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LARGE-CAPACITY QUADCOPTER'S DESIGNING ON THE CONTROLLERS OF THE PIXHAWK CUBE FAMILY

Abstract
The quadrocopter's design and configuration that capable to carry a payload of up to 30 kg based on the Pixhawk 2 Cube flight controller using Arducopter ver.4.1.5 firmware for FMUv3 devices was completed in the paper. For ensuring a flight range of 10-12 km, the using of 44000 mAh battery and payload of 10-15 kg is recommended. It has been established that when building large-sized copters, before setting up the PID controller, it's necessary to pre-configure the parameters that are used by the PID controller. The failure to do so will often cause the aircraft to crash on its first flight. These are motor thrust linearization parameters, acceleration values for different axes and filters that go to the input of the PID controller. Experimentally tested the stability of the quadrocopter's flight in windy weather in navigation modes for firmware Arducopter ver.4.1.5. At wind speeds up to 10 m/s with gusts up to 14-15 m/s, the flight stability was noted in automatic mode and in automatic return to the starting point mode. The high accuracy of the operation of the Ardupilot firmware navigation system was established when the cargo drop point was reached in automatic mode. The error was no more than 1.0-1.5 m at wind speed of 6-7 m/s. The effectiveness of mechanical vibration isolation for flight controllers of the Pixhawk Cube family has been experimentally established. When installing them on the frame of the copter, there is no need to use mechanical vibration decoupling. However, taking into account the low frequency of the frame oscillations from the operation of the propeller group (about 30 Hz), it's necessary to design the frame with the frequency of natural oscillations outside this range. The using of software dynamic notch filters to reduce the impact of vibrations from running motors on the readings of the accelerometer and gyroscope is considered. On the frame of 2000 mm quadrocopter, it's shown that such filters significantly reduce the amplitude of not only the detected fundamental frequency, but also their harmonics. The various ways of

setting up actuators controlled by servos and relays for dropping loads, switching operating modes by video systems, switching on and off spraying mechanisms when using such drones in agriculture are considered.
Keywords: GPS receiver, UAV, ESC controller, Failsafe, Arducopter, Ardupilot, Pixhawk Cube, FMUv3, notch filter, Mission Planner, STM32F427, X11 HobbyWing.

Introduction

Currently, the using of high-capacity drones is very relevant. They are used, for example, for delivering goods along a given route, spraying agricultural fields with plant protection products [1, 2, 3]. To address these issues, the unmanned aerial vehicles (UAVs) of rotary type can be used [1]. These are quadrocopters, hexacopters or octocopters, depending on the tasks, the weight of the transferred load and the reliability of cargo delivery [4]. So it's known that if one of the hexacopter motors fails, it remains controllable and its accident-free landing with an expensive cargo is possible. If one of the quadrocopter's motors is damaged, it loses stability and collapses upon impact with the ground.

For performing these tasks, the UAV must fly not only in manual mode according to FPV [6] but also in automatic mode. For example, to fly along the given trajectory, turn on and off the pump during spraying, drop cargo at given coordinates to determine the certain (given) flight trajectory, etc. The ground station software must ensure the formation of the flight path, control the actuators, transmit telemetry data between the aircraft and the operator [5]. On the other hand, the flight controller software must ensure the stable flight of the drone under changing external influences (for example, with gusts of wind). Such drones should be easily controlled from the control panel in manual mode using a video system, provided that the drone isn't within sight, but, for example, at the distance of 6-7 km. The software of the video system and the flight controller should superimpose telemetry data (speed, flight altitude, battery charge, distance from the launch point, distance traveled, coordinates, direction to the launch point) on the video screen of the operator's helmet for maximum control over the UAV flight at any time of the day [7].

Materials and methods

For solving the problems described above, it's very important that the UAV maintains navigation flight modes and is as a resistant to changing external influences as possible. Therefore, the flight controller firmware must use mathematical models that are able to provide maximum flight stability. The paper considers the construction of the quadrocopter and its configuration for the Arducopter [8] firmware, that is currently the most stable of the firmware with freely distributed code. This code can be modified by users. The adjustment is carried out experimentally with the large number of parameters, including the setting of PID controllers, that determine the stability of the copter with the given geometric parameters as well as the parameters of the propeller group. The Arducopter firmware mainly runs on Pixhawk [9] family controllers. The feature of this firmware is that it allows you to create scripts in LUA for more flexible drone control.

This article focuses on building a heavy-duty quadcopter with 40" propellers and motors greater than 5kW. For aircraft of this size, significant low frequency vibrations are possible. 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, position estimation may be impaired. This results in very poor performance in modes that depend on precise positioning [10]. Therefore, the software of the flight controller should include mathematical models that make it possible to identify the frequencies of the highest vibrations and exclude them using notch filters [11, 12].

