmanned aircraft in Class G airspace is carried out on the basis of the aircraft flight plan and airspace use permit and is carried out by establishing temporary and local regimes, as well as short-term restrictions in the interests of airspace users organizing unmanned aircraft flights (paragraph 52. of the Federal Rules for the Use of Airspace of the Russian Federation).

According to the Government of the Russian Federation decree of 03.02.2020№ 74 "On Amendments to the Federal Rules for the Use of Airspace of the Russian Federation" (paragraph 52.[1)] an airspace use permit is not required in the case of visual flights of unmanned aircraft with a maximum takeoff weight of up to 30 kg, carried out within a direct visibility during daylight hours at altitudes less than 150 meters from the ground or water surface:

a) outside the dispatch zones of civil aviation airfields, areas of airfields (helicopters) of state and experimental aviation, prohibited zones, flight restriction zones, special zones, airspace above places of public events, official sports competitions, as well as security measures conducted in accordance with the Federal Law "On State Protection";

b) at a distance of at least 5 km from control points of uncontrolled airfields and landing sites.

Thus, when flying within line of sight during daylight hours at altitudes less than 150 meters from the ground or water surface, UAVs with a take-off weight of less than 30 kg do not require an airspace use permit.

The approved lesson plan is the *basis for the UAV flight*. It is prohibited to launch a UAV without an approved lesson plan to perform training tasks.

The lesson plan is prepared by the practical training instructor and approved by the unit commander. An annex to the lesson plan is a calculation of the forces and means to be involved in the exercise, which specifies the number of UAVs required and the sequence of exercises to be performed by the UAV calculations.

The principle of safety is paramount in the conduct of exercises, and all efforts of the personnel must be directed towards its observance.

Training sessions on practical FPV drone flights include the following activities: preparing the UAV for operation, connecting and setting up the control equipment, flights and flight debriefing.

Training flights are performed in the course of practical (tactical and specialized) training.

The decision to prepare and conduct training sessions, taking into account the tasks at hand, expected weather conditions, air and ornithological situation in the flight area, the level of training of UAV crews, the state of UAV complexes, the landing site, control and flight support facilities, is made weekly by the military unit commander on the basis of the unit's training plan for the academic year.

On the basis of the decision taken, the unit commander draws up a training schedule. It specifies the time, place, personnel involved, material and technical support, as well as the tasks, standards and exercises to be practiced.

Prior to the start of the school day, the unit commander indicates:

– lesson leader (instructor), UAV observer;

– main goals and objectives of the class;

– the required number of complexes with UAVs;

– expected air, meteorological, ornithological and land (sea) conditions in the flight area;

– the procedure for preparation and use of launching and landing sites (polygons);

– the procedure for ensuring occupation: the procedure for using communication facilities, search and evacuation support of flights, use of objective control facilities;

– measures to ensure flight safety;

– the procedure for preparing UAV and UAV complexes calculations;

– time and procedure for conducting readiness control;

– time and place of targeted briefing before training sessions.

No member of the UAV crew may be authorized to operate the UAV without the necessary training and verification of its readiness to perform the flight task.

On the day preceding the class, during self-training hours, UAV calculations are pre-prepared for flight.

It includes:

– independent preparation of UAV crews for flight;

– a workout on the simulators;

– flight readiness control.

The content and duration of the preliminary training is determined by the lesson leader, depending on the novelty and complexity of the tasks to be performed, the level of training of the UAV calculations, and the capabilities of the training facilities. Most of the pre-training time should be allocated to independent training. In all cases, it should ensure that UAV crews are fully prepared for flight.

The order and duration of training of UAV crews on simulators is established by the unit commander, based on the availability of simulators and the possibility of organizing training on them.

Readiness check is the main type of UAV crew check prior to flight. It is conducted by immediate supervisors in a form that makes it possible to verify the readiness of UAV crews to perform flight tasks. The main form of control over the readiness of UAV crews for flight is the performance of a flight task on a simulator to fly a course proposed by the instructor on the simulator.

If the UAV crew is found to be insufficiently prepared for flight, the controller must organize additional training or suspend the UAV crew from flight.

The briefing of UAV crews for flights shall be conducted immediately before the start of training sessions, taking into account the specific meteorological, ornithological, air and land (sea) conditions prevailing at that time.

At the briefing, the briefing is communicated:
– start and end times of training sessions;
– actual meteorological, ornithological conditions and weather forecast in the area (on the routes) of flights;
– air, ground (sea) and navigation conditions in the flight area (routes);
– specifics of the use of communication tools;
– condition of the launch pad;
– peculiarities of flight missions and UAV operation;
– specific security measures security, based on actual weather conditions and the nature of the flight tasks.

Receiving and checking the readiness for flight of complexes with UAVs, preparation and checking of workplaces before the flight task is carried out by UAV calculations.

When conducting training sessions, the instructor informs the trainees of the training and educational objectives, training issues, the order of flight exercises, and safety precautions when working with FPV drones. One instructor may conduct a training session with no more than two crews, and only one UAV may be in the air at one training site.

When conducting training sessions, it is forbidden to take off in cases:
– if there are other UAVs or obstacles on the launch pad;
– if the UAV, engines and equipment are found to be malfunctioning;
– if the wind speed (its lateral component) exceeds the safe wind speed for this type of UAV;
– in other cases, if the safety of the takeoff is not ensured.

The debriefing is conducted at the end of the working day in order to prevent the recurrence of errors in piloting techniques, air navigation, operation of systems and equipment of the UAV complex, during the performance of flight tasks, as well as to prevent the admission of untrained UAV crews to subsequent flights.

To summarize the results are used:
– data from airborne and ground-based objective control equipment;
– reports of the UAV crew members who performed the flight task;
– results of personal observations of the inspector (instructor).

