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Research of a Vertical Takeoff and Landing Micro UAV in the Plane Mode with the Onboard Control - Measurement System

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Abstract:- The article describes the onboard control-measurement system developed for recording the main technical parameters of vertical takeoff and landing (VTOL) micro-UAV motors and the data determining the airframe's attitude during the flight. Using this system, the methodology of conducting a test flight has been developed to perform a diagnostic check of its motors and assess its condition using the VTOL micro-UAV in plane mode. Also, during the test flights, the number of revolutions, current consumption, and temperature of each motor, as well as angular changes along the three coordinate axes and acceleration of the airframe, were measured and recorded, and time graphs of the parameters were created based on these values. Analysis of the created time graphs allows for direct researching of the UAV in take-off, hover, flight and landing modes. The possibility of small-sized mini and micro unmanned aerial vehicles to diagnose their motors before, during, and after the flight, that is, to directly identify possible flight events in the air during the flight due to engine failure and to perform appropriate intervention has been shown by using of the developed onboard control - measuring system. It has been shown to allow time graphs and analysis of parameters by measuring and recording the number of revolutions, current consumption and temperature of each engine, as well as angular changes along three coordinate axes and airframe acceleration during test flights. This allows for a direct assessment of the state of the drone.

Keywords*:* VTOL, micro unmanned aerial vehicle, onboard control - measurement system, inertial measurement unit, accelerometer, gyroscope, RPM.

1. Introduction

Achievements obtained with the application of artificial intelligence in the fields such as mechatronics, information technologies, aerospace, have made it possible to increase the development of unmanned aerial vehicles to a higher level. Currently it is very relevant to solve the issue of comprehensively measuring, recording the technical and telemetric data in static and dynamic modes and transferring them to the monitor of the operator's control panel in real time during laboratory tests and practical flights of micro unmanned aerial vehicles (micro-UAVs). In order to solve this issue in medium and large UAVs, the required number of sensors and "flight data recorder" can be easily placed on board.

Despite the large volume of work in this direction, a comprehensive solution to this issue has not been presented for micro-UAVs. Existing micro-UAVs are known to transmit some telemetry data (e.g., horizontal and vertical flight speed, flight altitude and distance, flight duration, battery voltage and current consumption value, number of GPS satellites) from the board to the ground in real time via a radio transmitter. This data is received both at the ground control panel and at the operator's control display.

[1] describes the onboard control - measurement system developed to monitor the technical parameters of the micro-UAVs propulsion system and the attitude indicators of the airframe, as well as to comprehensively collect data about these parameters.

It is possible to synchronously record information about the technical parameters of the collectorless electric motors included in the propulsion system of the micro-UAV and the attitude indicators of the airframe using the onboard control-measurement system. Here, the technical parameters refer to the number of revolutions -

RPM1...RPM5 (revolution per minute), current consumption - I1...I5 and temperature - T1...T5 of four lifts and one thrust motor. Indications of the gyroscope - G1...G3 that generates data about the direction of the aircraft axes and the velocity vector and the accelerometer - A1...A3 are used as attitude indicators of the airframe.

The onboard control - measurement system allows to record the specified parameters both during ground operation and flight of the UAV. At the same time, the number of revolutions of the motors is transmitted to the ground control panel, which is used as a receiving display by means of a radio transmitter and recorded during flight. The propulsion system of the aerial vehicle and thus the safety of the flights is controlled during the real flight based on the number of revolutions indicated on the screen of the control panel. Based on the recorded values of the parameters, the aerial vehicle is diagnosed and it is decided to allow it to the next flight [2, 3].

Purpose of the work – is to diagnose the propulsion elements of UAV in different flight modes and to detect the problems in real time by systematically collecting data on the technical parameters of the VTOL micro-UAV motors, using the developed onboard control-measurement system.

2. Current situation

The works required for comprehensively diagnose the aviation equipment after the flight and evaluate the flight by recording the technical parameters of the collectorless electric motors included in the propulsion system of the VTOL micro UAV during flight, as well as to prevent the recurrence of the happened emergency situation in the next flights has not been found in the research works currently carried out in this direction as a result of the analysis of the scientific and technical literature.

