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ТЕХНІЧНІ НАУКИ
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CONSTRUCTION OF THE ROTOR AND AIRCRAFT UAVS FOR FLIGHT ALONG A GIVEN TRAJECTORY USING TELEMETRY. COMPARISON OF THE TECHNOLOGIES, BENEFITS AND PROSPECTS FOR USING

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Abstract

In this research, the budgetary (no more than $ 120) UAVs of aircraft and rotary types have been designed, that are able to maintain altitude and position, automatically return to the takeoff point on command from the control panel or in case of loss of communication with it, perform automatic flight along a given trajectory and fly with taking into account telemetry data. It has been shown experimentally, that for flight on the mission on airplane to ensure a straight-line flight, it's advisable to use only a GPS receiver for navigation. The compass setting distorts the plane's straight flight. It was found that in navigation mode, the UAV flight along waypoints, the INAV firmware works more correctly, when the compass is installed in the direction corresponding to the direction of the gyroscopic sensor of the flight controller. Based on the results of flight tests, it was found, that a quadcopter flies waypoints much more accurately, than aircraft. It's shown, that it's possible, using the Blackbox INAV 2.5.0 toolkit and the Google Earth Pro service, to form

a real flight path of the aircraft and quadrocopter, to determine the speed parameters, and the flight altitude according to the readings of the GPS receiver. The possibility of using 3DR modules for telemetry flight has been established. It's noted in the work, that for ground stations implemented by INAV Configurator ver.2.5, the Mission Planner for INAV (Android) only MSP protocol works. No automatic switching to LTM protocol detected, that limits telemetry range compared to Ardupilot firmware. The constructed aircraft and quadrocopter can be used to perform photo and video surveys of the terrain in automatic mode with a route length of 6-8 km, using a lithium polymer battery with a capacity of 1500-2200 mAh.

Keywords: OMNIBUSF4V3, INAV 2.5, GPS receiver, STM32F405, UAV, OSD, ESC controller, Google Earth Pro, MPU6000, Firefly q6, FlySky FS-i6, Failsafe, 3DR, telemetry.

Анотація

У роботі спроектовані бюджетні (не більше 120$) БПЛА літакового та роторного типів, які в змозі утримувати висоту та позицію, автоматично повертатися в точку зльоту по команді з пульта управління або при втраті зв'язку з ним, виконувати автоматичний політ по заданій траєкторії та політ з обліком даних телеметрії. Експериментально показано, що для польоту місією на літаку для забезпечення прямолінійного польоту доцільно для навігації використання лише GPS приймача. Установка компаса перекриває прямолінійний політ літака. Встановлено, що в режимі навігації, польоті БПЛА по маршрутних точках прошивка INAV коректніше працює при установці компаса в напрямку, що відповідає напрямку установки гіроскопічного датчика польотного контролера. За результатами польотних випробувань встановлено, що квадрокоптер значно точніше пролітає маршрутні точки, ніж літак. Показано можливість за допомогою інструментарію Blackbox INAV 2.5.0 та сервісу Google Earth Pro формування реальної траєкторії польоту літака та квадрокоптера, визначення швидкісних параметрів, висоти польоту за показаннями GPS приймача. Встановлено можливість використання модулів 3DR для польоту телеметрією. У роботі зазначено, що наземних станцій, реалізованих програмами INAV конфігуратор ver.2.5, Mission Planner для INAV (Android) працює лише протокол MSP. Автоматичного перемикання на протокол LTM не виявлено, що обмежує дальність телеметрії в порівнянні з прошивками Ardupilot. Побудовані літак та квадрокоптер можуть застосовуватися для виконання фото та відео зйомок місцевості в автоматичному режимі з протяжністю маршруту 6-8 км при використанні літій полімерної батареї, ємністю 1500-2200 мАг.

Ключові слова: OMNIBUSF4V3, INAV 2.5, GPS приймач, STM32F405, БПЛА, OSD, ESC регулятор, Google Earth Pro, MPU6000, Firefly Q6, FlySky FS-i6, Failsafe, 3DR, телеметрія.

Introduction

For the study of the terrain, for carrying out rescue operations, in the work of fire services for monitoring crops, reconnaissance, including military, other special operations, it's currently of interest to build vehicles that fly along the given trajectory both in fully automatic mode and in manual mode, using the technology of the flight by FPV and telemetry [1-5]. For these purposes, the most common vehicles are both fixed-wing (the flying wing, airplane) [2] and the rotary type [1] (the quadrocopters, hexacopters). It's of interest to consider the flight of such device using telemetry data, that are constantly displayed during the flight at the ground station [6]. As such a station, the computer with software is usually used, that allows to visually form the UAV flight on the monitor screen, overlaying it on the map and displaying such parameters as flight speed, direction, altitude, current consumption, battery voltage, etc. To ensure such flight, in addition to software, the radio stations installed both on the aircraft and on the ground station are used. The telemetry for some protocols makes it possible to change the coordinates of predetermined points on the trajectory in real time, that allows to quickly change the flight trajectory in the On-line mode. Since telemetry equipment operates at lower frequencies than control consoles and video transmission systems for flying in the FPV mode, this makes it possible to control an object and track its flight over long distances with the same transmitter power. The paper considers aircraft assembled from fairly common budget components that use free software products that are open to correction and support the following flight modes [7]:

1. The horizon holding. A gyroscope and an accelerometer are used.

2. The given height maintaining. It requires the GPS receiver and barometric sensor.

3. The maintaining the position both in the horizontal plane and in the height. The GPS receiver and the barometric sensor are used.

4. The mode of returning to the starting point on command from the control panel and in case of communication's loss with the control equipment. Additionally, the magnetometer is used.