The Ardupilot firmware uses the Enhanced Kalman Filter (EKF) [13] algorithm based on gyroscope, accelerometer, compass, GPS, airspeed and barometric pressure sensors to estimate the position, speed and attitude of the vehicle. To maintain a stable horizontal position of the drone, the firmware uses mathematical models of PID controllers. Moreover, epy different versions of Ardupilot firmware use modifications of the Kalman filter. For example, Arducopter ver.4.1.5 uses the Enhanced Kalman Filter 3 (EKF3) algorithm, that provides more accurate way to combine data from IMU, GPS,

compass, airspeed sensor, barometer and other sensors. It allows to perform more accurate and reliable assessment of the UAV's position for ensuring together with the PID controllers, a more stable flight compared to the EKF, EKF2 versions.
For the stable flight of the copter, it's also necessary to reduce the vibration amplitude, that is the characteristic of the engines (propellers) operation that rotate during flight. The purpose of vibration dampening is to reduce the vibration of the flight controller, that houses the barometer, gyroscope, and accelerometer. For dampening vibrations in UAVs, the mechanical vibration dampers are widely used. The paper considers and analyzes the using of notch filters for furthering eliminate vibrations. It's the software low-pass filter that removes most of the vibration noise left after the mechanical filter, but leads to less sensitivity of the drone when manually controlled by the control system. In the paper, the dynamic notch filters are adjusted to the range, related to the engine speed for the drone. For their analysis, the mathematical apparatus of the discrete Fourier transform is used, the application of that is covered in [14]. In the paper, for the given drone geometry, flight weight, propeller group of the drone, through numerous experimental tests, the parameters of the above mathematical models are selected to ensure stable flight.

Results
The paper uses the Pixhawk2 Cube flight controller, that is based on the FMUv3 equipment, that is open to distribution and change [15, 16]. The Pixhawk 2 Cube main features are Processor: 32-bit STM32F427 Cortex-M4F core with FPU, the clock speed of 168 MHz, 256 KB RAM, 2 MB flash, 32-bit STM32F103 co-processor, used in case of main processor failure.
The sensors are three redundant IMUs (acceleration, gyroscope and compass): MPU9250 and as the first and third IMU (acceleration and gyroscope); ST Micro L3GD20+LSM303D or ICM2076xx as a backup IMU (acceleration and gyroscope); two redundant barometers MS5611.
The interfaces are 14 PWM servo outputs, 5 general purpose serial ports, control system receiver inputs for PPM, S.Bus; 2 I2C ports, CAN bus interface, S.bus servo output.
The controller is installed on the quadrocopter with aluminum frame, with diagonal dimension of 2000 mm between the motor axes. The copter is also equipped with: motor X11 HobbyWing - 95kv; two-bladed propeller 40x132; regulator ESC 150A; GPS module Radiolink Mini SE100 with compass and M8N receiver; FPV unit with 1200 mW video transmitter; MininOSD; analog video camera Foxeer Micro Cat 3; SIYI FT24 control equipment receiver FR Receiver; two 12S rechargeable batteries with total capacity of 44000 mAh. As an experiment, the four-channel reset system was installed on the copter, assembled on the basis of four digital servos with increased torque. A relay system is also used to switch between the two video systems installed on the aircraft.

Voltage(V) 工作电压	Propeller 螺旋桨	Throttle (%) 油门	Thrust(g) 拉力	Current(A) 电流	Power(W) 输入功率	Speed(RPM) 转速	Efficiency(g/W) 效率
53.6V (14S LIPO)	40132 Inch Foldable Propeller	40%	5935	10.0	538.8	1591	11.01
		45%	7405	13.7	734.5	1777	10.08
		50%	9245	18.7	1007.7	1982	9.17
		52%	10035	21.1	1134.0	2063	8.85
		54%	10765	23.4	1255.2	2134	8.58
		56%	11775	26.6	1430.2	2227	8.23
		58%	12555	29.2	1571.1	2297	7.99
		60%	13470	32.4	1742.8	2375	7.73
		62%	14515	36.2	1947.4	2462	7.45
		64%	15145	38.6	2075.2	2512	7.30
		66%	16015	42.0	2257.5	2581	7.09
		68%	17305	47.3	2540.5	2680	6.81
		70%	18245	51.3	2756.5	2751	6.62
		75%	20955	63.9	3429.0	2945	6.11
		80%	23480	76.9	4126.5	3116	5.69
		90%	29445	113.0	6064.1	3476	4.86
		100%	34285	147.5	7909.7	3740	4.33

