Development of Multifunctional Rotary UAV Based on Pixhawk Family Flight Controllers

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Abstract:

The design of a copter has been carried out, that can be used to set up air interference, reducing the probability of impact of the enemy air defense systems, reconnaissance operations, and the transfer of military cargo. The developed hexacopter is capable of carrying a useful load of 2.5-3.0 kg, at a speed of up to 45 km/h, based on a Pixhawk family flight controller using the Arducopter firmware. Stability of the flight of a quadcopter on a frame of 850 mm during a gusty wind of 7-8 m/s in navigation modes for firmware Arducopter ver.4.0.7 has been experimentally tested. The use of software dynamic notch filters to reduce the impact of vibrations from running motors on the readings of the accelerometer and gyroscope is considered.

1 Introduction

Theoretical research and experience of the military unmanned aerial vehicles' (UAVs) practical application in the military, anti-terrorist operations and conflicts of the different countries in the number of civilian tasks allows to formulate a list of tasks, as well as to determine types and streamline the use of the UAVs. The military tasks from the viewpoint of importance, complexity, the special conditions and other extreme factors are superior to civilian, and therefore, the main trends of modern and

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prospective development of UAVs, are first of all being developed for military use [1-5]. The role and place of UAVs in the conduct of military conflicts have led to their massive, integrated and global application to address multiple challenges simultaneously [5-7]. The unmanned aerial vehicles were considered an important means of waging military conflict in the late twentieth century, but at that time their use was not so widespread; therefore, UAVs were used in military conflicts more for reconnaissance than for strikes. One of the reasons for this was that the technologies for the UAVs creation of various types and purposes were not developed sufficiently. It became possible to create smaller UAVs with the development of appropriate technologies, but still their capabilities were more appropriated for reconnaissance than for strikes. In addition, loitering ammunition, which is a type of unmanned strike aircraft, appeared, which greatly complicated the fight against it by means and forces of air defense. Analysis of various types of UAVs has shown that it is advisable to use quadcopters, hexacopters or octocopters to solve such problems, depending on flight parameters [5-7].

For solving the problems under consideration, the UAV must be able to operate in a fully automatic mode when flying around the territory along a given route, to perform actions specified before the flight, for example, turn on or turn off nozzles, to drop the load or descend to the ground, to unhook the load, to take off and continue to follow the trajectory to the next waypoint. The ground station software should be able to automatically generate flight paths and actions performed during the passage of specified sections [8]. It is important that during the flight the device is sufficiently resilient to external influences, for example, to gusts of wind, blast waves, precipitation, and so on. It is advisable to use the possibility of FPV flight [9] with the video system, displaying telemetry data on the screen of the helmet (the speed, flight altitude, battery charge, distance from the launch point, distance travelled, coordinates, direction to the UAV launch point) for the maximum control of the UAV flight management and the possibility of its return to the starting point [10].

2   Problem Formulation

A special task is the using of the UAVs to supply the firing positions, headquarters, storage facilities, etc. by small cargoes: devices, medicines, spare parts, etc. There should be a particularly large number of such UAVs in service, i.e. they must be budgetary, resistant to damage by enemy's air defense weapons, have the appropriate accuracy and flight parameters, and resilience to weather.

A separate task for these vehicles can be the creation of interference in the air by the using of a significant amount of them to protect strike means of destruction. For solving the problems described above, it is very important for the UAVs to not only support navigational flight modes, but also to be as resilient as possible to changing external influences and electronic warfare [3, 11, 12]. In this case, the flight controller must work under the control of firmware that uses modern mathematical models which allow to correctly evaluate the readings of the sensors and, on the basis of this, to adequately control the propulsion systems [13, 14]. In this regard, the paper considers the construction of a hexacopter and its configuration for the Arducopter firmware [15], which currently has a free distribution code. This code can be modified by users. The adjustment is carried out experimentally with the large number of parameters, including the PID controller settings [16, 17], as well as the parameters of the propeller group. The Arducopter firmware was created for APM 2.6, Pixhawk flight controllers

[18]. For other flight controllers based on microcontrollers of the STM32F4, STM32F7 family, the firmware is ported, so the functionality may be limited.

