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Original Research Article

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ON-BOARD CONTROL-MEASUREMENT SYSTEM FOR MICRO CONVERTIPLANE-TYPE UNMANNED AERIAL VEHICLES

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Abstract. *The article describes the on-board control-measurement system designed to record the main flight parameters of a micro-convertiplane type unmanned aerial vehicle and the element base used for this purpose. The methodology of conducting tests in stationary mode through the on-board control-measurement system was developed and tests were carried out. The engine's diagnostic check and condition assessment has been performed using the on-board control-measuring system. The possibility of on-ground check of the micro unmanned aerial vehicles power elements before and after the flight, as well as the possibility of monitoring the flight events that may occur in the air during the flight has been shown. The data on the power consumption and temperature of each engine in the stationary mode, the direction of the aircraft axes and the velocity vector have been recorded by mean of the developed on-board control-measurement system, as well as time dependence diagrams of the corresponding parameters have been built in comparative order based on the obtained values. A methodology has been developed for the diagnostics of the engine operation of the micro-unmanned aerial vehicle before and during the flight. It has been shown that the temperature, power consumption and number of revolutions of the engines included in the power system of the aircraft, as well as the aircraft axes and velocity vector direction data is recorded during the flight, by mean of the on-board control-measurement system designed to collect data on the flight-technical parameters of the convertiplane-type micro-unmanned aerial vehicles.*

Keywords: convertiplane, unmanned aerial vehicles, on-board control-measurement system, accelerometer, gyroscope, diagnosis, thermometer

1. Introduction

Achievements obtained in aerodynamics, navigation systems, electronics, robotics, information technologies, etc. have allowed to raise the development of unmanned aerial vehicles (UAV) to a higher level [1]. The directions of development of UAVs are mainly military, law enforcement, environmental monitoring, mapping, aerial photography, cargo transportation, film and TV industry and academic research.

Currently, it is very relevant to solve the problems of recording flight, flight-technical and telemetric data during laboratory and practical flight studies of micro UAVs, as well as transmitting them to the ground in real time. Despite the implementation of large-scale works by scientific-research, project-constructor and specialized companies operating in this direction, no comprehensive solution to the issue in dynamic mode during flight has been presented.

In order to solve these problems in medium and large UAVs, the required number of sensors and a centralized on-board recording system (FDR - Flight data recorder) are easily placed on board. Data received from the aircraft's power, power distribution, inertial navigation and propulsion systems is synchronously recorded to the permanent memory of the onboard recording system via a central computer, and is used

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during flight evaluation and post-flight diagnostics of aircraft equipment. Some telemetry data ($v_{horizontal}$, $v_{vertical}$, v_{wind}, H_{flight}, $T_{weather}$, $T_{flight\ duration}$, GPS_{number}, $D_{distance}$) is transmitted in real-time from on-board to the ground via a radio transmitter in micro UAVs. This information is received both at the ground control station and at the operator's display. However, in a convertiplane-type aircraft consisting of four lift engines, no research study has been found on the solution of a comprehensive approach to the works to be done in order to record the main flight, flight-technical parameters of each engine during the flight, flight evaluation and post-flight diagnostics of aircraft equipment, prevent the recurrence of the emergency situation in subsequent flights [2]. The following refers to flight-technical parameters:

- $\dot{I}_1...\dot{I}_5$ – current consumed by engines (A);
- $T_1...T_5$ – relevant temperatures of engines (°S);
- $RPM_1...RPM_5$ – revolution per minute;
- $A_1...A_3$ – accelerometer indication;
- $G_1...G_3$ – gyroscope indication.

Most of the UAV flight performance characteristics can be determined in the laboratory in stationary mode, but some of them must be determined only in dynamic mode during flight.

Work objective. Conducting tests in real flight conditions by creating an on-board control-measurement system to systematically collect information about the flight-technical parameters of the convertiplane-type UAV in flight mode ("online").