7.3 Liability for violation of airspace utilization rules

Violations of the procedure for the use of the airspace of the Russian Federation include:

(a) Use of airspace without authorization from the relevant center of the Unified System under the permissive procedure airspace utilization, except for cases specified in paragraph 114 of the FP IVP RF;

b) failure to comply with the conditions communicated by the center of the Unified System in the airspace use permit;

c) failure to comply with the commands of air traffic service (flight control) authorities and the commands of the on-duty aircraft of the Armed Forces of the Russian Federation;

d) failure to comply with the procedure for using the airspace of the border strip;

e) non-compliance with the established temporary and local regimes, as well as short-term restrictions;

(e) The flight of a group of aircraft in excess of the number specified in the aircraft flight plan;

g) using the airspace of a no-fly zone or flight restriction zone without authorization;

h) An aircraft landing at an unplanned (undeclared) airfield (site), except in cases of forced landing and cases agreed upon with the air traffic service (flight control) authority;

i) failure of the aircraft crew to comply with the rules of vertical, longitudinal and lateral echelon (except in the event of an emergency on board the aircraft requiring an immediate change in flight profile and mode);

j) unauthorized deviation of an aircraft beyond the boundaries of an air route, local air line or route by an air traffic service (flight control) authority, except when such deviation is due to flight safety considerations (avoidance of dangerous weather phenomena, etc.);

k) flying an aircraft into controlled airspace without authorization from the air traffic service (flight control) authority.

Violation of the requirements of the FP of the WUI RF shall entail liability in accordance with the legislation of the Russian Federation.

7.4 Fines for violation of the airspace utilization procedure

The Federal Air Transport Agency and air traffic service (flight control) authorities in the zones and areas established for them shall control compliance with the requirements of the Federal Air Traffic Regulations. The Code of Administrative Offenses of the Russian Federation, Parts 1 and 2, Article 11.4, defines the following types of responsibility:

1. Violation by an airspace user of the Federal Rules for the Use of Airspace, if this action does not contain a criminally punishable act, shall entail the imposition of an administrative fine:

for citizens in the amount from twenty thousand to fifty thousand rubles; for officials - from one hundred thousand to one hundred fifty thousand rubles;

for legal entities - from two hundred fifty thousand to three hundred thousand rubles or administrative suspension of activities for up to ninety days.

And if this action caused by negligence the infliction of serious harm to health or death of a person - imprisonment for a term of up to five years.

2. Violation of the rules for the use of airspace by persons not duly authorized to carry out activities related to the use of airspace, if this action does not contain a criminally punishable act, shall entail the imposition of an administrative fine:

for citizens in the amount from thirty thousand to fifty thousand rubles;

for officials - from fifty thousand to one hundred thousand rubles;

for legal entities - from three hundred thousand to five hundred thousand rubles or administrative suspension of activities for up to ninety days.

Paragraphs 1 and 2 of Article 11.5 of the Administrative Offenses Code punish negligent infliction of minor and moderate harm to health due to violation of flight clearance or flight preparation and performance rules. For citizens, the punishment is a fine of 1,500 to 2,000 rubles or deprivation of the right to operate an aircraft for a period of three to six months in the case of causing minor harm to health, and from 2,000 to 2,500 rubles or deprivation of the right to operate an aircraft for up to one year in the case of causing medium harm to health.

According to Part 5 of Article 11.5 of the Code of Administrative Offenses, flying an unregistered UAV is punishable by a fine of 2,000 to 2,500 rubles or deprivation of the right to operate an aircraft for up to one year.

In accordance with Federal Law No. 404-FZ "On Amending Certain Legislative Acts of the Russian Federation" dated 02.12.2019, the right to temporarily restrict the presence of unmanned aircraft in the airspace above the venue of a public (mass) event and the adjacent territory, as well as to prevent unauthorized presence of unmanned aircraft in the airspace, including by destroying and damaging such aircraft, suppressing or transforming remote control signals in order to protect the

- Federal Security Service;
- Home ;
- Federal Protective Service;
- Federal Penitentiary Service;
- Rosguard;
- Foreign Intelligence

Service. The law authorizes:

– The FSB can shoot down UAVs at will without any restrictions on the flight area, regardless of the availability of permits.

– The Ministry of Internal Affairs may shoot down UAVs "over the place of holding a public (mass) event and the adjacent territory, conducting urgent investigative actions and operational-search activities.

– The FSO is authorized to shoot down UAVs in order to ensure the security of State security facilities and to protect protected facilities. Without specifying territorial or other restrictions.

– The Federal Penitentiary Service may shoot down UAVs when flying over correctional facilities, detention centers and adjacent territories.

– The Rosgvardiya may shoot down UAVs in order to protect citizens, employees, protected territories, facilities, special cargoes, facilities on communications routes, the National Guard troops' own facilities, and over places where National Guard troops perform combat missions. It is not possible to precisely define the territories where an UAV may be shot down.

– The Foreign Intelligence Service has the right to shoot down UAVs when flying over the territories of their facilities.

All procedures for authorizing the destruction of UAVs are developed by the listed bodies independently. They also make decisions on destruction. Note that we are talking exclusively about the illegal, i.e. deliberate illegal and even terrorist use of UAVs for surveillance or delivery of dangerous substances to the target site.

Control questions

1. What is the penalty for violating airspace regulations?
2. What mass of UAVs must be registered?
3. Violation of which guiding documents entails liability in accordance with the legislation of the Russian Federation?
4. What are the main normative legal acts in the field of ABC you know?
5. What is the penalty for an airspace user's violation of the Federal Airspace Regulations if the action does not contain a criminal offense?
6. What punishment is provided for violation of airspace use rules by persons not duly authorized to carry out airspace use activities, if this action does not contain a criminally punishable act?
7. What is the punishment for negligent infliction of minor and moderate harm to health due to violation of flight clearance or flight preparation and performance rules?
8. What are the penalties for flying in an unregistered aircraft?

BPLA?

8 FUNDAMENTALS OF UAV COMBAT

The fundamentals of combat application of UAVs, including FPV drones, consist of knowledge on tactics of general military combat, supplemented by the theory and practice of preparation and conduct of combat by unmanned aerial vehicle (UAV) units, including in conditions of electronic and fire countermeasures. When planning and conducting combat operations, it is necessary to take into account the regularities, nature and content of combat, and the methods of its preparation and conduct.