In [4], the structural, aerodynamic, power and weight characteristics of the fixed-wing UAV were comprehensively researched, and the analytical methods were described for calculating its aerodynamic indicators. It has been noted that one of the important conditions for choosing the most efficient configuration of the airframe is to determine the aerodynamic characteristics of the UAV at the initial design stage. It has been shown that the method of numerical evaluation of aerodynamics is more efficient than the method of experimental research to solve this issue.

In [5], the design of the "onboard data acquisition system" to calculate the possible aerodynamic characteristics during the free flight of UAV, the functional scheme of the in-flight parameter registration system and the work algorithm are described. The hardware application of the proposed system for UAVs has been considered in the article and it has been shown that the collected data eliminates the need to test UAV models in the wind tunnels to determine their aerodynamic properties, and also saves time and money spent on developing new models. High accuracy of the trajectory parameters' measurement of the aircraft considering the linear accelerations and angular velocities that occur during movement is of particular importance in the calculation of the UAV's aerodynamic characteristics with the proposed method.

In [6], an "onboard recording device" for UAVs is described. The device receives, compresses, saves to the memory and transmits to the ground unit the telemetry data on board during the normal UAV operation. It has been noted that it is possible to control actuators, for example, the parachute release system, through the control interface in the emergency mode.

3. Technical support parts of the Onboard control – measurement system

The parts used in onboard control – measurement system are described in Table 1 [7].

Table 1: Parts used in the on-board control and measurement system.

№	**Item**	**Description**	**Qnt**
1	Main controller	ESP32, TTGO T-Display	1
2	Memory card	microSD	1
3	Onboard radio transmitter	FS-i6 "Flysky"	1

4	Voltage converter	12 V-u 5 V-a	1
5	Battery	3S LiPo	1
6	Inertial measurement unit	ITG/MPU-6050	1
7	Current sensor	ACS758	5
8	Number of revolutions sensor	FS-CPD02	5
9	Temperature sensor	DS18B20	5

4. List of supplies and equipment needed to conduct the tests:

VTOL UAV, 6S type battery, ground control panel (“Futaba”), ground display, 3 SD memory cards, onboard control – measurement system (Based on the ESP-32 controller), video camera or mobile phone, ground control panel of the onboard control – measurement system (“Flysky”), time measuring device (stopwatch or mobile phone) [8, 9].

a)

b)

Fig. 1. Practical test flights of VTOL unmanned aerial vehicle in VTOL-plane modes

5. Preparation for work

1. Verification of the installation reliability of the equipment on the aerial vehicle that serves to adjust and control avionics, as well as the aerodynamics;

2. Verification of the current, temperature, RPM sensors and inertial measurement unit’s (accelerometer + gyroscope) availability and installation reliability on the onboard control – measurement system;

3. Checking the accuracy of the centering of the aerial vehicle with respect to the center of gravity;

4. Formatting two microSD memory cards in FAT32 file system;

5. Inserting the first memory card into the card module (Onboard control – measurement system is turned on even when there is no memory card, in this case information about the absence of a memory card is displayed on the LCD screen);

6. Inserting the second memory card into the ground control display used as a telemetry data receiver (telemetry data is measured by the flight controller, so the monitor does not relate to the onboard control – measurement system);

7. Connecting a 6S Li-Po type battery to the aerial vehicle;

8. Connecting a 3S Li-Po type full battery to the onboard control – measurement system as an autonomous power source;

9. Starting the four lift motors and making sure the motors are running;

10. Ensuring that meteorological indicators are within the limits of the aerial vehicle's flight parameters.

The moment (time) of applying the voltage to the onboard control – measurement system is recorded based on the lit of the relevant indicators before the flight. At this time it is need to verify:

- starting from that moment, the technical parameters of the motors are being recorded to the memory card in the onboard control – measurement system ("SD card" text is displayed on the onboard control – measurement system screen);
- telemetry data is being recorded to the memory card in the control display;
- The values displayed on the screen of the control panel are being seen in the additional place used for recording the number of revolutions of the motors and are being recorded as a video image (are being recorded to memory).

6. Conducting tests of VTOL micro UAV in different flight modes

6.1. Tests conducted in stationary mode

To conduct the tests in the stationary mode, the position of the 4 lift propellers rotating clockwise and counter-clockwise has been changed. In this case, the rotation of the lift propellers does not generate lift and, on the contrary, presses the airframe of the UAV to the ground. No propeller was installed to the thrust motor for safety reasons, but the airframe was additionally attached to the laboratory bench.