5. The flight mode along the trajectory specified on the map. Used the GPS receiver, barometer, magnetometer.

6. The semi-automatic flight mode using the telemetry data and ground station.

Materials and methods

To build the UAVs mentioned above, that are able to perform the presented flight modes, the authors propose to use a 32-bit STM32F405 microcontroller with sensors connected to it, forming the flight controller (FC). The processing of the received data from the gyroscope, accelerometer, barometer, magnetometer, GPS receiver, control receiver is performed by the microcontroller using the free software INAV ver.2.5.2 [8], the release of that appeared in August 2020. The result of data processing is the formation of control signals on motors and servos for the UAV flight control. The choice of this software from the cleanflight / betaflight firmware family is due to the fact that INAV provides automatic point-to-point flight, return to take-off point, and is capable of holding the altitude and position of the UAV. The study of the capabilities of the freely distributed Ardupilot firmware, that has similar capabilities, isn't considered in this reseach. The computer with the installed INAV ver.2.5 configurator is used [8] to install the firmware into the microcontroller, configure its parameters to ensure the performance of the specified UAV functions. It will also act as a ground telemetry flight control station [6].

The firmware is software for the microcontroller that uses mathematical models such as PID regulators [9-11], Kalman filter, complementary filter, LPF and Notch lowpass filters, dynamic Matrix Filter [10], etc.

To ensure a stable UAV flight, to fulfill the specified flight modes, the firmware is adjusted by selecting parameters that depend on the UAV geometry, the installed propulsion system, sensors, speed parameters, and flight trajectory [9,10]. In some cases, the program code is also partially corrected. The aim of the reseach is to create a budget (no more than $ 120) UAV (the aircraft and quadrocopter), the experimental study of them on the implementation of the above flight modes based on the STM32F405 microcontroller and the latest version of the INAV firmware [12,13]. The method for solving the problem is the design and improvement of flight controllers for aircraft and rotary UAVs that provide automatic flight along the given trajectory and flight by telemetry, as well as setting up freely distributed firmware for performing the above flight modes as a result of numerous flight test tests. When designing modern UAVs, the authors used their own developments of technologies and tools to improve quality and reliability, as well as to extend the technical resource of the developed equipment [14-17].

The solution to this problem is to design the flight controller for airplane and quadrocopter, adjust the firmware parameters together with the performance of test flight tests to adjust these parameters and, based on the data obtained from the blackbox [12], check the compliance of the actual flight path specified by the program.

The simple standard layout of aircraft with the rectangular wing, a span of 1250 mm and the fuselage length of 800 mm was chosen as the carrier for the fixed-wing UAV (Fig. 1). The optimization of geometric parameters in order to obtain the high aerodynamic parameters of the aircraft wasn't considered in the work.

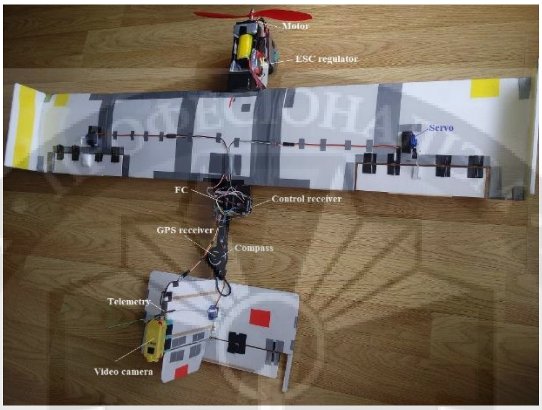

Figure 1 The photo of the tested aircraft.

The equipment is installed on the aircraft [18]:
– the A2212 / 1000KV motor with 30A ESC regulator;
– the propeller 12x4.5 inches;
– the GPS receiver - module GY-NEO6MV2 - GPS receiver u-blox NEO-6M;
– the budget control equipment - FlySky FS-i6 flashed from 6 to 10 channels with the communication range of up to 1.5 km [17];
– the flight controller - OMNIBUSF4V3 [19] based on STM32F405 LQFP64 microcontroller (168 Mhz, 1M Flash, 192 kB SRAM) with built-in gyroscope, MPU6000 accelerometer and BMP280 barometer;
– the battery 1800 mAh, 11.1 V;
– the recording video camera - Firefly q6;
– the telemetry 3 DR [6].

The flight weight of the aircraft was about 900 g.
The quadrocopter with the frame of 250 mm was chosen as the carrier for the rotor-type UAV (Fig. 2). The equipment is installed on the quadcopter:
the 2204 / 2300KV motor with 30 A ESC controller;

the propeller 5x3 inches;

the GPS receiver - u-blox NEO-6M;

the low-cost control equipment - FlySky FS-i6 flashed from 6 to 10 channels with a communication range of up to 1.5 km;

the flight controller - OMNIBUSF4V3 based on STM32F405 LQFP64 microcontroller (168 Mhz, 1M Flash, 192 kB SRAM) with built-in gyroscope, MPU6000 accelerometer and BMP 280 barometer;

the battery 1500 mAh, 11.1 V;

the video camera and video transmitter.

The flight weight of the quadcopter was about 500 g.

The connection diagram of electronic components for the aircraft is shown in Fig. 3. The servos of the wing ailerons, elevators and rudders are connected to the separate 5 V power supply. The flight controller, control receiver, GPS receiver are connected to another 5 V power supply, that is installed on the flight controller. The telemetry is connected to a 5V source, that is integrated with the ESC motor controller.

Figure 2 The photo of the tested copter.

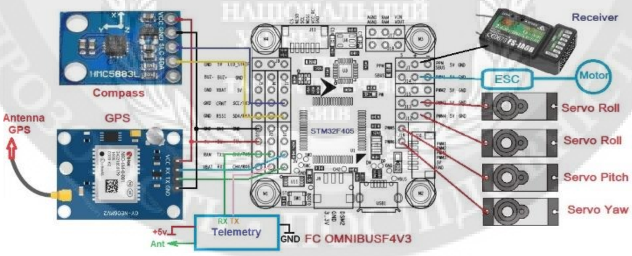

Figure 3 The connection diagram of the main electronic components for the aircraft.