It is important to realize that FPV drone tactics are constantly undergoing changes due to the dynamic development of weapons of the opposing parties, which in turn requires timely response of FPV drone operators.

The basic element of tactics are tactical techniques, defined as the chosen order of maneuvering and employing UAVs in single and group use.

The purpose of UAV operator combat training is to provide ***UAV operators with*** the skills to perform their intended tasks while controlling FPV drones in various meteorological, electronic and tactical environments.

As a result of FPV drone combat training, operators should be able to:

– competently and confidently handle suspension of shock loads (RPG rounds, fragmentation grenades, etc.);

– correctly select and execute tactical techniques to fulfill combat tasks for the intended purpose;

– search for and detect single and group small-sized and area (linear), stationary and mobile, uncloaked and cloaked objects on the earth (sea) surface and determine their coordinates;

– recognize (identify) detected intelligence objects, determine their characteristics and the nature of their activities, and conduct surveillance of them.

Despite the fact FPV drones used mainly for strike missions, the ***actual task*** for FPV drone operators is also to conduct reconnaissance missions, including in the interests of adjusting (servicing) artillery firing (Figure 8.1), in this case operators should: conduct radio communication with artillery units in the course of firing adjustment; ensure the transmission of video stream to artillery firing managers; correctly and promptly determine the deviations of shell bursts from the target and make timely reports when adjusting the firing of artillery shells.

To automate the processes of information support of shock tasks, software and hardware complexes (Figure 8.2) have been developed, which provide interfacing of equipment (tablets) of calculation operators

UAVs, artillery firing supervisors (senior officer on battery), with installed software products for processing

Currently, a software product has been developed to automate the process of artillery fire correction, such as the "Veterok" program. The principle of operation of the UAV (FPV drone) operator and the means involved are presented in Figures 8.1, 8.2.

Figure 8.1 - Joint work of FPV drone operator and corrector

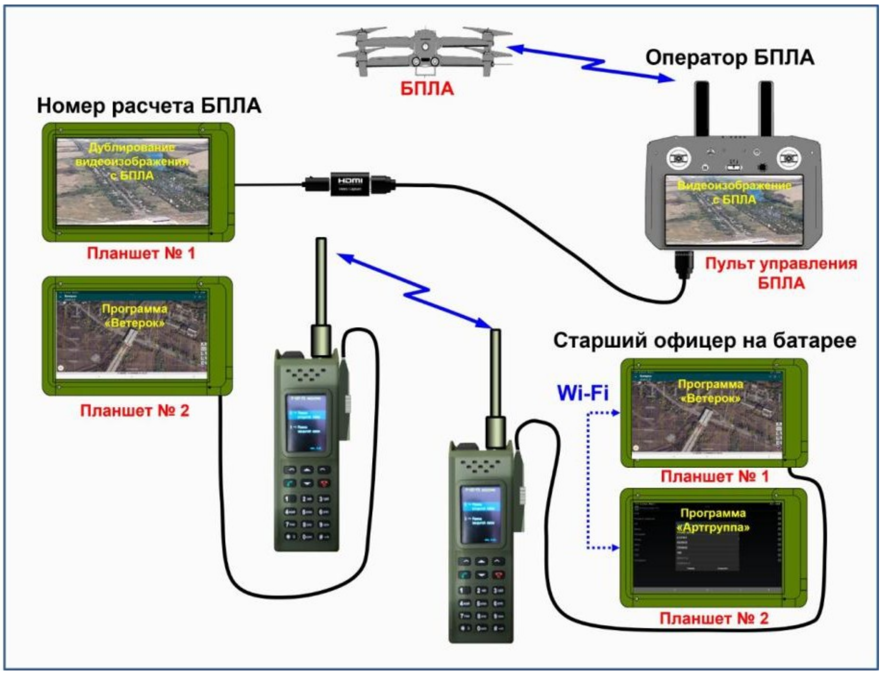


Figure 8.2 - Hardware-software complex for artillery fire correction

The purpose of incorporating FPV drone calculations into the defeat system is to form fully closed reconnaissance and strike (firing) circuits with maximum possible acceleration of information transfer, which includes intelligence and command and control commands must be provided:

– maximizing the reduction of time for processing and transmission of data on detected objects of fire damage;

– selection of objects of fire damage according to a complex criterion that includes the following indicators: importance/danger/remoteness;

– selection of the optimal (most effective) means to inflict fire damage on the identified objects.

Reconnaissance data of FPV drone calculations should be used organically with the whole spectrum of information sources (visual observation, radio and radio-technical reconnaissance means, reconnaissance means of manned aviation and UAVs with video, infra- and thermal imaging detection of the enemy, radar, acoustic, laser and other systems of extracting information about the type and coordinates of fire objects, etc.).

The system of reconnaissance and strike (firing) circuits with the inclusion of FPV drone calculations should have [21]:

– universality of applied algorithms, formats and protocols for processing and transmitting information to the reconnaissance and fire control loop, regardless of the software and hardware used;

– full interoperability of military and dual-use hardware and software products in the case of counter operation;

– sustainable feedback on the results of fire defeat of reconnaissance objects (targets).

Transmission (dissemination) of information from FPV drone calculations about detected objects should be not only to the senior superior (decision maker) and the commander of the means of fire, but also to all interested commanders of interacting elements of the combat order (operational formation) in order to increase their situational awareness on a near-real time scale.

8.1 Fundamentals of FPV drone tactics

The tactics of FPV drone use in the course of an air defense operation is determined on the one hand by the established postulates of combat operations, and on the other hand by the peculiarities of an air defense operation.

The most significant factor in choosing the tactics of FPV drone application can be considered the terrain and the relative location of the opposing parties on it. The positions of FPV drone operators should provide contradictory requirements, on the one hand, maximum radio visibility of UAVs, on the other hand, maximum secrecy of UAVs deployment. Thus, in urban areas it is easier to ensure the stealth of operations, but the issue of ensuring the range of line of sight is acute. At the same time, in field conditions, especially in winter time, it is easier to ensure the maximum possible range of direct line of sight

In the case of the UAVs, it is more difficult to achieve stealth, which requires more frequent position changes by the UAV calculations.