Fig. 1 The motor characteristics X11

The HOBBYWING X11 MOTOR motors installed on the quadcopter have the characteristics presented in the table in Fig. 1. The values in the table are valid for 40x132 propeller and battery voltage of 53.6 V (14S LIPO). The maximum thrust developed by the motor at the current of 147.5 A corresponds to 34 kg. However, its efficiency at this current is almost 3 times less than at the current of 10 A. Therefore, it's practically recommended to use these motors with an axial thrust of no more than 15 kg, that corresponds to the current of 38 A and an efficiency of 7.4 G/W. With such thrust, the stable position of the copter is ensured under dynamically changing external influences (for example, the gusty wind). The optimal flight weight of the quadcopter with such motors is 60 kg. The weight of the quadcopter with 44000 mAh batteries without payload is about 30 kg. The flight tests have shown that with payload of 10 kg and flight speed of 11 m/s, the copter is able to fly up to 5 km in the straight line from the launch point and return back. The wind speed shouldn't exceed 5 m/s, and the flight height shouldn't exceed 130 m. According to Fig. 1, the efficiency of the propeller-motor group here is about 9 G/W. The further increase in the payload requires an increase in the capacity and, therefore, the weight of the battery for the same range, that leads to the decrease in efficiency and may not give the noticeable effect when carrying cargo over long distances.

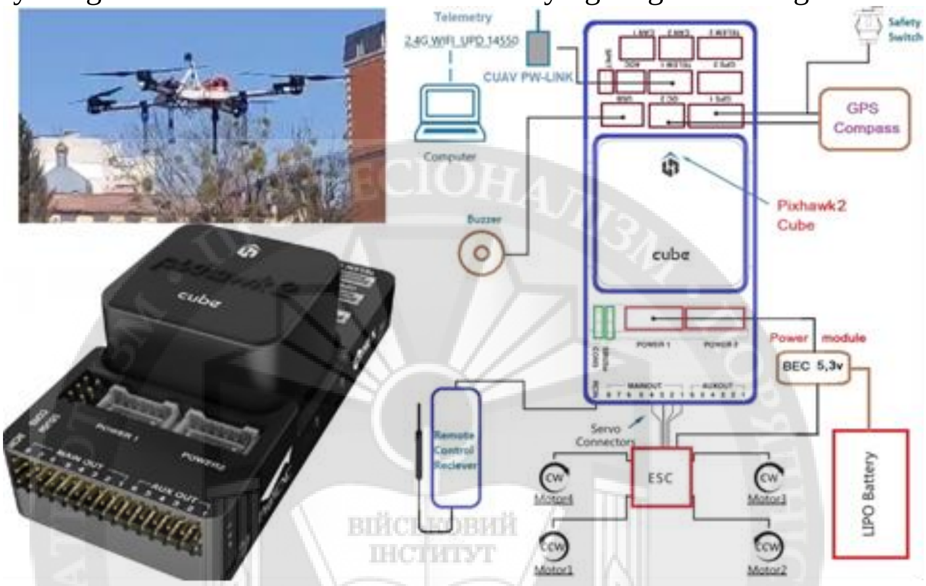

Fig. 2 The high-capacity quadcopter flight photo, flight controller and wiring diagram

Fig. 2 shows photos of the aircraft in flight and the Pixhawk Cube flight controller, the simplified block diagram of the connection of the flight controller with the power system, telemetry, magnetometer, GPS receiver, control system receiver, ESCs and motors. The figure doesn't show the connection of the reset system's servo drives and the relay switching of two video systems, however, the paper discusses the software method for setting them up.

The flight controller firmware is configured using the Mission Planner program [17]. For the Pixhawk 2 Cube, Arducopter 4.1.5 firmware is selected (the latest at the time of this paper), FMUv3 equipment (Fig. 3).