The collected information serves to increase the reliability and efficiency of the UAV's work, as well as the safety of flights. Based on the obtained flight data about the power consumption and temperature of each engine, the direction of the aircraft axes and the velocity vector, it is possible to carry out diagnostics of technical devices, especially engines and other propulsion elements, to timely detect and control events that may occur on the UAV’s board during flight.

2. Problem statement

Taking into account the arbitrary direction of the engine thrust vector, a method to increase the reliability of determining the flight characteristics of a UAV for a given aerodynamic configuration has been solved in the research work related to the field of experimental aerodynamics [3]. The method of determining the aerodynamic characteristics of the UAV is based on the measurement of the numerical value of the flight velocity using hardware and devices during the acceleration of the aircraft.

The parameters of electric drives and controlled movement of a tricopter-type UAV during vertical take-off and land are described in [4]. Taking into account the requirements of weight and dimensions, the calculation of the aerodynamic parameters of the UAV has been carried out using the "XFLR5" software. The lift and drag coefficients of the UAV were determined depending on the angle of attack based on the "vortex" method, and the influence of the wing profile on the calculated aerodynamic properties has been analyzed.

The design of an on-board data collection system to calculate the aerodynamic characteristics of the UAV, which is only possible during free flight, is described in [5]. A functional diagram and algorithm of operation of the flight parameters recording system are presented. The proposed solutions allow collecting a large amount of data and increasing the efficiency of the system due to selecting and compressing.

It has been noted that the collected data eliminates the need to test UAV models in wind tubes to determine their aerodynamic properties, and allows saving money and time spent on developing new models. It is shown that the frequency of polling-measuring devices is increased to speed up data transmission and increase the accuracy of measurements during data exchange between system elements. In order to calculate the aerodynamic characteristics of the UAV through the proposed method, it is noted that the parameters of the flight trajectory, as well as the linear accelerations and angular velocities that occur during the movement, are measured with high accuracy. The hardware version of the proposed system for UAVs has been reviewed in the article.

An on-board recording device for UAVs is described in [6]. The on-board telemetry data of the UAV is received, compressed, stored and transmitted to the ground unit via the device during normal operation. It has been noted that in emergency mode it is possible to control actuators, for example, the parachute release system, via the control interface.

The structural, aerodynamic, power and weight characteristics of an aircraft-type UAV were comprehensively studied in, and analytical methods for determining and calculating its aerodynamic characteristics have been described [7]. It has noted that one of the important conditions for choosing the most efficient configuration of the glider is the determination of the aerodynamic characteristics of the UAV at the initial and design stage. In order to solve this problem, numerical evaluation methods of aerodynamics are widely used instead of expensive experimental research methods.

The power consumption and temperature of each engine in the aircraft, the direction of the aircraft axes and the velocity vector data are recorded during the flight via the developed on-board control-measurement system [8].

3. Experimental technique

Technical support of on-board control-measurement system:

The description of the on-board control-measurement system installed on the convertiplane-type UAV is described in Fig. 1. The list of modules and elements used in the recording device is given below: ESP32 controllers; 5×ACS758 current sensor; 5×FS-CPD02 sensor; 5×DS18B20 digital temperature sensor; IMU sensor; TTGO T-Display module; microSD card module; FS-i6 “Flysky” ground control console; 12 V to 5 V voltage converter; 3S LiPo type battery [9].

Fig. 1. Convertiplane-type UAV with installed on-board control and measurement system.

4. Results and discussion

4.1 Research in static mode

Necessary supplies and equipment: convertiplane type UAV; ground control console (“Futaba”); ground monitor; on-board control-measurement system (based on ESP-32 controller); ground control console of the on-board control-measurement system (“Flysky”); 3S or 4S type battery; 6S type battery; 3 SD memory cards; video camera or mobile phone; timing device (stopwatch or mobile phone).