The data of the lift motors' starting moment and the number of revolutions of the motors displaying on the screen of the ground control panel ("Flysky") of the onboard control – measurement system has been recorded by a video camera. During the research, acceleration movements on 3-axis coordinate systems were performed by directing the aerial vehicle to the right-left and up-down together with the laboratory bench to which it was attached and the rotation of the motors at different speeds and the switch to the plane mode were performed. At this time, the thrust motor started to operate, and from that moment on, the lift motors gradually stopped operating.

The air temperature was 37 °C, the pressure was 760 mmHg, and the wind speed was 0 m/s in the laboratory conditions during the research.

Tests conducted in stationary mode and their results are described in detail in [1, 2, 8-11].

6.2. Tests conducted in VTOL mode

In order to research the take-off, hovering and landing of the aerial vehicle in VTOL mode, 4 propellers rotating clockwise and counter-clockwise were installed to the lift motors, and seven flights were performed with a duration of 6...7 minutes (Fig. 1, a). The air temperature was 12 °C, the pressure was 760 mmHg, the wind speed was 3-4 m/sec stable from 20°, the wind gust was 5-6 m/sec during the flights. Practical tests conducted in VTOL mode in the field conditions and their results are described in detail in [3, 7].

6.3. Tests conducted in VTOL-plane mode

In order to check the flight stability of the VTOL micro-UAV based on the hybrid flight concept, test flights were performed in the airfield conditions and the indicators of the propulsion system obtained by means of the onboard control – measurement system were researched.

In order to research the flight of the aerial vehicle in VTOL-plane modes, relevant propellers were installed to both the thrust and lift motors of the UAV, and 10 test flights were performed with a duration of 7...8 minutes in meteorological conditions suitable for flight at different times of the day (Fig. 1, b).

The time graphs created from the results of two flights are presented in the article as examples of recorded and archived data. The correspondence of the technical parameters of the motors and the output signals of the IMU shows the accuracy of the research. The time graphs of the various parameters have been created on the same scale to show the synchronous variation of the values recorded during the flight (Fig. 2 and Fig. 3).

6.3.1. Test 1

The air temperature was 22 °C, the pressure was 765 mmHg, the wind speed was 4-5 m/s from 185°, and the wind gust was 8-10 m/s during the test (Fig. 2).