The wiring diagram of electronic components for the copter is shown in Fig. 4. The video camera and video transmitter are connected to the separate power source. The copter sends telemetry data through the video transmitter, that are superimposed on the terrain image obtained from the video camera.

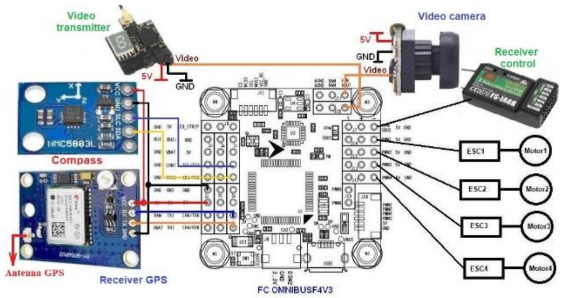

Figure 4 The wiring diagram of the main electronic components for the copter.

The firmware for the flight controller of the aircraft and the quadcopter is downloaded from the site: https://github.com/iNavFlight/inav/releases/tag/2.5.2, using the INAV 2.5.0 configurator, that is installed on the computer from the site: "https://github.com /iNavFlight/inav-configurator/releases/tag/2.5.0". The firmware can also be loaded into the controller, as presented in [19], if there are difficulties in loading through the configurator.

After starting the INAV 2.5.0 configurator, the computer is connected to the flight controller and the firmware parameters are set depending on the configuration of the aircraft and copter, used equipment, flight parameters, flight modes. For this, a sequential entry into the tabs of the configurator is performed with the setting of the necessary parameters [10,19]. The most necessary settings are discussed below.

The Mixer tab (on the Fig. 5a is shown for airplane and on the Fig. 5b is shown for quadcopter separately). The type of aircraft, the connection diagram of motors and servos to the flight controller are established. Sets the servo functions, such as which actuators control the elevators (Pitch), directions (Yaw), aileron (Roll).

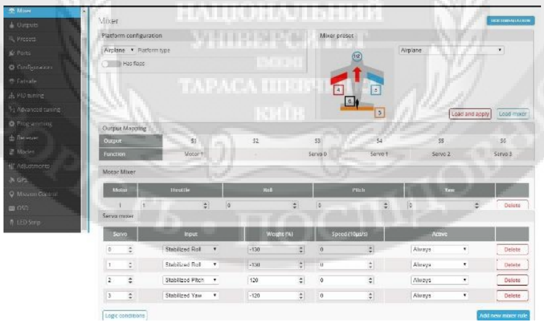

Figure 5 The Mixer Tab.

In the Calibration tab, the accelerometer is calibrated according to the scheme presented in this tab. In the Outputs tab, the protocols for the ESC operation of the motor controller, servo drives are set. The motor and servos are turned on - the Enable motor and servo output parameter and the motor is turned off, when the throttle is low - the Stop motors on low throttle parameter. In the Ports tab, the GPS receiver with speed of 38400 Bit / s is installed on the 6th port in accordance with the diagram of its connection to the flight controller in Figs. 3 and 4. For the aircraft, telemetry is connected to the flight controller on the UART1 port. The Fig. 6 shows the port setup in the Ports tab.

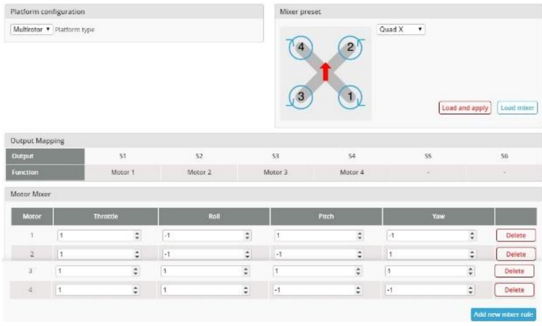

Figure 5b The Mixer Tab.

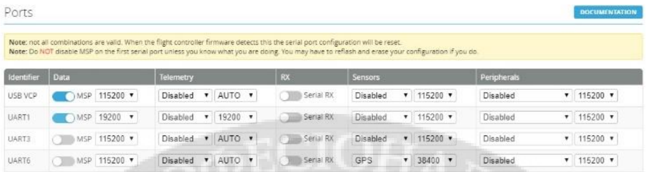

Figure 6 The installing ports for an airplane with telemetry.

In the Configuration tab, the parameters are set that determine the accelerometer, barometer, magnetometer, GPS receiver operation protocol, and the takeoff assistant mode is also enabled – "Permanently enable Launch Mode for Fixed Wing" (for an aircraft).

The Failsafe mode is being configured. To do this, use the Failsafe tab and the corresponding commands for this mode, that are entered in the CLI tab. The work uses the following case of failsafe activation.

Any channel is out of range, that can be determined using the commands in the cli tab: "get rx_min_usec"; "get rx_max_usec". In the reseach, in the CLI tab the command "set rx_min_usec = 940 was executed" is completed. When the control equipment is on, the minimum gas corresponds to the value greater than 1000. When it's off - 900 (it's how the receiver is configured). The value 900 is less than the minimum value of 940. It will trigger the Failsafe.

Before setting up Failsafe, the Flysky FS-iA6 receiver is preconfigured so that, when the remote control is turned off, it sends 900 µs pulse to the flight controller via the throttle channel (the 3rd channel - throttle), as presented in the source [20]. It means that failsafe will be triggered on this condition.

There are 4 commands available in Failsafe that are executed, when the failsafe occurs. The work uses the RTH command - return to the starting point. The INAV firmware automatically moves the UAV back to its original position and performs the landing of the quadcopter or circling the aircraft within a radius of 50 m above the landing site. The GPS receiver is used for this.