Preparation for work

1. A reset memory card is inserted into both ground monitor and on-board control-measurement system.
2. The horizontal position of the UAV is ensured.
3. The position of the 4 lifting blades rotating clockwise and counter-clockwise is changed. At this time, the rotation of the lift blades presses the glider of the UAV to the ground (no lift is generated).
4. For safety reasons, no blade is attached to the thrust engine.
5. 5 current, 5 temperature, 5 RPM sensors, accelerometer and gyroscope are checked for both presence and tight fastening in the on-board control-measurement system.
6. The ground monitor is switched on.
7. 6S type battery is connected to the UAV. From this moment on, the telemetry data transmitted from the flight controller to the ground is displayed on the ground monitor and recorded to the memory card in the monitor. The following are the telemetry data: - voltage of the battery on board, GPS number, flight altitude, flight range, horizontal and vertical flight velocities.

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8. First, 4 lift, then 1 thrust engine are activated by remote control.

9. A 3S or 4S type battery is connected to the on-board control-measurement system, from this moment the flight parameters are recorded to the memory card on it, information about the number of revolutions of each engine appears on the screen of the system's ground control console ("Flysky").

10. The information displayed on the screen of the on-board control-measurement system’s ground control console is recorded in video format. A video camera or mobile phone is used for this purpose, then the engines are shut down.

11. The system is ready for research.

Research progress

1. The life engines are started and the starting time is recorded.
2. The information about the number of revolutions of the engines, which appears on the screen of the ground control panel ("Flysky") of the on-board control-measurement system, is recorded by a video camera.
3. Depending on the duration of the study, the engines are rotated at different speeds.
4. Accelerations on 3-axis coordinate systems are performed by moving the laboratory table with the aircraft attached on it, to the right-left and up-down.
5. The switching to glider mode is performed, and the 5th engine is started, from this moment the lifting engines are gradually getting shut down.
6. During the study, timelines were recorded sequentially by parameters, all recorded indicators were archived and studied.

Based on the received data, appropriate timelines were created using the "Excel 2016" program *(Figure 2)*. It is determined from the diagram that at the start of the engines, the temperature and current consumption of the 4 engines operating in multicopter mode start to increase proportionally to the number of revolutions (5-th engine does not work) *(Figure 2, a and b)*. At this time, the power consumption and temperature of each engine begin to vary proportionally to the received flight information about the direction of the aircraft axes and velocity vector. It is more obvious from the diagram where the indicators of the accelerometer and gyroscope change according to the turning moments of the aircraft in the right-left and up-down directions *(Figure 2, d and e)*.

As described in Figure 2, c - When the UAV switches from the "multicopter" flight mode to the "glider" flight mode, that is, from the moment the thrust engine is started, the number of revolutions, temperature and current consumption of the 5th engine begin to increase over time, and the temperature and current consumption indicators of the lifting engines decrease accordingly, and also the revolutions number of the engines has a "zero" indicator. At the same time, the accelerometer and gyroscope indicators change depending on the movement dynamics of the UAV.

The diagram describes that shortly before the end of the experiment, the aircraft switches to the “multicopter” flight mode, and the indicators for this mode are repeated, as at the beginning of the flight.

The diagram of engine revolutions’ number versus time has been built on the basis of the data recorded from the screen of the ground control console of the on-board control-measurement system ("Flysky") via a video camera during the tests.

4.2 Diagnostics of engines

To diagnose the engine, parameters (S1...S4) and (RPM1...RPM4) have been used.

Here:

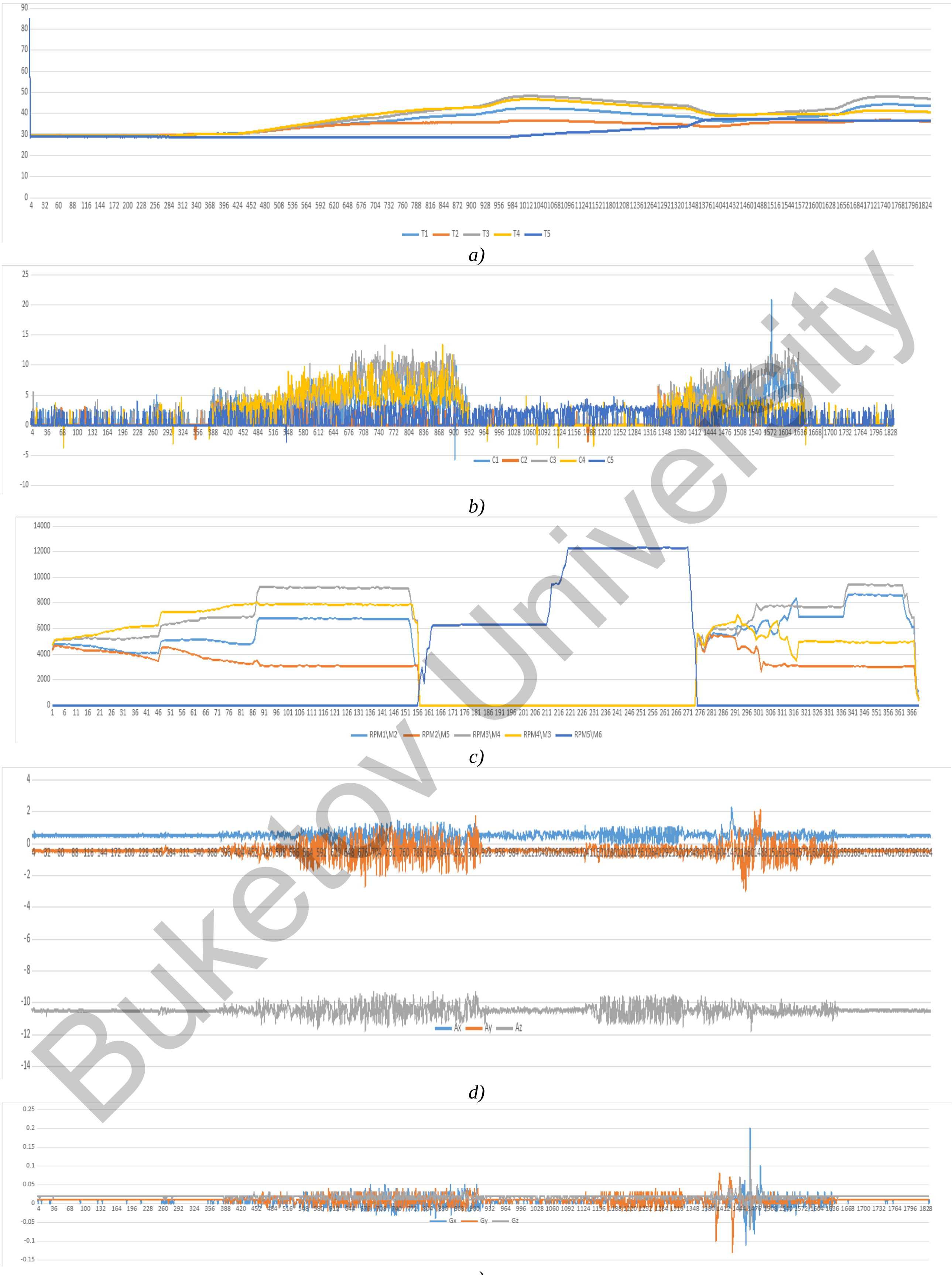
$S_1...S_4$ - is a control signal generated by the flight controller that controls the rotational speed of the four lift engines accordingly;

$RPM_1...RPM_4$ - is the number of real revolutions recorded at a given time for each engine.

The configurations obtained from the combinations of control signals applied to them while maintaining the location of the engines in the glider construction have been used for diagnostics (Figure 3). In all configurations (I-IV), the position of the inertial sensor (IMU) consisting of a three-axis accelerometer and a gyroscope and the value of the corresponding signals remained unchanged.

In configuration I described in Figure 3, for a given aircraft, the location of the engines on the glider and the sequence of distribution of the corresponding control signals in the flight controller is determined by the manufacturer (programmer).