The NWO is characterized by almost equal combat potential of the opposing sides, namely, both on one side and on the other, there are sufficient forces and means to conduct defense, mainly maneuvering, while there are not enough forces and means to conduct an effective offensive. In this regard, in a number of sections of the front as such there is no intensive fighting, there is a "positional stalemate", and the fighting is systematic. In this case, an increase in the intensity of FPV drone use is observed during the repulsion of the enemy offensive. In periods of reduced effectiveness of combat operations, less intensive flights are observed, while the way of performing the combat task of destroying manpower and defeating equipment can be characterized as
"free hunting."

The next factor characterizing the use of FPV drones is the level of supply of units. In the case when the endowment is high, FPV drones are used up to up to maintenance
"free hunting" of individual enemy soldiers.

A factor characteristic of the NWO is the widespread use of electronic warfare. In this regard, when implementing various tactical techniques, UAV crews are required to constantly monitor the electronic environment and take electronic defense measures.

The selection of launch sites during FPV drone combat operations is of paramount importance.

The selection of the launch site is done with consideration:

– operating range of the UAV complex;

– of the equipment's capabilities;

– altitude of the launch pad and transponder location (if any);

– terrain and other objects that interfere with the propagation of radio waves.

The higher the FPV drone operator or its transponder is located, the farther the radio horizon will be and, consequently, the more room for maneuver. It is also necessary to take into account the location of reference points on both sides of the boundary line. It is recommended to choose launch sites at some distance from your stronghold in order not to expose it to the risk of fire in case the enemy reveals your location.

Based on the experience of the NWO, the best location of the launch site is the maximum distance of the calculation from the line of contact with the possibility of guaranteed target engagement.

At the same time, it should not be too far away from the main force due to the fact that various kinds of support and provisioning, such as battery charging, may be required.

8.2 General tactical techniques for the use of UAVs

In general, the procedure for the use of FPV drones is to perform aerial reconnaissance in the specified direction with close-range or short-range UAVs, most often using multi-rotor UAVs (DJI, Autel, etc.). When identifying potential enemy objects for fire defeat, their location is recorded and their identification is performed [22]. The FPV drone control operators are given target instructions via secure communication channels. After receiving information about the enemy target, the following measures should be taken:

– assessment of information about the terrain in the area of FPV drone flights: type of terrain (forest, mountainous), height differences of the ground surface, availability of sites suitable for UAV launch, their coordinates, road conditions and presence of characteristic landmarks of designated enemy targets;

– selection of main and alternate launch sites;

– planning the route and altitude of UAV flight taking into account the terrain;

– Determination of the type of means of destruction, depending on the specified Goals;

– preparation of equipment, its adjustment with the help of special software, installing the means of destruction on the UAV. The next stage is execution of a special task by the team.

FPV drones to engage identified enemy targets. Objective control activities are currently performed by the calculations of complexes with short-range or short-range UAVs.

The following are used as payloads for FPV drones: TNT checkers, RPG-7V shot, KZ-6, OFSP 1.7, 2.5, etc.

Piloting to strike an enemy target is the most difficult to implement special task, which requires maximum concentration and attention from personnel. Practical training on FPV drones and simulators (simulators) is necessary to obtain a stable skill of firing at enemy targets and to maintain it at a high level.

Following the use of FPV drones, additional reconnaissance of the terrain is carried out using multi-rotor UAV systems in order to objectively monitor the results of fire attack on enemy targets.

The structure-logic scheme of the order of FPV-drones application for fire defeat of detected enemy objects is presented in Figure 8.3.

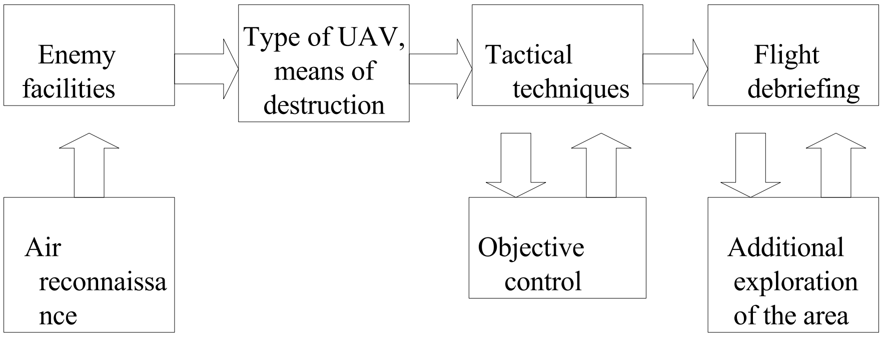


Figure 8.3 - Structure-logic scheme of FPV drone application organization

Thus, in the course of realization of measures on detection, identification, location and defeat of enemy objects by forces and means of UAV complexes' calculations, the most important task is to develop the right tactical technique.

A tactical method of performing reconnaissance and strike missions by a UAV complex means a pre-programmed or manually controlled flight of one or more UAVs in the area of a special mission aimed at full and sudden use of the combat capabilities of the UAV complex, its reconnaissance and navigation equipment, fire control equipment, UAV command and telemetry radio communications in difficult conditions for the enemy in order to successfully perform the assigned task.

Regardless of the intended purpose, the content of each tactical technique can be emphasized:

– UAV flight route with a given configuration;
– altitude and flight speed of the UAV;
– areas (zones) of application;
– radio frequency bands of the UAV control channel and payload parameters;
– UAV group flight order parameters (sectors, echelons, permissible distances between UAVs, radio frequencies).

The choice of this or that tactical technique is carried out taking into account:

– the UAV's combat capabilities and ;
– types of reconnaissance or targets;
– physical and geographical conditions in the area of the special task;
– expected countermeasures against the enemy's REB and air defense capabilities;
– of the flight performance of UAVs.

The basis of tactical techniques for the use of FPV drones to solve strike tasks is the smooth movement of UAVs in space without hopping, with the possibility of keeping it at altitude, smooth approach to the target, maintaining a minimum altitude before the fire attack.