In the PID tuning tab, the parameters of the PID regulator of the aircraft and the quadcopter are set [9,18,21] (Fig. 7). Their determination was carried out by sequential selection during test flights in order to ensure maximum flight stability. The INAV firmware allows automatic tuning according to the special algorithm during manual flight. However, it doesn't always provide the best PID tuning.

Name	Proportional	Integral	Derivative	FeedForward
Basic/Acro	Aircraft			
Roll	20	7	0	50
Pitch	20	7	0	50
Yaw	0	0	0	60

Name	Proportional	Integral	Derivative	FeedForward
Basic/Acro	Quadcopter			
Roll	60	30	46	0
Pitch	63	30	48	0
Yaw	90	50	0	0

Figure 7 The parameters of the PID controller.

The flight parameters are set in the Advanced tuning tab. The airplane is set to Cruise, and the copter is set to Attitude. In this case, the flight controller of the aircraft constantly reads the coordinates from the GPS receiver. For an airplane, the flight speed by points is set to 10 m / s – the parameter is "max CRUISE speed = 1000". For the copter – 8 m / s. When approaching the launch point, the aircraft will circle circles with a radius of 50 m without landing – the parameter is "Loiter radius = 5000". The aircraft will land. The experimental setting of the throttle valve (throttle) values are important parameters for the automatic flight of the aircraft. For example, the value of the parameters "Cruise throttle" and "Max. throttle". If they are too small, then the altitude hold mode will not be possible. With an insufficiently powerful motor, their values are chosen large. For the aircraft being tested, "Cruise throttle = 1700" (it is the throttle value for maintaining straight flight while maintaining altitude) and "Max. throttle = 1950" - corresponds to the maximum engine speed for taking the aircraft to the set altitude. In this tab, the roll, lift and dive angles are set for automatic flight. They are chosen depending on the power of the engine and the strength of the aircraft. For the considered aircraft, they have values: 20, 20 and 15 degrees, respectively. The "At least mode" is selected as the mode for returning to the starting point [21]. It returns the aircraft, quadcopter to the starting point at an altitude not less, than that specified in the RTH altitude parameter (set to 30 m). If the aircraft's altitude was less, than the RTH altitude, when the RTH was triggered, then it rises to the return altitude. If more, then it returns at the same height. In this tab, you can set the number of satellites to which the GPS receiver must be connected in order to be able to confidently fly along the trajectory and perform the Arming procedure. Six satellites have been installed in the research. During testing, the installed GPS receiver in the open area is connected to 9-11 satellites. Similar settings were chosen for the aircraft, except that "the Fixed Wing Navigation Settings" item wasn't considered for the aircraft. It was experimentally found that the altitude determined by the GPS receiver within 15 min fluctuated in the range of no more than 1 m (at the launch site 323-324 m). Therefore, when the flight controller OMNIBUSF4V3 was configured, the barometer, installed in it, was sometimes turned off during experiments. As experience with quadrocopters has shown, at speeds of about 30 km / h, the effect of "blowing" the barometer occurs, that leads to incorrect altitude determination. Therefore, the barometer was pasted over with foam rubber.

In the Receiver tab, the protocol with the receiver works - PPM, is set and the correct operation of the control equipment channels and the throttle channel triggering, when the equipment power is turned off is checked to enter the Failsafe mode.

The airplane and quadcopter flight modes are set on the control panel switches in the Modes tab (Fig. 8), the description of the modes set for the UAV:

ANGLE - provides automatic holding of the UAV in the horizontal plane using the accelerometer;

NAV ALTHOLD - when the switch associated with the 6th channel is turned on, the flight is performed at a constant altitude determined by the GPS receiver and the barometer (if enabled) at the time of switching;

NAV POSHOLD – the automatic horizontal position holding.

If the NAV ALTHOLD mode is on, the position will also be held in altitude. Therefore, the modes NAV ALTHOLD, NAV POSHOLD are linked to the three-position switch. The aircraft maintains a position by flying in the circle with radius of 50 m at a constant altitude. In this case, the quadcopter hovers in the given 3D position. The gyroscope, accelerometer, GPS receiver, barometer are used.

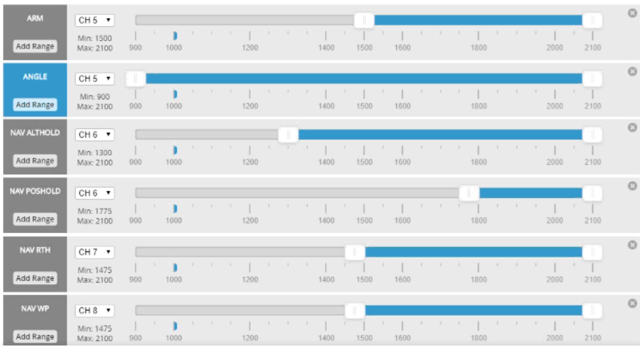

Figure 8 The setting flight modes on the control panel switches.

NAV RTH – the turning on of the 7th channel switch causes the UAV to return to the starting point. When approaching the launch point, the aircraft describes the circle with the radius of 50 m at the altitude specified by “the At least” and “RTH altitude” parameters of “the Advanced tuning tab”. The landing is performed in manual mode (ANGLE). The quadrocopter, when approaching the launch point, makes an automatic landing.

NAV WP - performs automatic flight to specified points on the geographic map. The launch is performed in manual mode, then this switch is turned on to follow the route. When approaching the launch point, the aircraft, as in the NAV RTH mode, flies in the circle with the radius of 50 m. The landing is carried out in manual mode after turning off the 8th channel switch. The quadcopter, when approaching the launch point, performs the smooth landing in automatic mode.