The paper considers the construction of the copter with the flight weight of 7-8 kg (useful load 2.5-3.0 kg), the frame size of 850 mm and motors with the total power of about 1.0-1.5 kW. For quadcopters of this size, the experience has shown that significant vibrations are possible. The autopilots are equipped with vibration-sensitive accelerometers. The values obtained by the accelerometer are combined with data from the gyroscope, barometer and GPS receiver to estimate the position of the UAV. Due to excessive vibrations, the position estimation may be impaired. This leads to inefficiencies in modes that depend on precise positioning [19]. Therefore, the flight controller software should include mathematical models that detect the frequencies of the highest vibrations and exclude them using notch filters [12, 20].

3   Research Methods

Starting with Pixhawk flight controllers, the multicopters have used the Enhanced Kalman Filter (EKF) algorithm [13] to estimate the position, speed, and angular orientation of the vehicle based on gyroscope, accelerometer, compass, GPS, airspeed, and barometric pressure measurements. For example, the INAV firmware [21] uses an Alpha-Beta filter (complementary filter) for position estimation [22]. This filter allows using the accelerometer and gyroscope to obtain fairly accurate pitch and roll values. However, with high engine vibrations, during windy weather, the accuracy becomes insufficient. It does not allow the joint using of magnetometer to assess position accuracy. Therefore, when switching to fully automatic control with INAV firmware, the aircraft behave unstably. The Enhanced Kalman Filter (EKF2) algorithm used in Arducopter ver.4.0.7 provides the way to combine data from IMU, GPS, compass, airspeed sensor, barometer, and other sensors to calculate a more accurate and reliable UAV position estimate.

To ensure a stable flight of the copter, it is also necessary to reduce the frequency and amplitude of vibration which are characteristic of engines (propellers) rotating during flight. The purpose of vibration dampening is to reduce the high and mid frequency vibrations of the flight controller that houses the barometer, gyroscope, and accelerometer. For dampening vibrations in the UAVs, the mechanical vibration dampers, such as rubber buffers, are widely used. In order to further eliminate vibrations in the UPVs, the notch filters are used, representing the program filters of the lower frequencies. The dynamic notch filters are adjusted to the range associated with the engine screw speed. For their analysis, the mathematical apparatus of the Discrete Fourier transform is used, the application of which is shown in [23].

4   Basic Material and Results

The Pixhawk 2.4.8 flight controller based on the FMUv3 equipment, opened to distribution and modification, is used in the research [24]. What is described here applies to any controller in the Pixhawk family. Pixhawk 2.4.8 main features are as follows: Processor: 32-bit STM32F427 Cortex-M4F core with FPU, clock speed – 168 MHz, 256 kB RAM, 2 MB flash, 32-bit STM32F103 co-processor used in case of main processor failure.

The sensors are MPU 6 000 gyroscope/accelerometer, IST8310 magnetometer, MS5611 barometer. The controller is installed on the hexacopter with a frame of size

850 mm. The following equipment is also installed on the copter: BE4108-380kv motor, 16×55 two-blade propeller, ESC 30A regulator; GPS module with M8N compass; Block FPV Radio Telemetry 500 mw, 433 MHz; MininOSD; video camera RunCam Phoenix 2 with video transmitter TS832; control receiver FS-IA10B; rechargeable battery 5S4P with a capacity of 9 000 mAh. A spray system with a capacity of 2.5 liters was installed on the developed copter as an experiment to determine the performance. Fig. 1 shows a photo of the developed experimental copter with the spray system.

Fig. 1 Prototype of developed hexacopter with liquid spray system

Fig. 2 shows a block diagram of the connection of the flight controller with the power system, telemetry, magnetometer, GPS receiver, control system receiver, ESC controllers and motors for building the considered hexacopter. It is also a photo of the stand for the initial setup of the equipment before installing it on the frame.
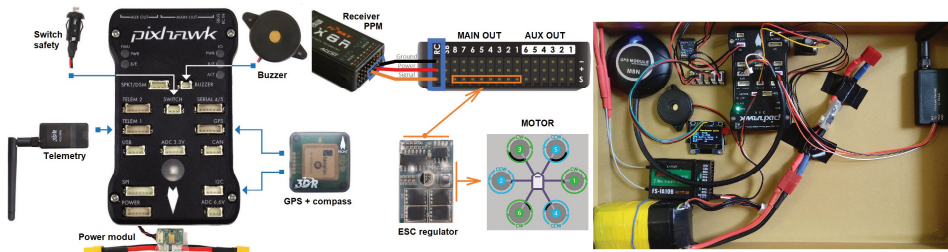

Fig. 2 Connecting of hexacopter's main components

The flight controller firmware has been configured using the Mission Planner Program [25]. The firmware Copter 4.0.7, FMUv3 has been selected for Pixhawk 2.4.8 (Fig. 3).