The following tactics are recommended during cross-country piloting:

– ***Obstacle avoidance*** - performed when the target is a unit of enemy armament and military or special equipment and it is located in a relatively open area. It is performed by taking off according to the plan, flying along the route with enveloping the underlying surface and entering behind natural obstacles (trees, bushes) from different sides at the required distance, working in the analog signal, before entering the firing line it is performed by climbing to a height of 60 - 100 m, performing the maneuver "dive" on the object, destroying the object.

– ***Flight with approach into a building (window, doorway)*** - performed when the target is the location of personnel in protective structures. To perform this task, takeoff is performed, flight along the route with enveloping the underlying surface at the required distance, flight into the building through the opening. It is recommended to use analog mode of video transmitter operation.

– ***dive on moving or stationary enemy objects*** is performed at the end of the FPV drone's flight path. For effective execution of the tactical technique, the dive should be carried out at the most vulnerable point of the enemy object.

The engagement of detected targets using the impact load should be carried out taking into account the most vulnerable locations of enemy armored vehicles, such as those shown in Figure 8.4.

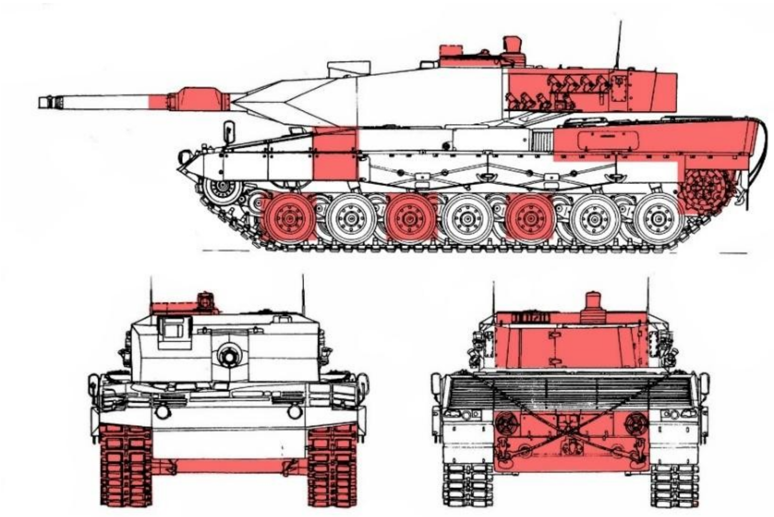


Figure 8.4 - Vulnerabilities of Leopard tank

8.3 Intelligence and objective control tasks

The main tasks of aerial reconnaissance by operators of reconnaissance UAVs are detection of strike objects, determination of their coordinates, and timely transmission of reconnaissance data to control centers by day and night.

Air reconnaissance should be conducted using at least two types of sensors operating in the visible and infrared wavelength ranges.

The following tactical methods of aerial reconnaissance using UAVs are known:

Shuttle search - is performed when the given reconnaissance area is relatively open terrain. When reconnaissance of heavily rugged or forested terrain, this tactical technique can be performed from different directions. It is used to search for group and single objects in the tactical and close operational depth of enemy combat orders. When performing the technique, the barraging zone is a rectangle, one side of which is a line segment of a given route defined by two turning points of the route (TPR). The other side is directed to the right of the specified segment. Barraging is performed in directions along the line segment of the specified route, which defines one of the sides of the barraging zone.

The number of passes in the barrage area is determined so that the barrage area is fully covered by the field of view of the reconnaissance equipment. Turnaround areas should be placed outside the barrage area to ensure that the area can be viewed on straight flight paths.

The advantage of this technique is relatively simple planning of reconnaissance and easy processing of its results in conjunction with the results of other UAVs. The main disadvantage of this tactical technique is the long time required for reconnaissance and the possibility of missing moving enemy objects.

One or two turns of up to 180° ("two by 180°") - a technique that is performed when the reconnaissance area is small and "viewing" can be performed by two or three passes.

In the case when the extended object is non-linear, the personnel of the UAV complexes calculations should exclude non-viewable areas at the expense of their professional skills and abilities.

Overflight of a given boundary with several passes is used, as a rule, when there is a need for detailed opening of objects with determination of object coordinates with high accuracy. This technique can be performed by linear or cross patrolling.

This technique is the main method of reconnaissance in the search for objects in the tactical depth of the enemy's combat orders, in the transfer of intelligence information in time mode close to real time.

The disadvantage of this technique is that, compared to other techniques, it reduces the stealth of UAVs. The best reconnaissance results are achieved when using UAVs with a long flight duration. However, in this case, a UAV with a radio control or information transmission channel activated and low flight speed is a notable target for tactical and army aviation enemy and anti-aircraft missile systems of military air defense.

For reconnaissance of mobile objects moving along roads, railroads, off-roads, rivers, the same tactical techniques are used as for reconnaissance of extended objects.

Hovering in the target waiting area is the most common option, due to the oversaturation of the line of contact with REB assets and the possibility of hitting own firepower.
"friendly fire." It is the least energy-consuming method. It is used for rapid identification of enemy targets, as well as direct support of assault units.

Sector search is usually used when searching for objects in a known *sector of* their possible location or when flying in a group of UAVs.

This technique of object search is used to detect mainly mobile and slow-moving objects in the enemy territory. In this case, the area of intelligence gathering is divided into separate sectors, in each of which a separate UAV performs a combat task. This tactical technique is expedient to use in the absence of a continuous line of contact between troops, as well as when the enemy is marching and deploying troops, for reconnaissance of enemy reserves.

B in general in general terms sequence work calculation FPV drone is represented by:

- selecting the position for calculation and the drone's starting position;
- preparing equipment and putting the drone on "combat duty";
- Receiving target designation (usually from a reconnaissance UAV);
- a combat ;
- confirmation of target engagement by means of objective control;
- re-departure if necessary.

8.4 Operation in conditions of fire and electronic countermeasures by the forces and means of the armed forces of Ukraine

It is especially important for FPV drone operators to take into account the composition of the AFU REB units in their area. It is known that the specifics of tactical operations of the REB units of Ukrainian troops (forces) consisted in conducting REB by regular or temporarily created mobile (maneuverable) REB groups (REB mg) in order to counter UAVs.