In the Mission Control tab (Fig. 9), the UAV flight is configured along the given trajectory. The computer with the INAV configurator must be connected to the Internet. The section of the map, where the flight is planned, is selected. The waypoints are set by clicking the mouse button. Each waypoint after the second click on it with the mouse displays its coordinates with the parameters of the flight height above it and the speed. These values can be edited. If you need to return to the starting point, check the box on the RTH at the end of the mission parameter. Above it, the plane will circle with radius of 50 m, that is specified in the Loiter radius parameter in the Advanced tuning tab. The quadcopter will hover over the start point at the RTH altitude parameter. If set to “Landing”, the aircraft will automatically land. The generated route is recorded by “the Save mission to FC” and “Save Eeprom mission” commands. The waypoint flight can be performed, if the radio control switch is set to NAV WP flight mode in the Modes tab.

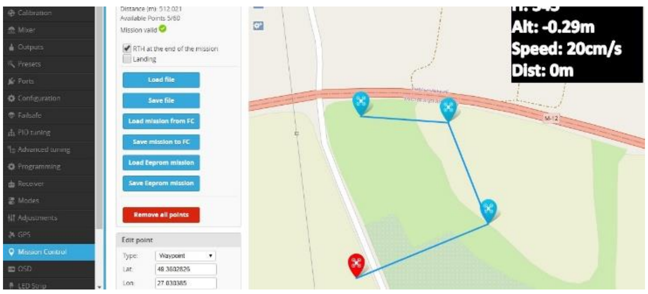

Figure 9 The formation of the aircraft flight path.

The point, to that the UAV returns after completing the mission, isn't displayed on the map. This point corresponds to the launch point, that can be anywhere. The sequence of points flown corresponds to the sequence of forming points on the map.

After loading the mission, "Arming" will be executed only, if the distance from the launch point of the aircraft, quadcopter to the first waypoint is less, than specified in "the nav_wp_safe_distance = 10000" parameter (100 m by default), the value of that can be increased to 650 m.

The parameter "nav_wp_radius = 100" in cm by default determines the distance of the UAV to the given waypoint in order to accept it as reached. For a quadrocopter, this value is set at 200 cm in operation. For an airplane, this parameter is set at 1000-3000 cm. It is due to the slowness of the GPS receiver (takes coordinates 5 times per second), the high speed of the airplane and the probable deviation from the trajectory, for example, due to wind. In operation, in the CLI tab, the command set "nav_wp_radius = 1500" (15 m) was executed. If the plane, for example, due to the wind deviates from the route and doesn't hit the point with diameter of 30 m, then it will describe the arc and return to re-pass the point until it hits it (Fig. 10).

To record the UAV flight parameters on the MicroSD card, in particular, the trajectory, speed, flight altitude, etc., the Blackbox tab is used. This tab enables recording of flight parameters to MicroSD [18].

In [18] it's shown, that for the aircraft-type UAV, it isn't necessary to use the compass and barometer for automatic flight along the given trajectory and return to the starting point. In this research, we experimentally studied the behavior of the aircraft, when flying by points with compass, barometer and GPS receiver and only with GPS receiver. To do this, using the INAV configurator, the flight mission was set as in Fig. 9, and the real flight route of the aircraft was drawn, using the generated LOG files on the MicroSD and the method for decrypting LOG files, that is indicated in [18], using the Google Earth Pro program [22]. The barometer and magnetometer were turned on and off in the Configuration tab. In fig. 10, from left to right, the aircraft flight paths are shown in the cases (the GPS receiver is turned on in all cases):

1) the flight trajectory without barometer and compass;

2) the flight trajectory with barometer and compass. The direction of installation of the compass and the flight controller is the same;

3) the flight trajectory with barometer and compass. The direction of the compass is rotated 270 degrees relative to the direction of the flight controller. This rotation is typical for GPS receivers with the integrated compass, for example, the Beitian BN-880 model, that is allowed by the INAV software. The rotation of the compass relative to the flight controller is set in the Configuration tab.

Figure 10 The flight trajectories of the aircraft with and without compass.

In Fig. 10 the yellow buttons show the points, that are set in the INAV navigator, when setting flight mission (Fig. 9). The analysis showed, that the INAV firmware works more correctly, when the compass is installed in the direction of the flight controller. The best results for the aircraft-type UAV are obtained, when using only the GPS receiver while flying along the trajectory in automatic mode.

The quadcopter initially requires the installation of GPS receiver, compass and barometer for flying to points. Based on the experience with aircraft-type UAV, the compass on the quadcopter is installed as in Fig. 11. In Fig. 12 shows the formation of the route, using the INAV configurator and the real flight route of the quadcopter according to the data from the Blackbox.

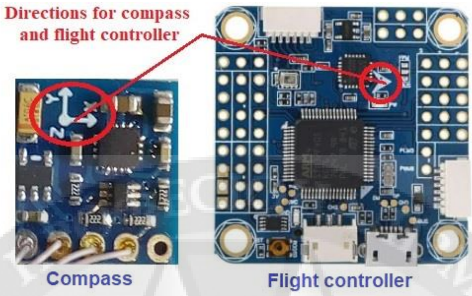

Figure 11 The selecting of the correct compass and flight controller direction.

The experimental studies have shown, that the quadcopter flies points much more accurately, than airplane. Despite the significant speed (about 30 km / h), the quadcopter manages to slow down, when approaching the point, turn around in the area of this point (the radius of 2 m is indicated), calculate the new direction and fly to the next point at given speed while maintaining the straight-line route. The plane overshoots the point at speed of 36 km / h at distance of 15-30 m. At high speeds, this distance increases.