The accelerometer, compass, control equipment and ESC controls are calibrated. Fig. 4 shows the combination of settings tabs. It should be noted that it is advisable to calibrate the magnetometer at the place where the copter is launched by rotating it along six axes until Mission Planner displays a message about the end of the calibration. The location of the magnetometer relative to the flight controller is determined automatically. The adjustment of ESC regulators is carried out in accordance with the ESC Calibration tab.
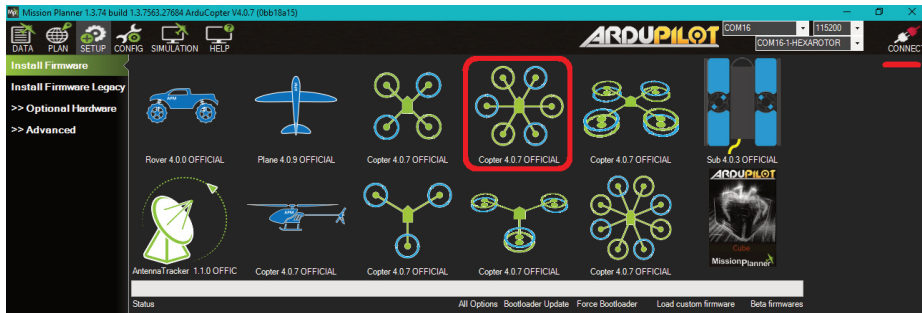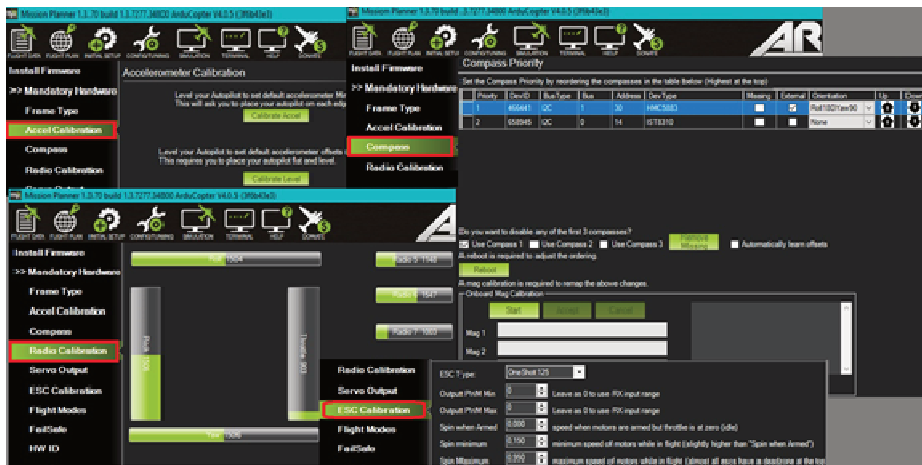
Fig. 3 The hexacopter firmware interface

Fig. 4 Combination of tabs for setting parameters

The FailSafe mode is set to minimum throttle. When the control equipment is on, the throttle value is set to 1 000 pulses, and when the connection with the remote control is interrupted, this value should be equal to 900 pulses. FailSafe will be triggered if the value is set below 950. This will turn on the Enabled Continue with Mission and Auto mode – the continuation of the flight mission in automatic mode in case of communication's loss with the control panel. You can also enable the Return to Home (RTH) mode that will return the hexacopter to the starting point in case of connection's loss.

In the Extended Tuning tab, the PID controller parameters and some navigation flight modes (red rectangles) have been configured. Here, too, certain flight modes and actions can be set to some switches on the control equipment. For example, the seventh channel switch RC7 is set to emergency engine shutdown, and RC8 is set to auto landing (yellow rectangles).