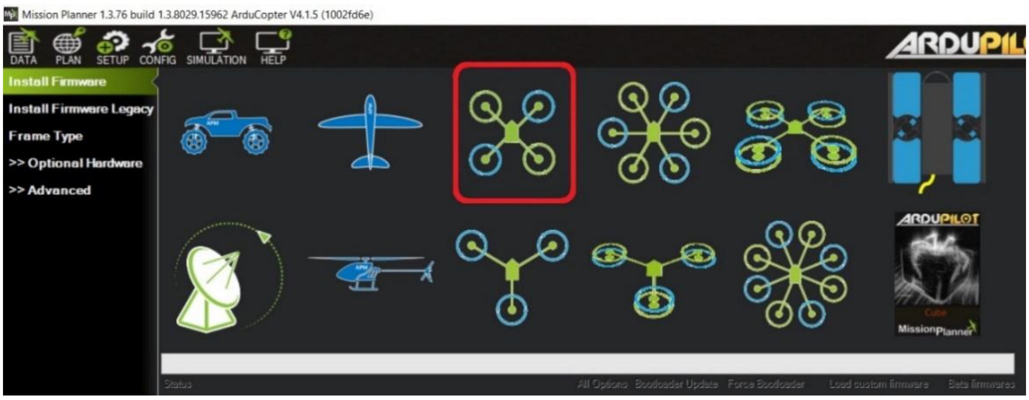

Fig. 3 The quadcopter firmware for Pixhawk 2 Cube

Next, the frame type is selected and the accelerometer, compass, and control equipment are calibrated [18]. The flight modes are set. The Fig. 4 shows the combination of tabs for these settings. It should be noted that it's 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 direction of the magnetometer in the GPS module must match the direction arrow on the flight controller. For X11 HobbyWing motors, ESC adjustment isn't carried out.

Fig. 4 The Tab combination for flight controller settings

The FailSafe configuration is done in the FailSafe tab. It's only performed for the radio remote control. In case of connection's loss with the remote control, the return to the trigger point mode is activated - Enabled always RTL.

Let's consider the parameters that need to be selected based on the recommendations of the Ardupilot firmware developer and subsequent numerous flight tests [19]. These parameters are important for building large quadcopters. The incorrect selection of these parameters often results in the aircraft tipping over.

It's important that the thrust curve of the vertical takeoff and landing aircraft engines is as linear as possible. The linear thrust curve means that changes in the actual thrust generated by the engine are directly proportional to the thrust required by the ArduPilot software. If the thrust curve is highly non-linear, then further selection of the Ardupilot parameters will not allow the correct setting, that can lead to the unstable copter in flight and its further crash. The most common three causes of the non-linear thrust curve are: the voltage drop when increasing the throttle on the control panel; the incorrect setting of the endpoints of the range of PWM ESC regulators; the non-linearity of thrust generated by the propeller, ESC and motor.

In the paper, the parameters used to linearize the engine thrust curve were set as follows:

MOT_BAT_VOLT_MAX: 4.2V * number of cells in LIPO BATTERY

MOT_BAT_VOLT_MIN: 3.3V * number of elements in LIPO BATTERY.

The next step was to adjust the traction. In this case, the motor with the propeller was installed in the thrust stand with dynamometer, and the true thrust was accurately measured when the throttle position was changed. Next, the exponential value was adjusted so that the thrust between the end points was as linear as possible. Thus, the value of the MOT_THST_EXPO parameter was adjusted. It's an easier way to adjust this parameter depending on the diameter of the propellers. Fig. 5 shows the value of this parameter depending on the size of the propeller in inches. By default, the value of this parameter in the firmware is given for a 10-inch propeller.

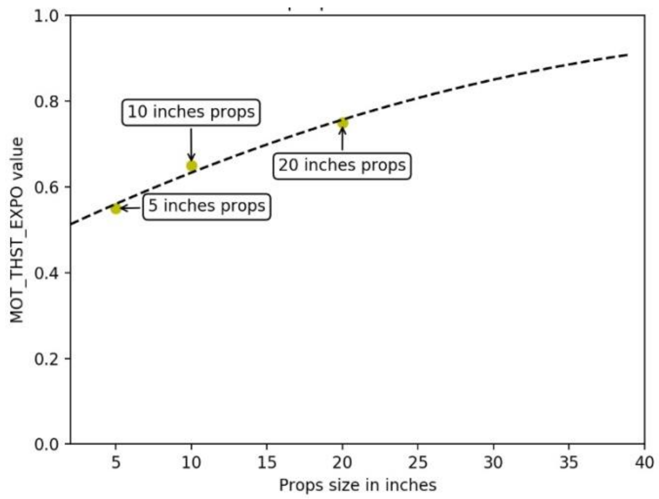

Fig. 5 The recommended values of the MOT_THST_EXPO parameter depending on the propeller diameter