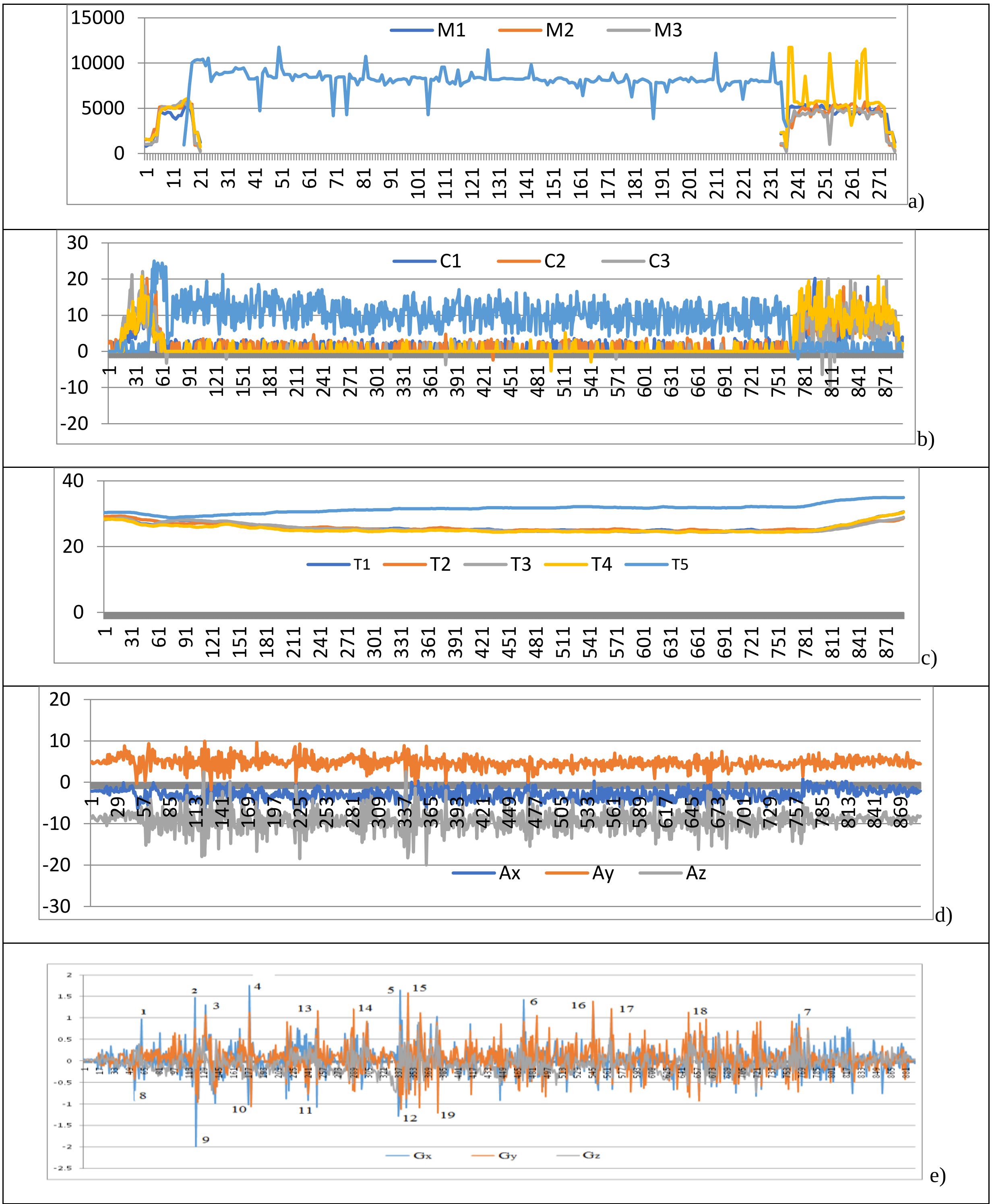

Fig. 2. The time graphs of motors' number of revolutions (RPM) - a, current consumption (A) – b, temperature (°C) – c, accelerometer – d and gyroscope – e output signals created based on the values recorded by the onboard control - measurement system during the test flights performed in the VTOL-plane mode under simple metrological conditions

The test period can be divided into four stages based on the time graphs of the motors number of revolutions: 1) Motor operation while the UAV is on the ground; 2) UAV climbing or take-off and hovering in the air; 3) Transition of the UAV to the plane mode and flying in this mode; 4) Transition of the UAV from plane mode to hovering mode and landing (Fig. 2, a).

In the first stage, the number of revolutions increased from zero to less than 5000 RPM for the lift motors and was zero for the thrust motor. The current consumption increased from zero to 10 A for the lift motors, but did not reach this value, and it was zero for the thrust motor during this period (Fig. 2, b). There was no change in the temperature of both thrust and lift motors at this stage (Fig. 2, c).

In the second stage, the number of revolutions increased from zero to 5000 RPM for the lift motors during increasing speed or climbing, and then remained at about this value during the hovering. Current consumption increased from 10 A to 20 A for lift motors during climbing, and was equal to zero for thrust motor (Fig. 2, b). Despite the increase in current consumption during climbing, the temperature of the lift motors decreased by 1...2 °C from the initial value (Fig. 2, c).

In the third stage, the number of revolutions decreased from 5000 RPM to zero for the lift motors and increased from zero to 10000 RPM for the thrust motor at the moment of transition (Fig. 2, a).

During this period, the current consumption decreased from 20 A to zero for the lift motors, and on the contrary, it increased from zero to approximately 25 A for the thrust motor (Fig. 2, b). As a result, the temperature of the lift motors decreased with a certain delay and adapted to the ambient temperature.

The thrust motor temperature increased relatively proportionally to the power applied to it from the moment of transition to the plane mode and then remained relatively constant in the steady state of flight (Fig. 2, c).

Finally, in the fourth stage, the number of revolutions of the thrust motor decreased to zero, and increased from zero to 5000 RPM in the lift motors (Fig. 2, a). The current consumption decreased from 10 A to zero for the thrust motor and increased to more than 10 A for the lift motors (Fig. 2, b). The temperature of the lift motors started to increase in proportion to the supplied power during the hovering and landing (Fig. 2, c).