The PID controllers are tuned by manual selection based on visual control over the stability of the aircraft's behavior. For the convenience of setting the parameters during the flight, the specific PID parameters (green rectangles) are set on the sixth channel of the control equipment - the potentiometer. The flight parameters in navigation modes are lined by a red rectangle. For example, in auto trajectory or Loiter mode, the speed is set to 800 cm/s (8 m/s).

To ensure stable flight, it is important to reduce the vibration amplitude, which is characteristic of the screw's operation of motor group. For ensuring the stable flight, it is important to reduce the vibration amplitude that is characteristic of the operation of the propeller – the motor group. For this purpose, the flight controller has been installed on the frame using damping gaskets (Fig. 5).
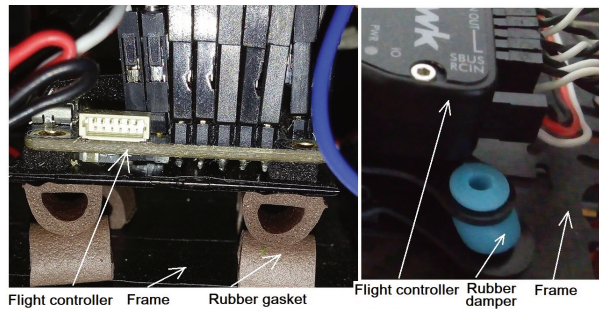

Fig. 5 *Installation on the frame of flight controller using damping gaskets*

To pre-configure the anti-vibration gaskets between the copter frame and the flight controller, the Arducopter firmware uses a flash data log message, which is stored in the autopilot flash memory (microSD card) in the form of logs that can be downloaded after the copter has flown.

The logs are copied from the flight controller using the MAVLink protocol [26]. To do this, the computer with the installed ground station (Mission Planner) is connected to the UAV, the "DataFlash Logs" tab is selected from the DATA window and the selected log files are copied to the computer. The vibration graphs are displayed in the same tab. The result is shown in Fig. 6.
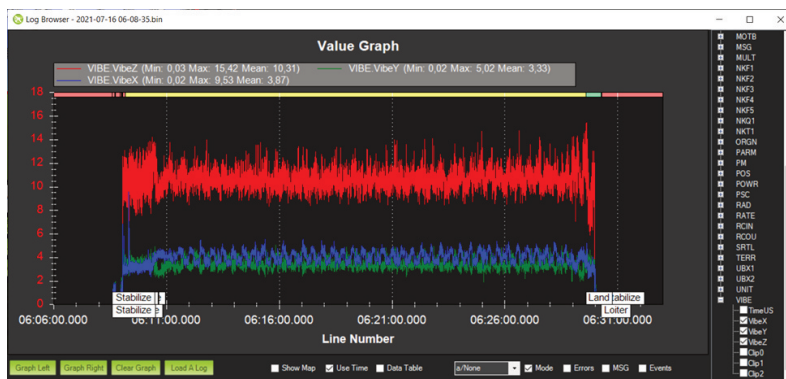

Fig. 6 *Graphs of VibeX, VibeY and VibeZ values of VIBE message*

The VibeX, VibeY, and VibeZ values of the VIBE message are plotted in this window. They show the deviations of the accelerometer output signal in $[m/s^2]$. As recommended by the source [27], acceptable vibration levels are the levels below 30. The levels above 30 m/s^2 can cause problems, and levels above 60 m/s^2 usually cause problems with maintaining position or altitude. Fig. 6 shows that the maximum vibration value did not exceed 15.4 m/s^2.

The considered mechanical damping may not be sufficient and software filtering should be used to remove additional noise. For the autopilot, the vibration noise looks