The motor tuning. The engine parameters are determined by the PWM range that the flight controller sends to the ESC controller. It's important to ensure that the entire range of gas used in flight is within the linear range of the propulsion system. The following parameters are used to determine the output range sent to ESC:
MOT_PWM_MAX is the maximum PWM value to be output to the motors;
MOT_PWM_MIN is the minimum PWM value to be output to the motors;
MOT_SPIN_ARM determines the value at that the motors will reliably start after the aircraft's putting into the ARM state;
MOT_SPIN_MAX: 0.95 is the value of the parameter at that the thrust of the motors is maximum;
MOT_SPIN_MIN indicates the value at that the thrust starts. It's the first point of the motor's linear thrust range;
MOT_THST_HOVER: 0.25 is the actual percentage of motor thrust at that the copter is expected to hover.
The initial setting of the PID controller. Before tuning the PID controller, you must set the value of the following parameters. Otherwise, the default PID settings may cause the heavy-duty aircraft to crash. The value of these parameters are recommended by the creators of the Ardupilot firmware and are set depending on the diameter of the propeller. The final parameters are set during flight tests to ensure maximum flight stability.
The parameters presented below are the acceleration values for different axes and filters that go to the input of the PID controller. These parameters are critical for tuning as they directly affect the PID controller.
The filter cutoff frequency for accelerometers INS_ACCEL_FILTER is 10Hz.
The filter cutoff frequency for gyroscopes INS_GYRO_FILTER is 20Hz for 20 inch props (Fig.6).
The maximum acceleration along the axes (Fig. 6) are:
ATC_ACCEL_P_MAX – 20000 for 30 inch props;
ATC_ACCEL_R_MAX – 20000 for 30 inch props;
ATC_ACCEL_Y_MAX – 9000 for 30 inch props;
ACRO_YAW_P – 0.5 * ATC_ACCEL_Y_MAX/4500.
Other filtering options that are derived from INS_GYRO_FILTER:
ATC_RAT_PIT_FLTD – INS_GYRO_FILTER/2;
ATC_RAT_PIT_FLTT – INS_GYRO_FILTER/2;
ATC_RAT_RLL_FLTD – INS_GYRO_FILTER/2;
ATC_RAT_RLL_FLTT – INS_GYRO_FILTER/2;
ATC_RAT_YAW_FLTE – 2;

ATC_RAT_YAW_FLTT – INS_GYRO_FILTER/2.

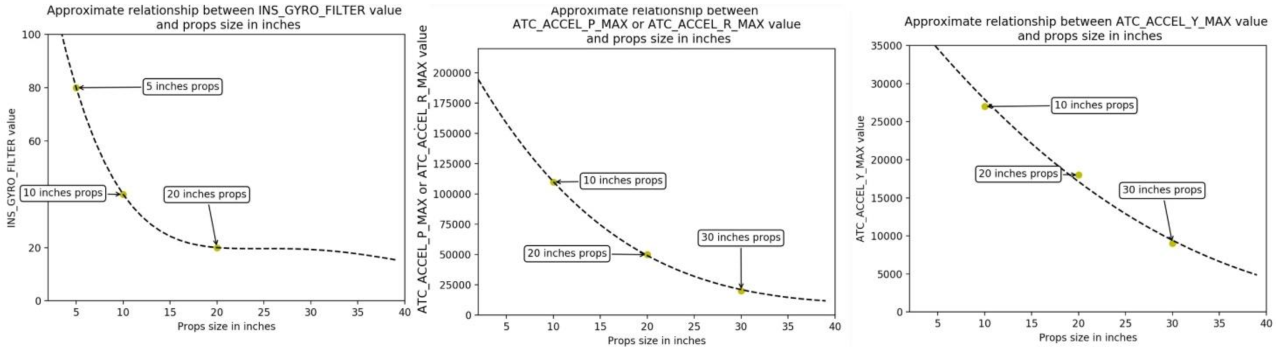

Fig. 6 The relationship between the propeller diameter and the parameters discussed above

After numerous flight tests, the PID controller parameters were set, that are presented in the Extended Turning tab (Fig. 7). It also shows the settings for some of the navigation flight modes (green box). For example, the waypoint speed is set to 11 m/s, the descent and ascent speed is set to 2.5 m/s. Some switches on the control equipment are set to flight modes and actions performed (orange box). For example, the sixth channel switch RC6 is set to return to the starting point, and channel RC9 works as a relay that switches two video systems.