It is clear from the graphs that the number of revolutions and temperature of the motors are proportional to their current consumption in all stages of flight (Fig. 2, a – Fig. 2, c).

However, despite the increase in the current consumption of the motors to provide the necessary lift during the climb, the reason for the temperature of the motors to decrease from the initial value is the increasing air flow coming from the propellers due to the motor’s high rotation speed.

In general, in the case of both an increase and a decrease in the applied power, the moment of change in the temperature of the motors is delayed with respect to the moment of change in the number of revolutions and current consumption. This is more obvious in transition between modes.

For example, the number of revolutions of the motors and accordingly the air flow coming from the propellers which serves to reduce the motor’s temperature, decreases sharply, and finally becomes zero during landing at the end of the flight. As a result, in a short time, the temperature of the motors increases by 2-3 °C without reaching dangerous limits, and over time, the temperatures of the motors and the environment become equal.

During the flight, it is proven that the VTOL micro UAV provides horizontal balance and stability, and the output signals of the gyroscope and accelerometer along the x, y, z axes are stable against wind and wind gust (Fig. 2, d and Fig. 2, e). The increase of the gyroscope output signal along the X-axis at points 1-12 of the wind reverse resistance and along the Y-axis at points 13-19 is described in Fig. 2, e.

6.3.2. Test 2

During the tests, the air temperature was 25 °C, the pressure was 757 mmHg, the wind speed was 6-7 m/s from 200°, and the wind gust was 11-12 m/s. According to the motors’ number of revolutions graphs, the 2nd test flight has been divided into seven stages (Fig. 3) [9].