like an external disturbance (for example, the noise of the rocket, aircraft, wind) which the autopilot must take into account in order to control the UAV. The ArduPilot uses a software low pass filter to remove most of this remaining vibration noise. However, filtering has an undesirable effect: it removes information about the orientation of the copter and its control. This problem becomes especially acute on quadcopters with very high levels of vibration noise on the rotor rotation harmonics. To remove the vibration noise, the firmware uses the notch filter that targets the frequency band that occurs when the motors rotate. The ArduPilot is supported by dynamic notch filters that can be adjusted to the range related to the multicopter's engine speed. The dynamic notch filters are a set of several filters placed on the harmonics of the filter's fundamental frequency. Therefore, with proper tuning, the harmonics of the fundamental oscillation frequency can also be weakened. The global dynamic notch filtering is enabled by setting the parameter INS_HNTCH_ENABLE = 1. After restarting the flight controller, all additional parameters will appear that can be seen in the Full Parameter List tab (Fig. 7).
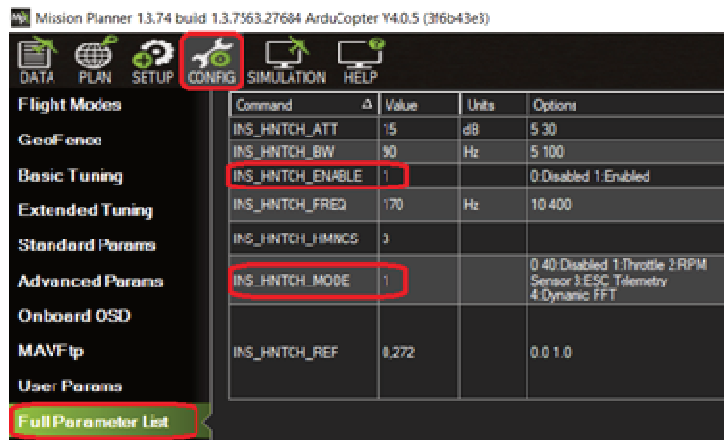

Fig. 7 Setting dynamic notch filtering

The basis for the operation of the dynamic notch filter is the control of its center frequency. The paper considers the method based on the position of the throttle. In this case, the mid-throttle frequency is determined by analyzing the logs. A change in throttle position above the average value is used to monitor an increase in vibration noise frequency. This method is enabled by setting INS_HNTCH_MODE = 1. To configure the dynamic notch filter, the throttle needs to be set to thebase level, that identifies engine noise at the hover level of the multicopter. For this, the IMU (Inertial Measurement Unit) periodic package sampler is used to obtain logs for analysis. It writes the high frequency data from the IMU sensors to the flash log on the autopilot. This data is subsequently analyzed post-flight to diagnose vibration problems using the Fast Fourier Transform (FFT). The accelerometer data recorded during the flight is converted into vibration frequency graphs. The peak on these graphs corresponds to the rotational speed of the propeller blade. This causes vibrational acceleration in the body of the multicopter.

Let us consider the steps for "cutting" vibrations from the analysis of the flight controller. First, the pre-flight setup is performed, i.e. the following parameters are set in the "Full Parameter List" tab:

- INS_LOG_BAT_MASK = 1 to collect data from the first IMU,
- the IMU_RAW bit in the LOG_BITMASK parameter must not be checked. For example, the default value of the LOG_BITMASK parameter does not check the IMU_RAW bit.

The flight and post-flight analysis when setting up the system:

- the normal flight of 3-4 minutes performs with followed downloading flash memory logs,
- the .bin log file is selected in the Mission Planner (Fig. 8).

Fig. 8 Sequence of steps for opening windows to access analysis using
Fast Fourier Transform

The accelerometer data is displayed in the upper left window, the gyro data – at the top. The amplitude of oscillations is plotted along the vertical axis, and the frequency is plotted along the horizontal axis. The resulting graph is used to determine the vibration frequency, but not to analyze whether the amplitude levels are too high or not. This part of the default filtering setup displays raw accelerometer and gyroscope data before filtering. The second part of tuning is filtering to prevent motors noise from entering the PID control loops. Therefore, it is important to view the data after it has been filtered. Figure 9 shows graphs of vibration noise for the tested copter before filtering: on the right – accelerometer data, on the left – gyroscope data.

For filtering the noise peak, the average throttle value is determined when the copter is hovering. For this purpose, in the "Full Parameter List" tab, the MOT_THST_HOVER parameter is searched and its value is viewed, provided that the MOT_HOVER_LEARN parameter = 2. For the tested hexacopter with an 850 mm frame and 1 655 propellers, the MOT_THST_HOVER parameter = 0.136 (light weight, powerful motors).