The other three configurations (II-IV) have been used for diagnostic evaluation purposes. In configuration I, the rotation speed of the 1st front engine was higher than the 2nd one.



a)

b)

c)

d)

e)

Fig. 2. Timelines built based on the indicators recorded by the on-board measurement system during the tests conducted in the stationary mode – temperature (°S) a), current (A) b), number of revolutions of the engines (RPM) c), accelerometer d), gyroscope e) and "Excell 2016" software.

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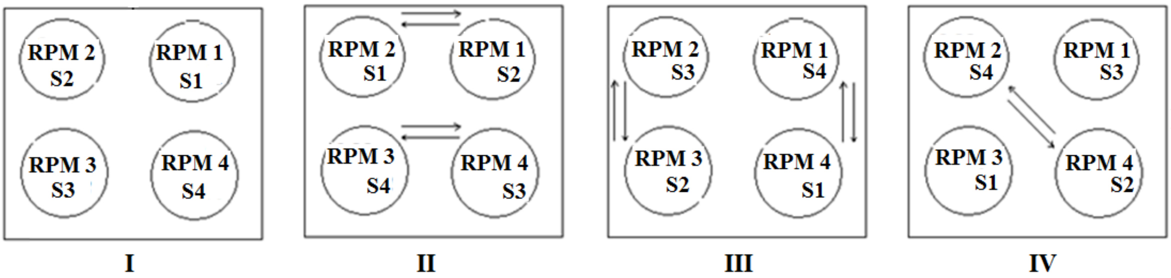


Fig. 3. Configurations corresponding to the possible displacement of the control signals of the lift motors in the flight controller.