Let's consider the use of telemetry, when flying the UAV, using the INAV firmware. Currently, it’s of interest to track UAV flight on the map in real time displayed on the computer screen, using the INAV software. With stable operation of equipment and software, it’s also possible to consider the possibility of controlling the aircraft based on the display of its flight on the computer screen according to telemetry data. To use this feature, you must use and configure some supporting technologies, including [6]:

- the GCS (the ground control station). GCS typically provides functions for creating the waypoint (WP) missions, loading WP missions to the flight controller (PC), checking a mission, completing a mission and registering a mission;

- the telemetry equipment. In order to transfer the mission to the PC and monitor it in real time during the mission, it’s necessary to install and configure the telemetry system between the GCS and the aircraft.

In order to transfer missions from the GCS to the flight controller and track / log flight data, a data link must be established between the GCS and the aircraft. For this purpose, the following most popular technologies are used [6]: Bluetooth; 3DR (433 MHz / 915 MHz); Wi-Fi (ESP8266); HC-12 (433 MHz, analog 3DR); Openlrs / Openlrsng devices (e.g. orangerx 433 tx / rx combo); LoRA (868/433 MHz options).

The work uses radio stations 3DR. They operate in the 433 MHz and 900 MHz bands. The 3DR standard firmware is designed for the MAVLink protocol. The current INAV recommendation is to use standard firmware with MAVLink options disabled. 3DR - medium range technology, at least 1 km.

Figure 12 The comparison of the quadcopter planned and real flight by points.

The data is transferred between the GCS and the flight controller using a "telemetry protocol". The INAV currently offers two protocols: MSP and LTM [6], MSP - Serial MultiWii is the “native” messaging protocol for INAV. It’s well supported by the INAV configurator and many OSDs that overlay telemetry parameters on the flight terrain display screen. The protocol has everything for loading missions and tracking flights. The disadvantage is that it’s the polling protocol and to monitor a mission, the GCS must request data, and the flight controller must respond to requests. This limits performance, when monitoring the mission.

LTM is a "push" telemetry protocol. Here, the flight controller is sending unsolicited data to the GCS. This avoids the "half duplex" MSP time delay on 3DR radios. Unlike MSP, LTM only provides flight data. To improve performance and increase range, MSP is used before Arming, LTM for Arming.

For INAV, the following rules apply [6]:

- if the UART detects both MSP and Telemetry Protocol (LTM), then MSP is active, when there is no Arming, and push-telemetry protocol is sent from FC, when it’s in Arming – e;

- if only MSP is enabled for USART, it’s always available (with Arming and without Arming).

Figure 13 The Example of Configuring Telemetry Ports.

In the example, shown in Fig. 13, MSP is available on USART1, when there is no Arming and LTM, when Arming (in this case, the 3DR telemetry radio and an mwp ground station are used). The baud rate is set the same for MSP and LTM. In operation, the port settings for telemetry are shown in Fig. 6, i.e. only MSP is enabled, as it has been experimentally determined, that the INAV configurator doesn’t support LTM during flight.

In operation, the 3DR radio station was selected as the equipment for telemetry. Its main characteristics: the weight <4 grams without antenna; the working frequency 433-434.79 MHz; the range is determined by the antenna, for a half-wave dipole at least 1 km; the receiver sensitivity - 121 dBm; the transmitter power 20 dBm (100 mW); the data rate up to 250 kbps (default 56700 bps).

A photograph of the 3DR radio modules with the supplied antenna is shown in Fig. 14. The experiment showed, that the range of the modules with such an antenna doesn’t exceed 100-150 m for viewing the flight using the INAV ver.2.5 configurator as a ground station. The Mission Planner for INAV (Android) showed similar results. The module on the plane was connected to the UART1 port as in Fig. 3. To increase the operating range, instead of installing the supplied antenna, two pieces of wire from the "twisted pair" network cable 165 mm long were soldered to the antenna output. Thus, the "classical half-wave dipole" antenna was installed. During testing such an antenna made it possible to establish a stable radio communication at the distance of up to 1 km. No further testing was performed.

Figure 14 The modified antenna-dipole 3DR modules with the frequency of 433 MHz.

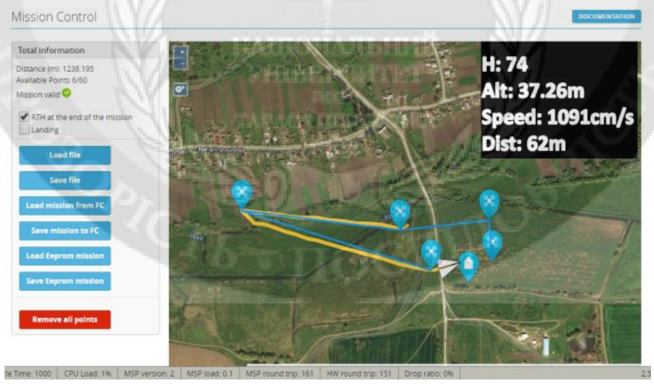

Figure 15 Airplane flight trajectory in on-line mode according to telemetry data.

During testing, the 3DR ground module with USB port was connected to the laptop via the USB extension cable. The 3DR module was attached to the wooden pole and the dipole antenna was positioned vertically. On the plane, the module was attached to the keel of the plane, so that the antenna - dipole was also vertical. Figure 15 shows a screenshot of computer screen during an aircraft's flight along the given trajectory in the Mission Control tab of the INAV configurator.

In the reseach, using Blackbox, the LOG files of flight parameters were obtained using only the GPS receiver. The data from these files were converted into the flight path and displayed, using the Google Earth Pro service, as presented in [18]. The maximum distance from the starting point was chosen at the distance of about 1 km so, that the communication is guaranteed to receive telemetry data.