From the graphs in Fig. 9, we find the motor frequency hover_freq = 80 Hz, and from the value of the MOT_THST_HOVER parameter, the thrust value hov-

er_thrust = 0.136 for a soaring flight. To configure harmonic notch, the parameters in the "Full Parameter List" tab are installing:

- INS_HNTCH_ENABLE = 1, enable harmonic cut,
- INS_HNTCH_REF = 0.136, set the harmonic notch reference value,
- INS_HNTCH_FREQ = 80, set the reference frequency of the harmonic notch (fundamental),
- INS_HNTCH_BW = 80/2, set the bandwidth of the harmonic notch,
- INS_LOG_BAT_OPT = 2, capture gyroscope data after filter.

After a 3-4 minute flight, the vibration noise graph changed, as shown in Fig. 10.
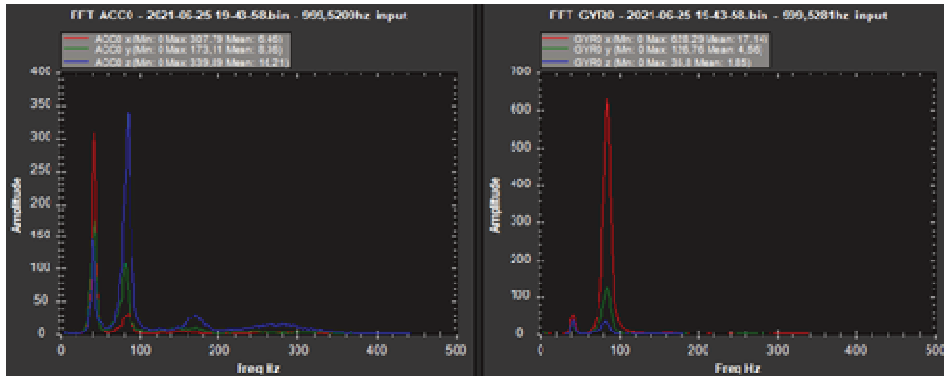

Fig. 9 Vibration noise of quadcopter with 850 mm *frame before filtering: right for accelerometer, left for gyroscope*
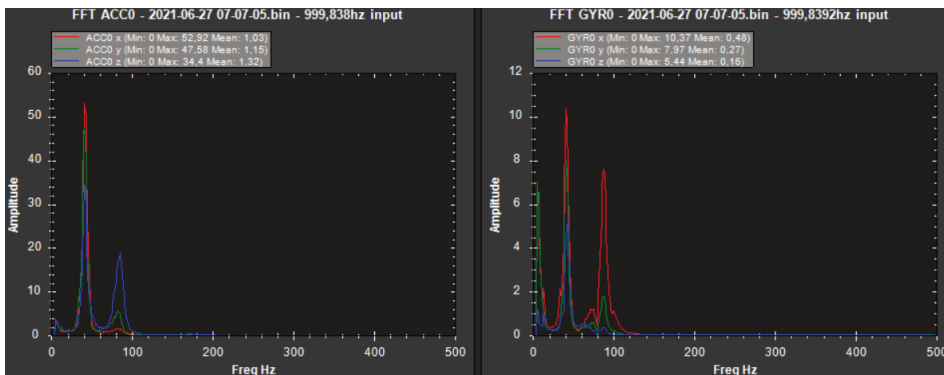

Fig. 10 Result of filtering vibration noise of the copter

The comparison of Figs 9 and 10 shows that the amplitudes decreased from 300 to 54 and from 350 to 20 for the accelerometer; for the gyroscope – from 630 to 7.5 units. After performing these settings, an experimental result was achieved to reduce the heating of the engines and increase the flight stability of the copter. The notch filter setting shown here for aircraft with flight controllers installed on a frame with insufficient vibration isolation can reduce vibration noise and ensure stable flight of the aircraft. The barometer is a particularly sensitive sensor to vibration noise. For example, if the accelerometer and gyroscope can withstand vibrations and the copter keeps the stable horizontal position, then when switching to the barometer altitude

hold mode, the copter starts to behave inappropriately, which often leads to its fall. In this case, it is advisable to configure the notch filters.