The AFU command considers it expedient to engage such groups as separate units in the combat composition of an ombr or battalion tactical group.

Mobile REB teams to combat UAVs within the AFU. For the timely detection and countering of UAVs in the areas of responsibility of operational commands in 2022 , were established in 2022 .

combined groups, which included regular R and units of the ombras and attached *maneuverable electronic warfare groups*. The mobile electronic warfare groups provided a continuous electronic suppression zone in a number of directions in a band up to 5 kilometers wide.

In accordance with the "Combating UAVs" methodological recommendations, the AFU command considered radio-electronic suppression (RES) to be the most promising method of combating UAVs (including FPV-type drones), providing interference to onboard communications and navigation equipment, as well as interception of drone control channels.

The combat order of the mobile REB *group* provided a dispersed and covert deployment of forces and means, taking into account the camouflage and protective properties of the terrain, as well as the possibility of rapid maneuver in the necessary direction.

Depending on the assigned tasks of engagement in the interests of troops of various levels, *the typical composition of REB MFs* included the following REB means:

– Bukovel-AD R4 UAV countermeasure REB complex;

– the Prometheus-MF5 universal radio station;

– portable tools countermeasures UAVs EDM4S-UA, "Jammergan 3."

In addition, the following REB means are used to counter UAVs (including FPV-type drones):

– *the Anklav* radar system;

– *Polonez* multifunctional REB complex

– *Xmara-2* REB system.

Air defense equipment of the AFU. The following Ukrainian and foreign-made electronic warfare equipment was used to solve FPV-type drone EW tasks.

Ukrainian multifunctional *Polonez* REB complex (Figure 8.5) includes a radar and optoelectronic module mounted on a 5.5-meter-high telescopic mast. They provide capture and tracking of detected targets. The maximum UAV detection ranges are up to 10 km. The complex also includes a block for suppressing signals of UAV control commands and telemetry, a transmitter and a formulator of barrier interference with receivers of Navstar and GLONASS signals. The maximum range of aiming interference is 10 km.

Data on detected UAVs can be automatically transmitted to the fire control equipment.

Figure 8.5 - Polonez mobile multifunctional REB complex

The Prometey-MF5 REB complex (Figure 8.6) is designed for radio reconnaissance, suppression of UAV control, navigation and telemetry channels, Wi-Fi and Wi-Max wireless networks. The telescopic mast with a height of 14 m provides a maximum range of up to 30 km for radio reconnaissance and up to 25 km for radio suppression.

Figure 8.6 - Prometheus-MF5 mobile REB complex

The "Khmara-2" ("Cloud-2", Figure 8.7) REB complex is designed to detect and set targeted jamming to suppress CRNS signals at a range of up to 30 km, and UAV control channels - up to 15 km. The station's equipment is installed on a cross-country vehicle.

Figure 8.7 - Khmara-2 mobile REB complex

Interference protection measures. The UAV's on-board receiver is the target for radio suppression of control channels. In the case of radio suppression of video transmission channels from the UAV, the target is the ground-based video receiver (glasses) or repeater. To increase the efficiency of FPV drone use, it is possible to use the following interference protection measures:

1. Use a special flight technique that consists of maintaining the antenna pattern orientation in a position that maximizes the control signal strength. If the control antennas are oriented horizontally, maneuvering close to the target should be avoided, because when the UAV is rotated, the radiation pattern of its receiving control antenna may orient its minimum in the direction of the control panel. Since the UAV is often positioned directly on the target hull and the UAV is always forward of the target, its radiation pattern will be maximized relative to the receiving antenna on either side of the swoop, Figure 8.8.

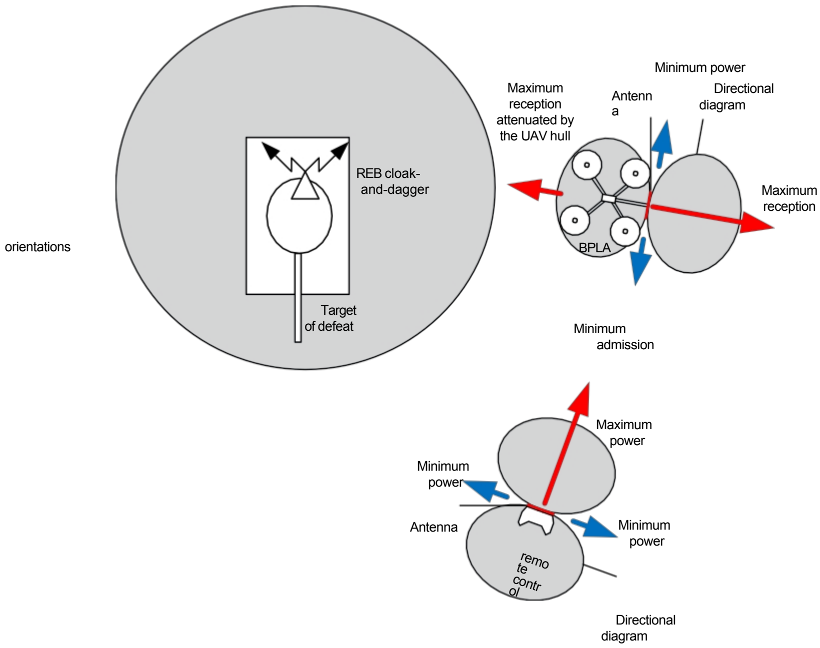


Figure 8.8 - Characteristics of signal levels from the control panel at the UAV receiver when the UAV hits the target from the side

The raid should be carried out according to the preliminary target designation, in a straight line relative to the control panel, without sharp maneuvers, so that the UAV and control panel antennas are placed parallel to each other, Figure 8.9.