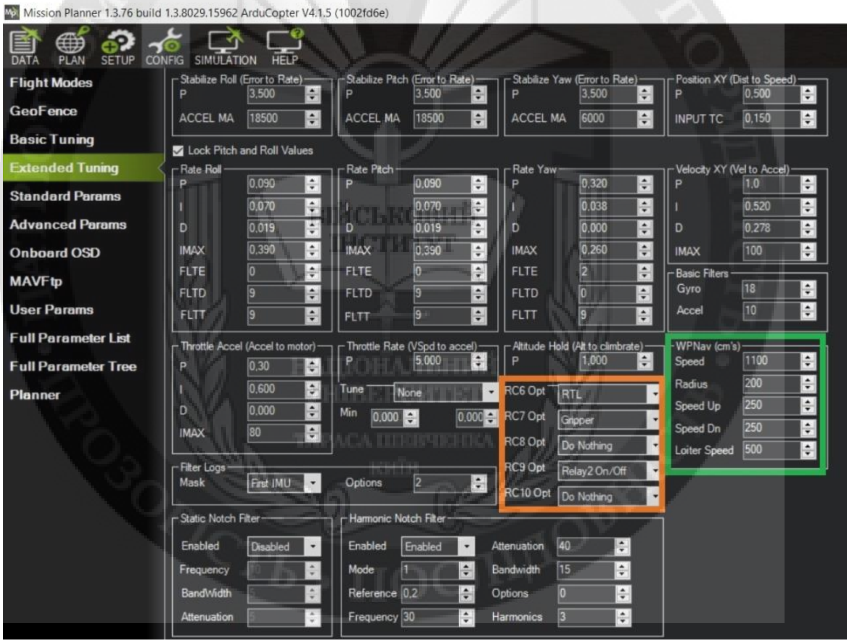

Fig. 7 The PID controller parameters

The Pixhawk family of flight controllers use the AUX OUT 1…6 ports for controlling the actuators. By default, the first four are used to connect servos, the AUX OUT 5,6 is to connect relays. However, these pins can be changed to servo outputs by setting BRD_PWM_COUNT to 6 and RELAY_PIN and RELAY_PIN2 to -1. The servo actuation modes can be different. For example, operation directly from the control panel. However, if limited servo travel is required, the appropriate channel must be set on the control panel. For example, the minimum value is 1250, the maximum is 1550. The second case, the servo setting is performed in the Camera Gimbal tab. In this case, the servo response range is configured in the flight controller. Moreover, each servo drive is assigned its own control equipment channel (Fig. 8). For example, the SERVO9 is assigned channel RC8. It should be noted that the AUX OUT ports 1…6 correspond to the SERVO9…14.
The servo can be assigned as Gripper. It's necessary for that:

- to set the output to RC, for example, the RC7 (7th channel) and to set the SERVO13_FUNCTION parameter to 28. In this case, the AUX OUT 5 on Pixhawk is used (Fig. 8);
- the GRIP_ENABLE parameter to 1 to enable the capture function, after that you need to reload Pixhawk;
- the GRIP_TYPE to 1 to enable servos in grip mode;
- the GRIP_GRAB to the PWM value (i.e. 1000 … 2000) for closed grip position;
- the GRIP_RELEASE to the PWM value for grip open position.
- the GRIP_NEUTRAL to the PWM value for the grapple's neutral position (usually the same as its closed position).

In the paper, the Gripper is tied to SERVO13 and RC7 (Fig. 8).

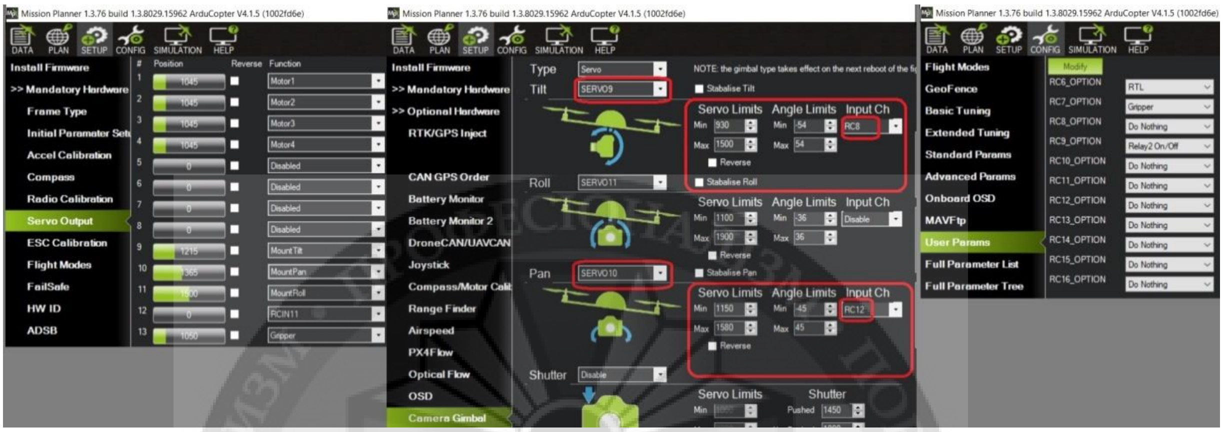

Fig. 8 The configuring flight controller pins for servo operation

In the paper, the switching between two video systems is performed using the relay output of the flight controller AUX OUT 6. For this, the BRD_PWM_COUNT parameter is set to 5. In the Standard Params tab, the AUXOUT6 is turned on at the Second Relay Pin (RELAY_PIN2) (Fig. 9).