Let us consider the capabilities of the flight controller and firmware ArduCopter ver.4.0.7 to control the executive equipment. In the first case, the device for turning on the sprayer pump, which is controlled by servo drive, is used for this purpose. In the flight controller, servos can be connected to the AUX OUT pins (Fig. 2). When connected to AUX OUT 2, the Mission Planner recognizes it as SERVO10 (highlighted in yellow in Fig. 11, Camera Gimbal tab). The channel number from the control equipment is also indicated here (RC6, configured according to Fig. 4). The pump will be turned on when the switch controlling channel RC6 is moved from one extreme to the other.
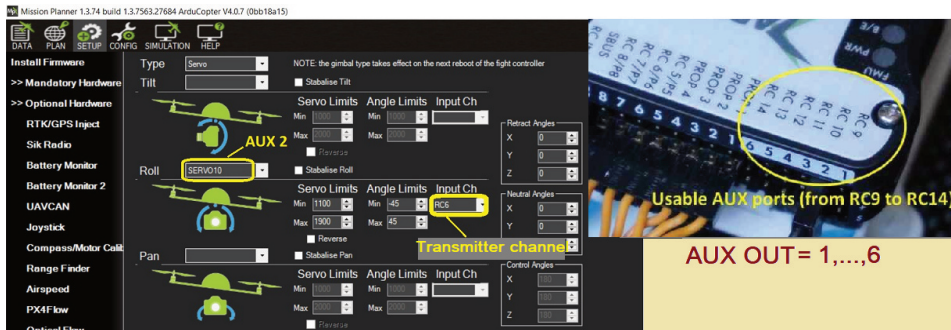

Fig. 11 Setting load drop device on command from control panel

The second way to control the actuator (turn on the pump, release the load) is a command from the flight controller when passing through the trajectory point during flying in automatic mode. The actuator is connected via a servo drive to the AUX OUT 2 pin. As in the first case, the system perceives it as SERVO10. To activate this mode, in the "Full Parameter List" tab, the RC10_FUNCTION parameter must be set to 0 (Fig. 12).
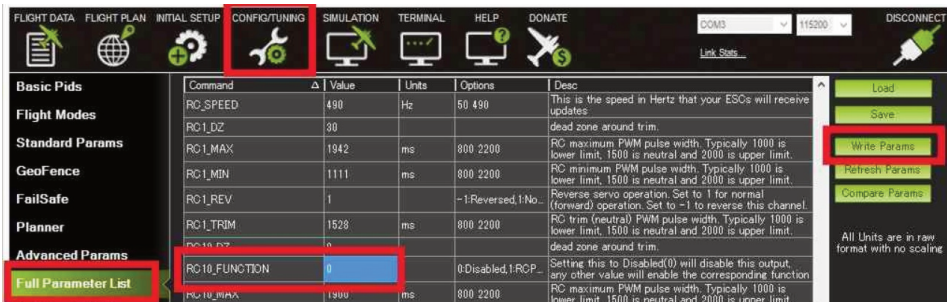

Fig. 12 Setting RC10_FUNCTION parameter when running the mission

In this case, the control via channel RC6 on the console will be automatically disabled. When compiling the flight mission, in the "PLAN" tab (Fig. 13), the DO_SET_SERVO command is added indicating the number of the servo (10) and the value of the impulse that must be applied to it (1 100). This command must follow the flight point at which the actuator is to be actuated.
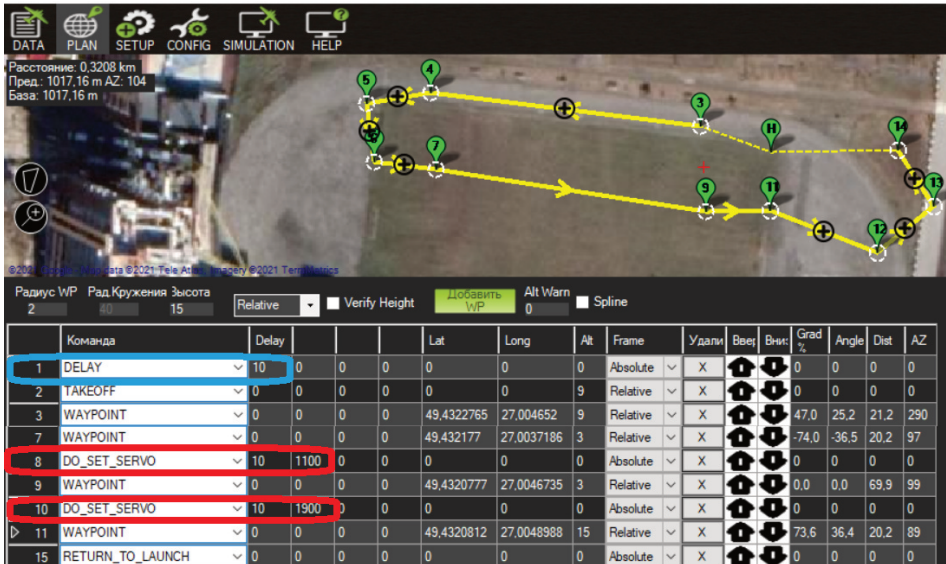
Fig. 13 Real results of the flight with turning the mechanism on/off