In Fig. 16 shows the flight paths of the aircraft along the flight points set in the INAV configurator. The flight trajectory of the aircraft was tracked in on-line mode, using telemetry data, as in Fig. 15. The function of the ground station was performed by the INAV configurator in the Mission Control tab. No signal loss was observed, when the 3DR modules were operating at this distance and flight altitude of 50 m. The red buttons in Fig. 16 indicate the points on the map set by the configurator, when forming the route and recording it into the microcontroller's memory. The use of only the GPS receiver for navigation without the compass showed an accurate passage through the flight points and a straight line flight from point to point, that wasn’t observed with the additional use of the compass (Fig. 9).

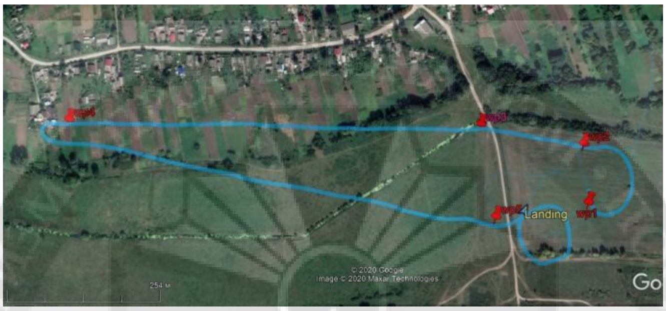

Figure 16 Flying using only GPS receiver at the distance of up to 1 km from the starting point.

For quadcopter flight using telemetry, the OSD setup was performed for INAV firmware. The OSD (On Screen Display) is a software chip (AT7456) in the flight controller, that overlays flight data (the telemetry: flight altitude, speed, distance from take-off point, direction to take-off point, etc.) to the video transmitted from the quadcopter. In Fig. 17 shows the OSD setting [9]. As a result, the video image of the terrain will be superimposed on the flight speed, distance to the take-off point, flight altitude, flight time, number of received satellites, battery voltage, flight mode, horizon level.

Figure 17 The OSD setup.

With so using of telemetry, the set telemetry parameters are located in the convenient form on the monitor screen of the video receiver, while simultaneously viewing the flight terrain. However, the range of the video transmitter is shorter, than, when using the telemetry presented above for an aircraft at the same transmit power. Also, the ground station better allows you to track the route on the map. Experience has shown that the best control option, tracking UAV flight, is the simultaneous use of these two technologies.

Results and discussion

As a result of the research:

1. The low-cost (no more than $ 120) UAVs of aircraft and rotary types have been created, that are able to maintain altitude and position, automatically return to the take-off point on command from the control panel or if communication with it is lost, perform automatic flight along the given trajectory and fly from taking into account telemetry data.

2. It has been experimentally shown, that for flight on the mission on airplane to ensure the straight-line flight, it's advisable to use only the GPS receiver for navigation. The compass setting distorts the plane's straight flight. It's shown as for INAV firmware ver.2.5 on the example of airplane and it was noted, when testing the quadrocopter on the INAV firmware with an earlier version (ver.2.2.1).

3. It's shown, that in the navigation mode, the flying along waypoints, the INAV firmware works more correctly, when the compass is set in the direction corresponding to the direction of the gyro sensor of the flight controller.

4. Based on the results of flight tests, it was found, that the quadcopter flies waypoints much more accurately, than an aircraft. Despite the significant speed (30 km/h), the quadcopter manages to slow down, when approaching a point, turn around in the area of this point, calculate a new direction and fly to the next point, maintaining the straight-line route. The aircraft overshoots the waypoint at speed of 36 km / h at the distance of 15-30 m.

5. It's shown, that it's possible, using the Blackbox INAV 2.5.0 toolkit and the Google Earth Pro service, to form a real flight path of an aircraft and the quadrocopter, to determine the speed parameters, and the flight altitude according to the readings of the GPS receiver.

6. It has been established, that for ground stations implemented by INAV Configurator ver.2.5, the Mission Planner for INAV (Android), only the MSP protocol works. No automatic switching to LTM protocol detected, that limits telemetry range compared to the Ardupilot firmware.

7. It has been established, that for the significant increase in the telemetry range on 3DR modules, it's necessary to replace the supplied antennas with the simpler and lighter antenna "half-wave dipole". Its disadvantage is its increased size (the length of the dipole is 330 mm).

aircraft flight controller prior to launch, using the configurator.

Conclusions

1. The paper presents the results of designing budget UAVs of aircraft and rotor types with a cost of no more than $ 120, that are able to maintain altitude and position, automatically return to the take-off point on command from the control panel or in case of communication's loss with it, perform automatic flight according to the given trajectory and flight taking into account telemetry data. It's shown that for flight on a mission on an airplane to ensure a straight-line flight, it's advisable to use only the GPS receiver for navigation.

2. It was found, that in the navigation mode, the UAV flight along waypoints, the INAV firmware works more correctly, when the compass is set in the direction corresponding to the gyroscopic sensor's direction of the flight controller. Based on the results of flight tests, it was found, that the quadcopter flies waypoints much more accurately than an aircraft.

3. The possibility is shown, that with the help of the Blackbox INAV 2.5.0 toolkit and the Google Earth Pro service, the formation of a real flight path of aircraft and the quadcopter, determination of

speed parameters, flight altitude according to the readings of thr GPS receiver. The possibility of using 3DR modules for telemetry flight has been established.

4. There is no automatic switching to LTM protocol detected, that limits telemetry range compared to Ardupilot firmware. The constructed aircraft and quadrocopter can be used to perform photo and video surveys of the terrain in automatic mode with the route length of 6-8 km, using the lithium polymer battery with capacity of 1500-2200 mAh.

References

[1] A. Boyko. Fields of application of drones, Available at: http://robotrends.ru/robopedia/oblasti-primeneniya-bespilotnikov, accessed December 2020.

[2] Modernized Spectator Drone from OJS S.P. Korolyova “Meridian Company”, Available at: https://www.youtube.com/watch?time_continue=6&v=HvLErmgBRX4&feature=emb_logo, accessed December 2020.