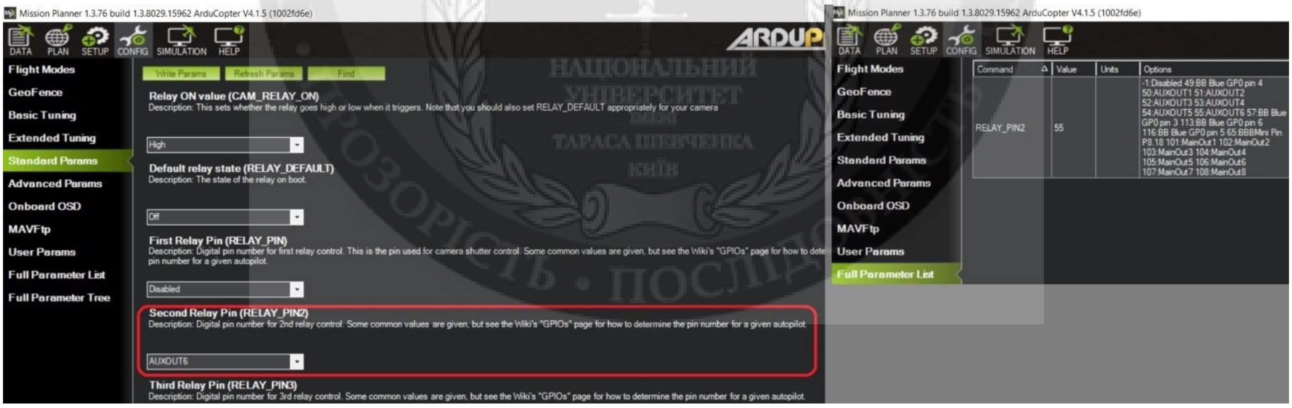

Fig. 9 The setting of the relay output to AUX OUT 6

After that, the value of the RELAY_PIN2 parameter will become equal to 55 (Fig. 9).
For ensuring the stable flight, it’s important to reduce the vibration amplitude, that is the characteristic of the propeller’s operation - the motor group. For this purpose, the flight controller is usually mounted on the frame using damping pads. However, the Pixhawk Cube family of flight controllers have the very effective damping pad, so they are rigidly attached to the frame. When assembling the original aluminum frame, the strong vibration was observed, that was apparently related to the natural frequency of the frame. The slight increase in the length of the beams of the frame led to the change in its oscillation frequency. After that, the flight vibration decreased to an acceptable value.

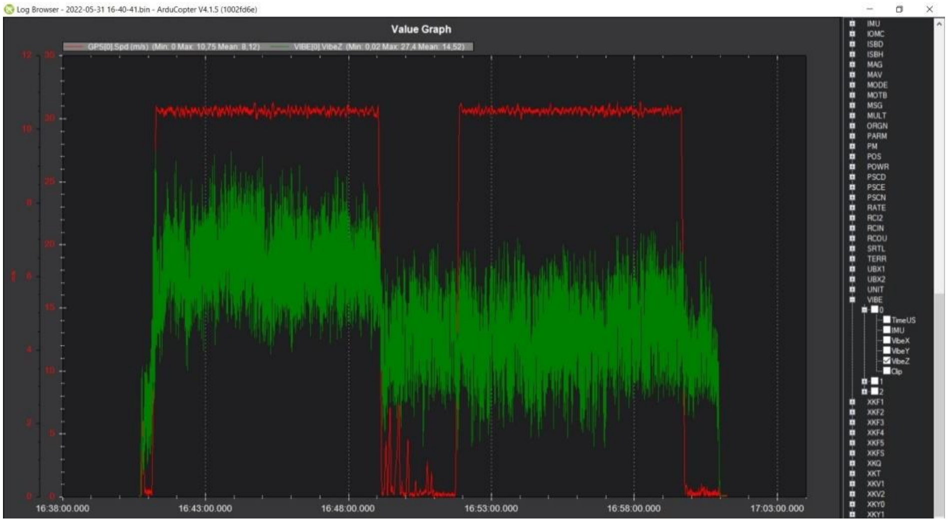

Fig. 10 The vibration pattern of the quadrocopter when flying at the distance of 10 km against and downwind

To remove additional vibration noise that cannot be removed using mechanical dampers inside the flight controller, the software filtering was used in the paper, that is implemented in the Ardupilot firmware. This is the notch filter that targets the frequency band generated by the rotation of the motors. The dynamic notch filters are the set of several filters placed on the harmonics of the fundamental frequency of the filter. Therefore, with proper tuning, the harmonics of the fundamental oscillation frequency can also be weakened. The basis for the operation of the dynamic notch filter is the control of its center frequency of motors rotation.