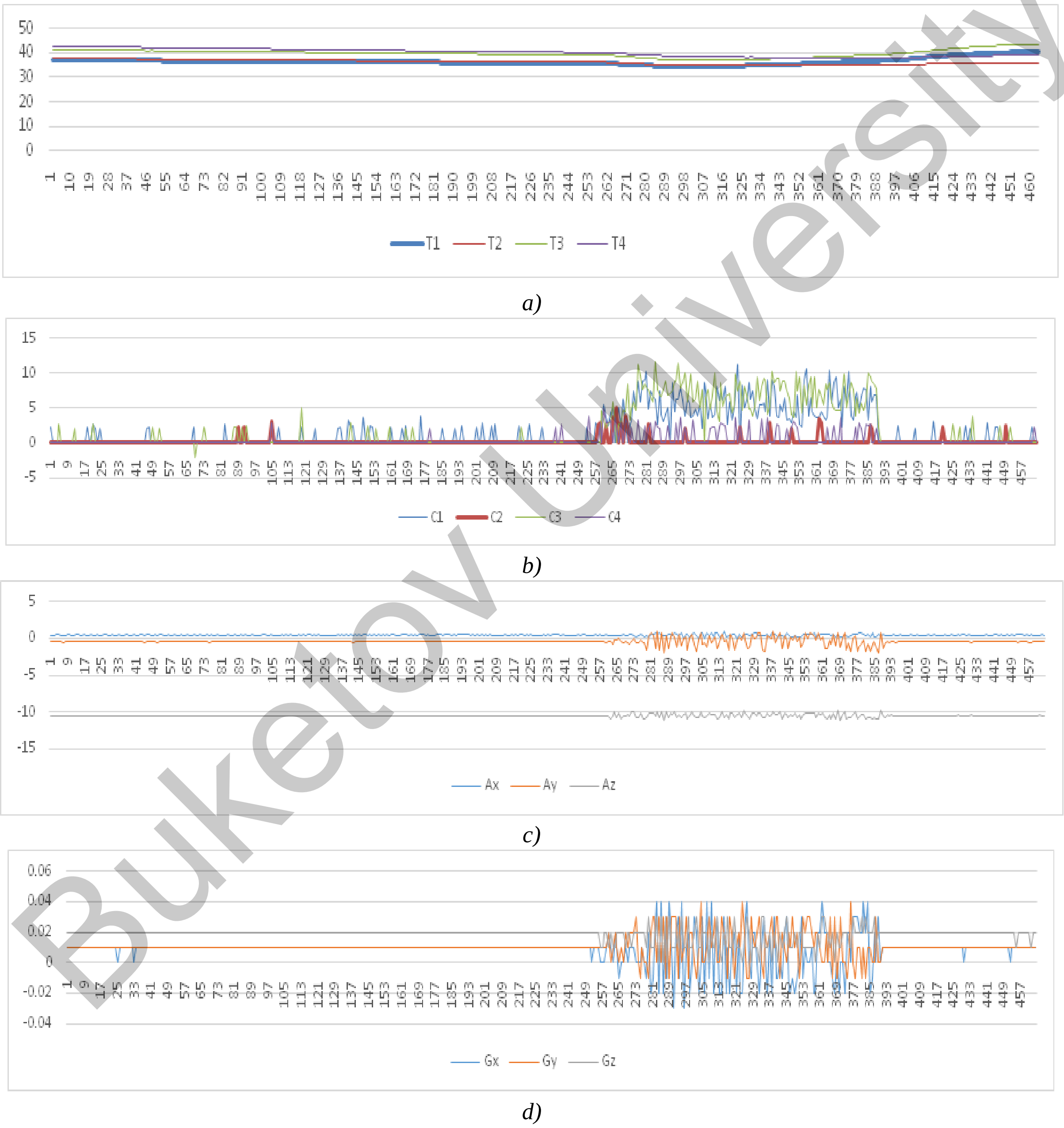
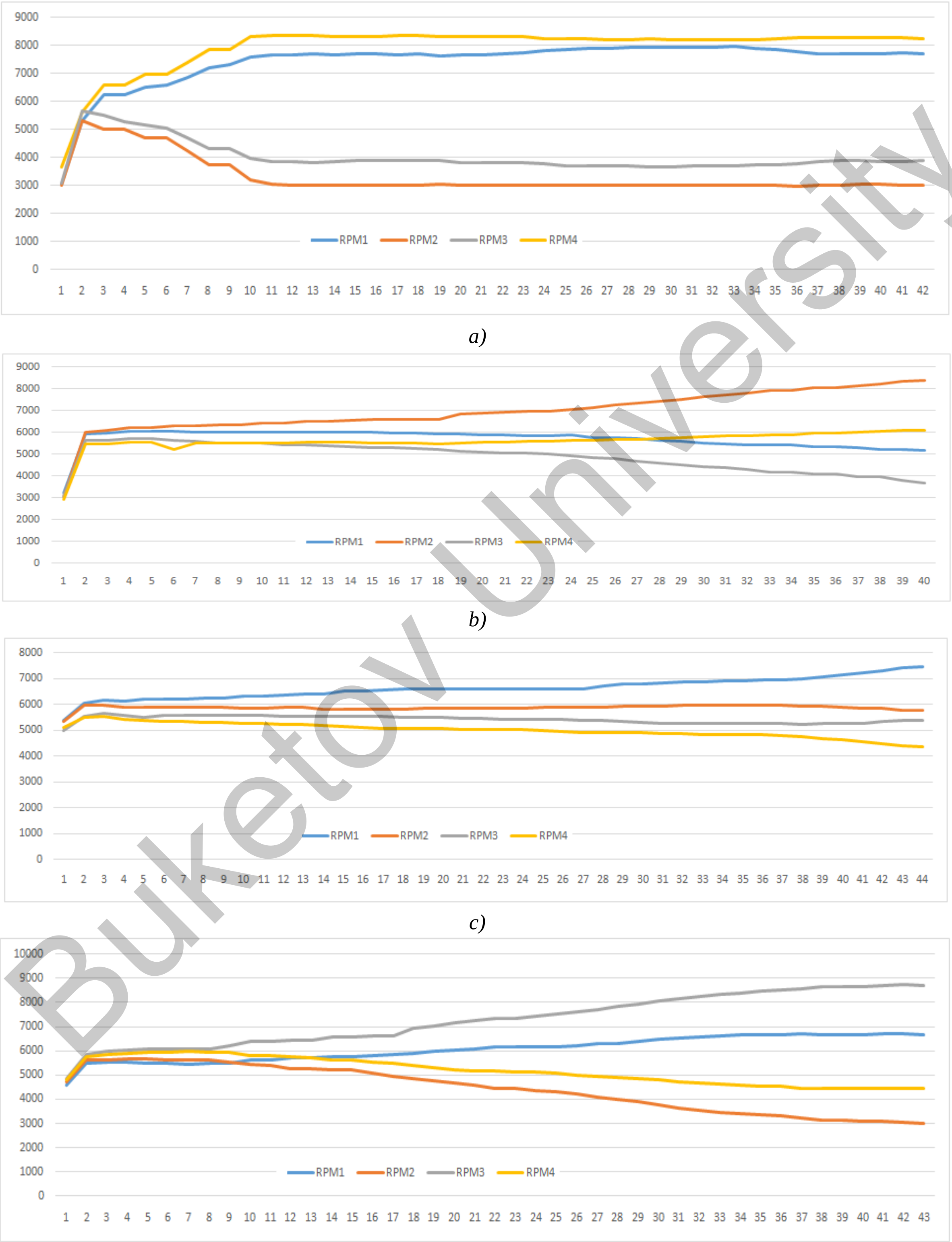