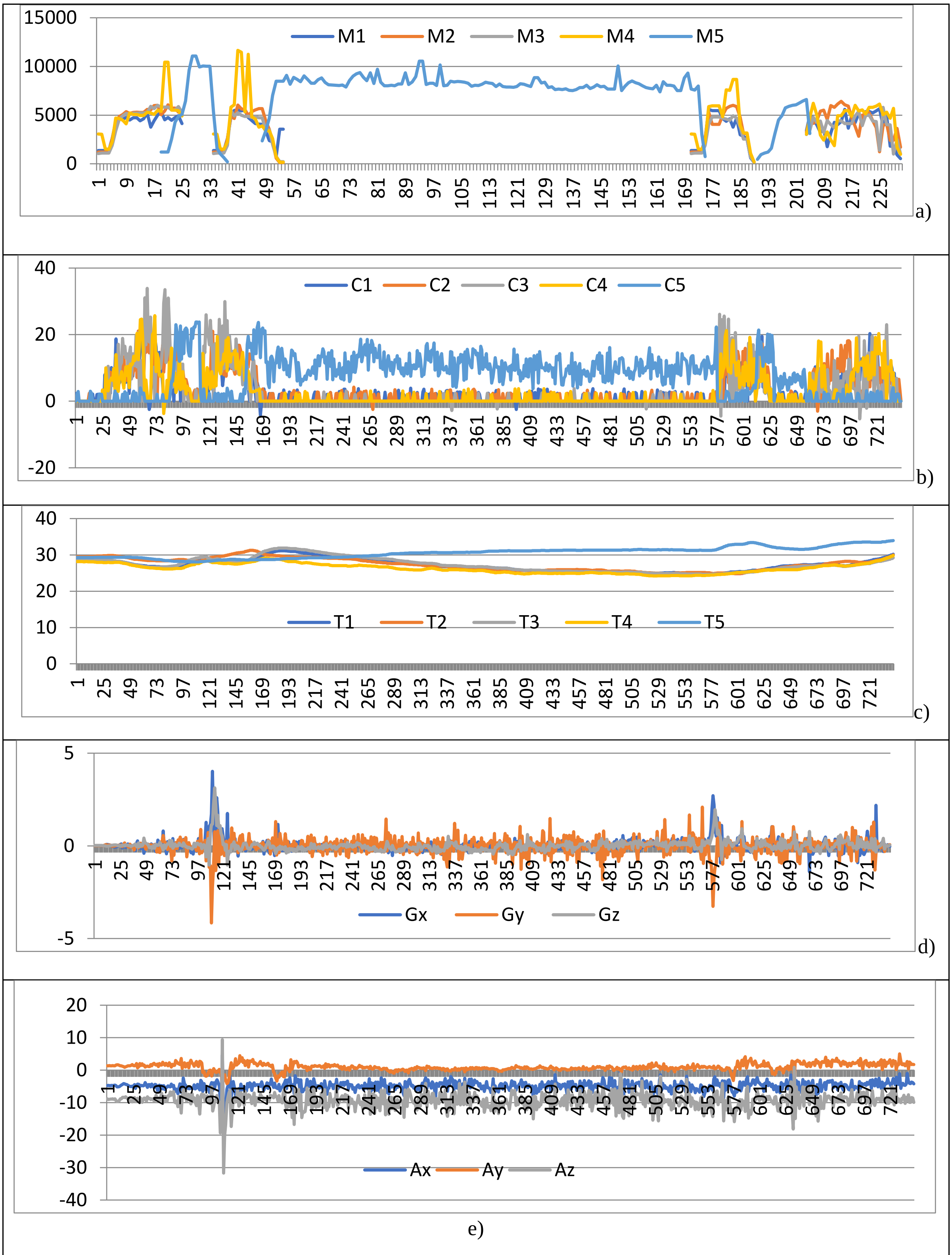

Figure 3. The time graphs of motors' number of revolutions (RPM) - a, current consumption (A) – b, temperature (°C) – c, accelerometer – d and gyroscope – e output signals created based on the values recorded by the onboard control - measurement system during the test flights performed in the VTOL-plane mode under complex metrological conditions

1. The UAV started flying in VTOL mode and the flight duration lasted 30 seconds. In this mode, the number of revolutions of the lift motors was more than 5000 RPM, but the number of revolutions of the thrust motor was zero.

2. The transition to plane mode begins. At this stage, the number of revolutions of the lift motors has decreased to zero, and the number of revolutions of the thrust motor increased over 10,000 RPM. After 25 seconds of flight in plane mode, an increase in wind gust has been detected, and for safety reasons it was switched to VTOL mode.

3. The UAV has been brought closer to the ground to a height of 1-2 m in VTOL mode, and the number of revolutions of the motors matched to 20...25% according to "throttle" handle.

4. The flight was continued by switching from VTOL mode to plane mode. The longest flight was performed at this stage. The UAV showed stability against the wind during the flight.

5. The plane mode has been changed to VTOL mode for experimental purposes.

6. After 30 seconds of flight in VTOL mode, the UAV was returned to the plane mode.

7. A safe landing of the aerial vehicle was ensured by switching from plane mode to VTOL mode at the end of the flight.

It is possible to determine the number of revolutions, current consumption and temperature of the motors corresponding to the stages of the UAV flight from the time graphs presented in Fig. 3, a – Fig. 3, c.

Comparing the graphs in Fig. 3, a and Fig. 3, b, it can be seen that the number of revolutions and current consumption of the lift and thrust motors have increased according to the power required to maintain the aerodynamic balance in hover and plane modes due to the increase in wind gust in the 3rd and 4th stages of flight.

It is possible to clearly see the transition moments of the UAV from VTOL to plane mode and vice versa from the time graphs of both the number of revolutions (Fig. 3, a) and the output signals of the IMU (Fig. 3, d and Fig. 3, e). It can be seen as well from the time graphs that the IMU output signals are smooth while the motors are running on the ground, but the noise level in the output signals increases relatively from the moment of take-off. Thus, it is possible to determine whether the UAV is on the ground or in the air based on the level of noise in the output signals of the IMU.

7. CONCLUSION

1. Diagnostic checks and condition assessment of the motors of the VTOL micro-UAV were carried out in plane mode and the methodology of conducting test flights has been developed using the onboard control-measurement system designed to record the main technical parameters of the motors of the VTOL micro unmanned aerial vehicle and the data determining the attitude of the airframe during flight.

2. Creation and analysis of the time graphs of the parameters by measuring and recording the number of revolutions, current consumption and temperature of each motor, as well as the angular changes along the three coordinate axes and the acceleration of the airframe during test flights, allows direct assessment of the state of the unmanned aerial vehicle.

3. It is possible to diagnose the motors of small mini and micro-UAVs before flight, during flight and after flight, and to identify possible flight events in the air due to motor failure and immediately perform appropriate intervention by using the developed onboard control - measurement system.

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