The paper considers the method based on the position of the throttle valve. In this case, the mid-throttle frequency is determined by analyzing the logs. The change in throttle position above the average value is used to monitor an increase in vibration noise frequency. Fig. 11 shows the amplitude plots for the gyroscope and accelerometer before and after the use of notch filters. For example, for an accelerometer, the amplitude of vibration oscillations decreased by more than 50 times at the frequency of about 30 Hz.

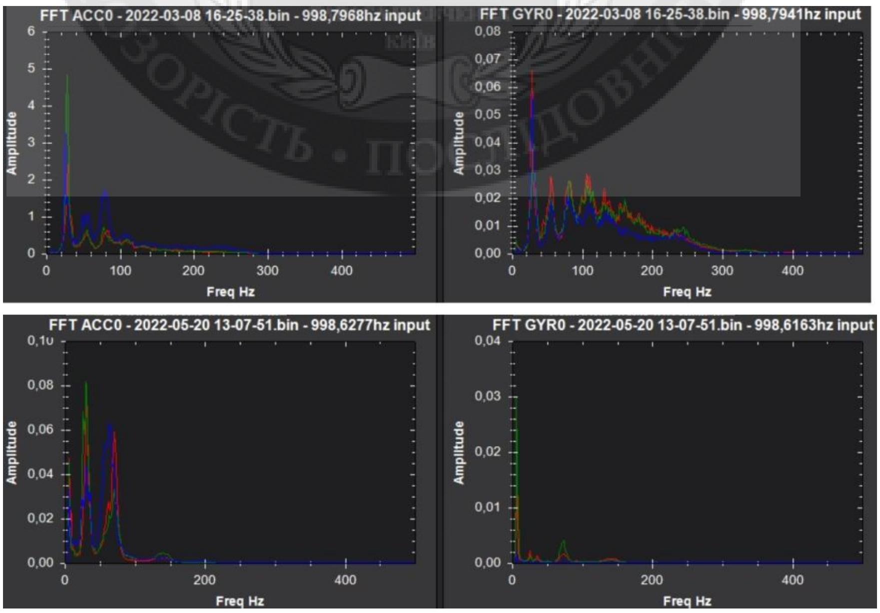

Fig. 11 The changing of the oscillation amplitude before and after the application of notch filters

A simple flight mission compiled using the Mission Planner ground station to test the copter flight over the distance of 10 km with payload drop from the height of 120 m is shown in Fig. 12.

Fig. 12 The flight mission of the designed quadrocopter at the height of 120 m with cargo drop

Conclusions

1. The design and configuration of the quadrocopter capable of carrying a payload of 10-15 kg at a speed of 38-40 km/h for 20-25 min, based on the Pixhawk 2 Cube flight controller using the Arducopter ver.4.1.5 firmware for FMUv3 devices, has been completed.
2. When building large quadcopters, before setting up the PID controller, it's shown that it's necessary to perform preliminary tuning of the parameters that are used by the PID controller. The failure to do so will often result in the large aircraft crashing on its first flight. These are motor thrust linearization parameters, acceleration values for different axes and filters that go to the input of the PID controller.
3. Experimentally tested the stability of the flight of the quadrocopter in windy weather in navigation modes for firmware Arducopter ver.4.1.5. At wind speeds up to 10 m/s with gusts up to 14-15 m/s, the flight stability was noted in automatic mode and in automatic return to the starting point mode.
4. The high accuracy of the Ardupilot firmware navigation system was established when the cargo drop point was reached in automatic mode. The error was no more than 1.0-1.5 m at a wind speed of 6-7 m/s.
5. The efficiency of mechanical vibration isolation of flight controllers of the Pixhawk Cube family has been experimentally established. When installing them on the frame of the copter, it's no need to use mechanical vibration decoupling. However, taking into account the low frequency of the frame oscillations from the operation of the motors (about 30 Hz), it's necessary to design the frame with the frequency of natural oscillations outside this range.
6. The using of software dynamic notch filters to reduce the impact of vibrations from running motors on the readings of the accelerometer and gyroscope is considered. On the frame of 2000 mm quadcopter, it's shown that such filters significantly reduce the amplitude of not only the detected fundamental frequency, but also harmonics.
7. The various ways of setting up actuators controlled by servo drives and relays for dropping loads, switching operating modes by video systems, switching on and off spraying mechanisms when using such drones in agriculture are considered.

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