Fig. 4. Timelines of the revolutions during changes of control signals according to possible configurations: a) temperature (ºS), b) current (a), c) accelerometer, and d) gyroscope.

However, when the signals from the flight controller to the engines were switched, the rotational speed of the 1st engine was less than that of the 2nd. In configuration I, the number of revolutions of the 4th engine was higher than in other cases (Figure 5, a). At the same time, it was observed that the current consumption (I1...I4) and temperature indicators (T1...T4), as well as the indicators of the accelerometer and gyroscope changed according to the number of engine revolutions. (Figure 4, a, b, c and d).



a)

b)

c)

d)

Fig. 5. Timelines of the revolutions a), b), c), d) based on the indicators recorded in configuration I by mean of the on-board control-measurement system

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Then the displacement corresponding to the 2nd, 3rd and 4th configurations was carried out (Figure 3). During the study, based on the recorded accelerometer and gyroscope indicators (Ax, Ay, Az and Gx, Gy, Gz) for each configuration, it was found that the horizontal position of the UAV is not ensured. Therefore, in the combination according to configuration I, the control signal of 4th engine corresponds to a relatively high number of revolutions.

Getting the corresponding engine to its highest rotational speed when applying this signal sequentially to the 2nd, 1st, and 3rd engines according to the 2nd, 3rd, and 4th configurations, confirmed once again the thesis that the horizontal position of the UAV is not ensured (Figure 5, b, c and d). Thus, it was determined that being different number of revolutions for a given case is not an indication of engine failure.

5. Conclusion

1. For the first time, an on-board control-measurement system has been created in order to comprehensively record the main flight-technical parameters (I1...I5, T1...T5, RPM1...RPM5, A1...A3, G1...G3) of the mcro convertiplane-type UAV.
2. Data on the power consumption and temperature of each engine, the direction of the aircraft axes and the velocity vector have been recorded in the stationary mode by mean of the developed on-board control-measurement system.
3. Based on the values obtained during the tests, the corresponding parameters versus time diagrams have been built in comparative order.
4. The on-board measurement system created for the micro-UAV allows for full monitoring of technical parameters online, which makes it possible to make operational decisions by noting changes in the situation that may occur on board during the flight.
5. A methodology has been developed for the diagnostics of the engine operation of the micro-unmanned aerial vehicle before and during the flight.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement

Nabiyev R.N.: Conceptualization, Methodology, Supervision, Data curation; **Abdullayev A.A.:** Writing- Original draft preparation, Visualization, Writing- Reviewing and Editing; **Qarayev Q.I.:** Software, Investigation, Validation.
The final manuscript was read and approved by all authors.

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