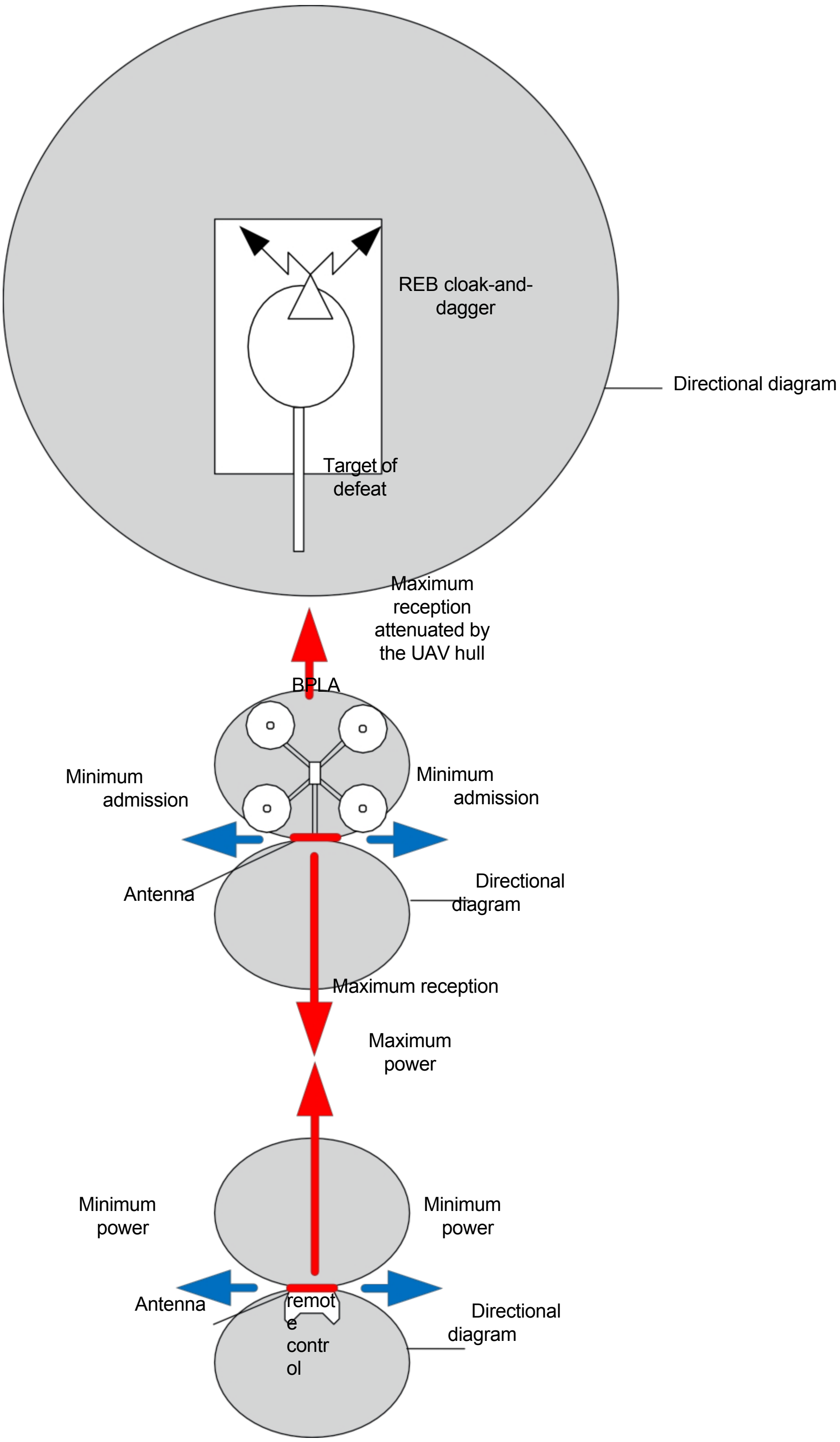


Figure 8.9 - Characteristics of signal levels from the control panel at the UAV receiver during a straight-line swoop on the target

For UAVs with vertically placed control panel antennas and UAVs, these features do not need to be taken into account.

2. When flying in one area, constantly change the polarization (angle of installation) of the antennas (vertical, horizontal, 45 degrees) depending on the enemy's radio suppression equipment. The antenna polarization of the UAV and the control panel must be the same.

3. Change the frequency ranges of the control and video drop channels during preflight preparation and by using different receivers and transmitters during UAV assembly. Combine UAVs with control and video transmission receivers of different bands in the same area of application to prevent adaptation by enemy electronic warfare equipment.

4. Increase the power of the control panel (use directional antennas and broadband amplifiers).

5. Use repeaters of control and video transmission signals, place them at the most accessible altitude, use a UAV carrier as a repeater.

6. Shield the UAV's control channel antenna from the front (in the direction of the enemy) and place the receiving antennas at the rear of the UAV's hull. It should be noted that this recommendation may result in the drone being lost if the drone is rotated.

7. When customizing the OSD data overlaid on top of the video transmitted from the UAV, add information that may mislead as to the UAV's identity (inscriptions in Ukrainian, component arrangements and markings characteristic of enemy UAVs).

The basis of tactical techniques in REB conditions are:

– *bypassing the zones of electronic suppression* is achieved by selecting the FPV drone flight route over the joints between ground forces units, over the terrain with the lowest possible probability of enemy detection equipment location (swamps, forests, water bodies, etc.). The flight route should provide access to reconnaissance objects (in the zone of special tasks) from directions unexpected for the enemy and create favorable conditions for aerial reconnaissance and strike actions;

– *FPV-drone flight path control* in case video signal loss and FPV-drone is at the stage of target search, it is necessary to increase the altitude and continue moving, in case FPV-drone is on the dive *trajectory* it is necessary to hold control knobs (sticks) in the initial position.