During flight, the flight controller writes flight parameters to the microSD card. The Mission Planner program allows to extract the recorded data after the flight and present them in the graphical form. Also, the file is automatically generated, which in the Google Earth program displays a three-dimensional representation of the flight of the copter using GPS-receiver data. Figure 14 shows the flight path planned in Mission Planner (shown in grey in accordance with the plan in Fig. 13) and the actual three-dimensional trajectory (pink) generated by Google Earth using flight controller data. Fig. 14 shows a close correspondence between the planned flight trajectory and the real one. The discrepancy was no more than 2 m. This indicates the high quality of the ArduPilot firmware when performing navigation functions.
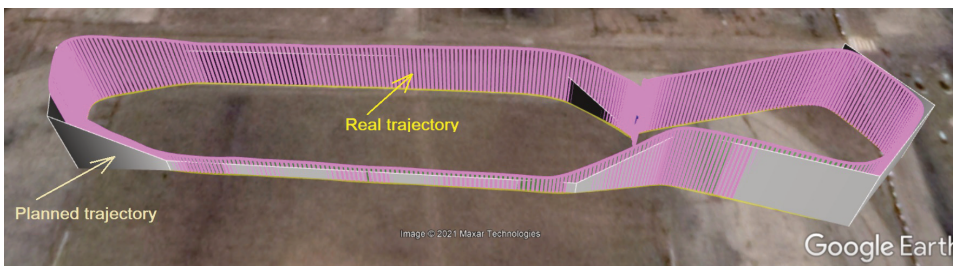

Fig. 14 Flight trajectory of the aircraft under test (pink)

5   Conclusion

The design and configuration of hexacopter, capable of carrying a useful load of 2.5-3.0 kg at a speed of 40-45 km/h based on flight controllers Pixhawk family using Arducopter firmware, are developed. The designed copter can be used for military cargo transfer, air jamming, reducing the probability of enemy air defense systems, and military video intelligence.

The stability of the flight of a quadrocopter on a frame of 850 mm during gusty winds (7-8 m/s), air explosions and other interference in navigation modes with firmware Arducopter ver.4.0.7 have been tested empirically. A high stability of flight in automatic mode and in the mode of automatic return to the starting point is noted.

The high accuracy and stability of flight along a given trajectory in automatic mode and the correct execution of commands during the passage of waypoints, for example, for the tasks of transferring cargo, video filming at given coordinates, etc., have been experimentally established, when using Arducopter ver.4.0.7.4. firmware.

The flight tests have shown that the Arducopter firmware contains an effective tool that allows to detect and control vibration levels.

It has been established that after choosing a specific type of vibration-insulating material for installing the controller on the frame, it is necessary to evaluate the vibration isolation using the tools listed in the paper. Based on this assessment, if needed, vibration isolation adjustments (change the attachment geometry, material elasticity, add additional weights to make the flight controller heavier, etc.) have to be performed.

It was established that with the right choice of mechanical vibration protection and the use of notch filters, an experimental result is achieved in reducing the heating of the engines and increasing the flight stability of the copter. It is especially noticeable for large multicopters. It has been observed that during FPV flights when flying on course video camera on the large quadcopter (850 mm), the vibration of the video image has significantly decreased.

In the course of numerous flight tests, it was found that the correct choice of the parameters of the mathematical models of PID controllers, the extended Kalman Filter, dynamic notch filters can significantly increase the stability of the copter flight.

The possibility of displaying the three-dimensional UAV flight trajectory based on sensor readings using the Google Earth program has been shown.

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