[3] S. A. Shvorov, N. A. Pasichnyk, S. D. Kuznichenko, I. V. Tolok., S. V. Lienkov, L. A. Komarova. Using UAV during Planned Harvesting by Unmanned Combines, *IEEE 5th International Conference Actual Problems of Unmanned Aerial Vehicles Developments*, ISBN: 978-172812592-3, 2019, p. 252-257.

[4] V. Lysenko, Y. Gunchenko, S. Shvorov, S. Lenkov, S. Kuznichenko, E. Lenkov. Methodological Bases of Construction of Intensive Training Flight Simulators of Aircrews. *Proceedings 5th International Conference “Methods and Systems of Navigation and Motion Control”,* ISBN: 978-153865870-3, p. 198 – 203.

[5] First Person View (FPV), Available at: https://ru.wikipedia.org/wiki/First_Person_View_(FPV), accessed December 2020

[6] INAV Flight Missions, Available at: https://github.com/iNavFlight/inav/wiki/iNavFlight-Missions, accessed November 2020.

[7] Modes, Available at: https://github.com/iNavFlight/inav/wiki/Modes, accessed November 2020.

[8] INAV Configurator 2.5.0, Available at: https://github.com/iNavFlight/inav-configurator/releases/tag/2.5.0, accessed October 2020.

[9] S. Lienkov, A. Myasischev, O. Banzak, Y. Husak, I. Starynski. Use of rescue mode for UAV on the basis of STM32 microcontrollers. *International Journal of Advanced Trends in Computer Science and Engineering.* Vol. 9, No.3, ISSN 2278-3091, p. 3506-3513, DOI: 10.30534/ijatcse/2020/156932020.

[10] A. A. Myasishchev. Features of Implement of INAV Firmware On Omnibusf4v3 Flight Controller for Rotor Type UAV, Khmelnytskyi: ХНУ, № 2, 2020, p. 126-134.

[11] N. Pasichnyk, S. Lienkov, S. Shvorov, L. Komarova, D. Komarchuke, O. Opryshko. The use of UAVs with the "Slantrange" sensor system to estimation crop safety base on technological stress and intoxication of plants. *Information Security*. №45, ISSN: 0861-5160, p. 21-33, 2020, DOI: 10.11610/isij4502.

[12] The Basics of Getting iNav Working on an Airplane, Available at: https://github.com/iNavFlight/inav/wiki/Fixed-wing-guide, accessed December 2020 .

[13] Serhii Lienkov, Oksana Banzak, Yuriy Husak, Ihor Muliar, Viktor Cheshun, Evgeny Lenkov. The Development of an Intelligent Complex of Radiation-Technological Control of a Safety Barrier. *International Journal of Emerging Trends in Engineering Research.* Vol. 8., No. 7, ISSN 2347 – 3983, p. 3483-3486, 2020, DOI: 10.30534/ijeter/2020/97872020.

[14] S. Lienkov, G. Zhyrov, O. Sieliukov, I. Tolok, A.-S. M. Talib, I. Pampukha. Calculation of Reliability Indicators of Unmanned Aerial Vehicle Class 'μ' taking into account Operating Conditions at the Design Stagempukha, *IEEE 5th International Conference Actual Problems of Unmanned Aerial Vehicles Developments*, ISBN: 978-172812592-3, p. 52-56, 2019.

[15] S. Lenkov, G. Zhyrov, D. Zaytsev, I. Tolok, E. Lenkov, T. Bondarenko, Y. Gunchenko, V. Zagrebnyuk, O. Antonenko. Features of modeling failures of recoverable complex technical objects with a hierarchical constructive structure. *Eastern European Journal of Advanced Technology*. №4/4(88), p. 34 – 42, DOI:10.15587/1729-4061.2017.108395.

[16] G. Zhyrov, S. Lienkov, Yu. Husak, H. Banzak, I. Tolok. Analysis of problem optimization of parameters maintenance process according to state with constant periodicity of control. *International Journal of Emerging Trends in Engineering Research*. Vol. 8, No. 6, ISSN 2347–3983, DOI: 10.30534/ijeter/2020/63862020.

[17] S. Lienkov, O. Sieliukov, E. Lienkov, I. Tolok, V. Loza. Evolution of Radars Resolution Capability Using Simulation Mathematical Model. *Proceedings 5th International Conference "Methods and Systems of Navigation and Motion Control",* ISBN: 978-153865870-3, 2018, p. 195 – 197.

[18] S. Lienkov, A. Myasischev, O. Banzak, L. Komarova, N. Lytvynenko, O. Miroshnichenko. Construction of an Aircraft-Type UAV for Flight Along a Given Trajectory in the Automatic Mode. *International Journal of Emerging Trends in Engineering Research*. Vol. 8, No. 9, ISSN 2347 - 3983, DOI: 10.30534/ijeter/2020/200892020.

[19] A. Myasishchev. Possibilities of the CC3D Flight Controller with INAV Firmware, *Visnik KhN, Technical sciences*, №1, 2019, p. 129-136.

[20] Failsafe quick setup for APM with Flysky-i6 Setup arducopter failsafe, available at: https://www.youtube.com/watch?v=aZ1A5rAK0uo&t=127s.

[21] S. Lienkov, A. Myasischev, L. Komarova, N. Lytvynenko, V. Shvab, O. Lytvynenko. Creation of a Rotor-Type UAV with Flight Controllers, Based On a ATmega2560 and STM32f405

Microprocessors. *International Journal of Emerging Trends in Engineering Research*. Vol. 8, No. 8, ISSN 2347 – 3983, DOI: 10.30534/ijeter/2020/104882020.

[22] Google Earth, Available at: https://en.wikipedia.org/wiki/Google_Earth, accessed December 2020.