The basis of tactical methods of countering enemy fire defeat is:

– *the use of favorable meteorological* conditions is based on the fact that in complex meteorological conditions (cloud cover, presence of haze, fog, precipitation) the probability of detection by enemy means with optical, radio-technical and infrared reconnaissance systems will be minimal. The approach to the object (to the zone of special tasks) of reconnaissance is advisable to be carried out from the clouds and from the side of the sun;

– *the choice of a rational combat order* is to use two UAVs simultaneously. The basis of the tactical technique that reduces the probability of UAVs being hit by enemy firepower when flying in pairs is:

A pair flight using a diversionary UAV, whereby on approach to a reconnaissance target, one UAV of the pair gains the programmed altitude and distracts the enemy. The other UAV performs aerial reconnaissance or engagement of the enemy target at optimum altitude. This increases the probability of the second UAV performing special missions and decreases the probability of the second UAV being hit;

A pair flight with simultaneous entry to reconnaissance objects (into the area of special tasks), with UAVs entering simultaneously or at short time intervals from different directions and at different altitudes. This creates a difficult air environment for the enemy and increases the probability of accomplishing special missions.

In all cases, it is advisable to use television reconnaissance equipment *to detect UAV firing* by enemy *firepower* in order to perform a timely maneuver and, consequently, reduce the probability of UAV engagement.

The main tactical techniques for UAVs to overcome the enemy's REB and air defense capabilities include:

– flight at low and extremely low altitudes with minimum dwell time over the object of reconnaissance;

– reducing the UAV's flight altitude at the maximum allowable speed;

– performing the "snake" maneuver when the UAV is in the area of detection, target designation, launch and engagement by air defense assets.

To calculate the UAV conducting *aerial reconnaissance* and *target designation* and interacting with the FPV drone operator, the following recommendations are formed:

1. Reconnaissance of small-sized objects (small areas) is usually performed by flying a single UAV along a route that bypasses the most dangerous areas and reaches the target objects.

2. Reconnaissance of linear objects is conducted by single UAVs flying along the object.

3. Reconnaissance of large areas should be performed by flights of several UAVs on parallel routes.

4. In the case of reconnaissance of a large area, a single UAV makes several consecutive passes along parallel sections of the route.

In each specific case, calculations are performed and the required number of passes of one UAV is determined depending on the area of the object, payload variant, and flight altitude.

For successful work at a short distance from the line of contact with the enemy, you should know some rules that will help to avoid detection. For small copters, which have a small range, it is worthwhile to gain altitude against the background of some high buildings, power lines, slag heaps. It is advisable for the crew to raise the copter to a low altitude, move it to the side, and then reach the working altitude.

In reverse order, the UAV is landed. It is highly undesirable to take off and land near any military personnel, whether enemy or friendly. Friendly units shoot down UAVs more effectively than the enemy because over enemy fire is anticipated and maneuvered. If friendly fire has started, do not try to land or fly toward you, it is simply dangerous. Try to climb up and notify the shooters.

It is recommended perform reduction as as return к landing site, making sure, of course, that it is safe to do so.

Avoid sharp turns. Smooth turns will save battery power and are less disconcerting than sudden course changes.

General requirements к actions calculation FPV drone in combat application:

do not allow the position to be de-emphasized;

prepare equipment for re-flight as necessary;

In case of possible fire damage to the position, the crew should move to cover or change position;

Continually improve the level of knowledge on FPV drone and FPV ammunition design and software.

8.5 Information security

Ensuring information security in practice is realized in the following ways:

1. Limiting the operating time of the UAV's optoelectronics;

In order to prevent the dissemination of photographs and videos, the activation of optoelectronic equipment should be carried out already in the area where special tasks are carried out.

2. Cleaning the on-board data storage device;

In order to prevent intelligence data from falling into the hands of the enemy, it is always necessary to delete without possibility of recovery photos and video materials from the onboard storage device after they are transferred to the ground control station. The autopilot log also needs to be cleared.

3. Proper operation of the ground control station;

The ground control station is a mobile handheld device and is designed to control the UAV and its payload in the different operating modes by means of commands generated in special software. It is forbidden to use this device not for its intended purpose or without an anti-virus program installed.

4. Observing safety in radio broadcasting.

Supervisory Questions:

1. Give a definition of a tactical technique.
2. Give a definition of a tactical use of the BPLA.
3. Disclose the structural and logical scheme of FPV drone application organization.
4. Disclose tactical techniques for conducting aerial reconnaissance.
5. Disclose tactical techniques for the use of FPV strike drones.
6. Disclose the tactical methods of overcoming the enemy's REB and air defense capabilities by UAVs.
7. State the procedure for selecting launch sites.
8. Name the types of interference.
9. State the safety requirements when operating FPV drones.
10. State the order of position selection under enemy fire conditions.
11. Name the limitations in the use of radio equipment.
12. State the site use restrictions.

CONCLUSION

The presentation of the course "Operation and use of unmanned aerial vehicles (FPV-drones)" has been completed. Let's summarize some results of the studied material, taking into account the priority target audience - military cadets who have passed the introductory classes of the higher school.

The course allows you to acquire initial knowledge and skills in a short period of time for training FPV drone operators and has an original presentation of the material. The originality of the presentation, first of all, lies in the attempt to combine theory and practice under conditions of strict time constraints.

The peculiarity of the theoretical component of the course is the widest possible coverage of the initial knowledge and basic concepts on mini UAVs - FPV drones, starting from the basics of construction to special applications. Such content is intended to give the most holistic view of the object and the areas of knowledge required for its development and operation. In this regard, a learner who has carefully studied the course gets a good start for further self-education. For example, to expand theoretical knowledge, it is enough to refer to the content of the chapters of the manual and independently search for additional materials.

In practice, the manual is also self-sufficient to ensure further self-development of students. First, the relatively simple radio engineering decomposition of the FPV drone design presented in Chapter 4 allows students to start assembling the drone under the guidance of specialists. Then, using the materials of Chapter 5, those who wish to develop their FPV drone piloting skills can hone their flight skills on a simulator.

The content of the manual, in addition to the trainees, can also be useful for organizers of training to compile a course of lectures and practical classes. В In conclusion, we would like to point out that crowning achievement of anyendeavor is the ability to practically apply the techniques learned, so, turning to the к to the saying of the great Russian military leader Suvorov Alexander Vasilyevich: "Theory without practice is dead, practice without is blind", we wish the students of the course not to lose faith in themselves and constantly to improve their skills and abilities.

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