Study of the Possibility of Increasing the Survivability of Quadcopters Under External Influences

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Abstract: When operating quadcopters (QC), situations arise such as unauthorized intersections of flight paths with flocks of birds and aircraft, physical obstacles along the flight path, and areas with elevated electromagnetic fields. These situations can lead to the QC's destruction. To increase the QC's survivability in such situations, an additional propulsion system (APS) can be installed, allowing for rapid changes in trajectory and flight coordinates. The difficulty in implementing this design solution lies in synchronizing the operation of the main and auxiliary engines. To address this issue, research was conducted and a control system (CS) was developed that synchronizes the engines when the APS is activated, quickly removing the QC from the zone of adverse external influences and maintaining controllability during the rest of the flight.

Keywords: Quadcopter, Quadcopter control system, Increasing quadcopter survivability, Quadcopter survivability.

1. INTRODUCTION

In recent years, unmanned aerial vehicles in the form of copters have found increasing application in various fields of human activity. These are typically small, intelligent, remotely controlled, low-power aircraft capable of following any three-dimensional trajectory and performing various aerial missions [1-3]. They feature innovative features such as maneuverability, low noise levels, artificial intelligence, etc. [4, 5].

Civilian applications for copters vary widely and include agriculture, industry, reconnaissance, entertainment, power line monitoring, logistics, critical facility monitoring, control of hard-to-reach areas, traffic analysis, forest monitoring, etc. [6-14]. Some of the applications for quadcopters are shown in Figure **1**.

Compared to other aerial vehicles, copters offer the following advantages [15, 16]:

- cost-effectiveness;
- ease of use;
- the ability to reach high speeds, glide, and hover over a designated flight point;
- lower cost of production and operation compared to other unmanned aerial vehicles (assuming equal mission effectiveness);
- no risk of injury to the pilot in the event of an aircraft crash, etc.

The following subclasses of copters are distinguished: octocopters, hexacopters, quadcopters, tricopters, and bicopters. This article examines the issue of increasing the survivability of quadcopters.

A modern quadcopter is a complex nonlinear electromechanical system. It can be divided into the following main elements [17-19]:

- supporting frame;
- propellers;
- brushless motors, typically electric motors with power amplifiers or, which is still rare, variable-speed electric drives [20, 21];
- battery;
- parameter sensor unit;
- control system.

A distinctive feature of the quadcopter is the presence of four rotors, with two opposing rotors rotating in one direction and the other two rotating in the opposite direction (Figure **2**, [22]). This allows the quadcopter to maneuver by changing the rotor speed [23, 24].

The quadcopter's simple design reduces its resistance to external influences, both from its operating environment and from other factors, in operating modes. This necessitates solutions to improve the quadcopter's survivability.

A conventional flight control system operates effectively only when all quadcopter motion parameters are precisely defined. The airspace in which a quadcopter operates is always subject to various

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(**a**) (**b**) (**c**)

Figure 1: Use of quadcopters for road patrol (**a**), border protection (**b**), and agriculture (**c**).

disturbances: wind, changes in air density, etc. These factors, characterized by a random distribution of parameters, affect the control accuracy of the flight control system [25-27]. To improve the quality of quadcopter control under these conditions, high-order sliding controllers [28], fuzzy adaptive controllers [29], and other intelligent controllers [30] are used. This helps minimize the negative impacts of the non-stationarity of the external operating environment [31].

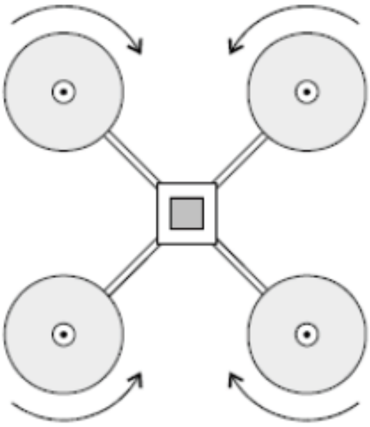


Figure 2: Simplified diagram of a quadcopter.

A completely different picture emerges if a quadcopter enters an area with an elevated electromagnetic environment during flight [32-37], suddenly crosses the flight path of a flock of birds or other aircraft, or encounters a physical obstacle, etc. These abnormal situations can lead to negative consequences, including a QC crash [38-41]. They cannot be predicted or resolved using the quadcopter's control system alone.

A solution to such situations is to equip the quadcopter with an innovative capability that allows it to abruptly change its flight mode and remove it from the danger zone. This can be achieved by generating and applying an additional thrust pulse to the quadcopter, independent of the main motors, which deflects it from its flight path and abruptly changes its position. However, the resulting overloads on the quadcopter's motors and propellers can lead to flight instability, crashes, and even destruction. To prevent this, the quadcopter's control system must respond instantly, adjusting the rotation speed of each motor based on data received from the flight parameter sensors, and ensuring flight stability when the quadcopter exits the hazardous external environment.

The purpose of the presented research results was to develop a quadcopter control system that allows the implementation of the specified functions.

2. MATERIALS AND METHODS

We will introduce an innovation into the quadcopter design in the form of an additional propulsion system, which will ensure the implementation of a scenario of its movement with a sharp change in the direction of flight and the QC's position in space.

A propellant charge can be used as an additional propulsion system. At the required moment, it is triggered, creating an external impulse acting on the quadcopter, which leads to a sharp change in its motion parameters (*e.g.*, flight altitude).

The introduction of a propellant charge into the quadcopter design leads to a slight increase in weight and dimensions. For example, a commercially available rocket engine, generating a total thrust impulse of 50 N·s, has a small (compared to a quadcopter) weight of 107 g and dimensions (outer diameter 29 mm, length 123 mm) [42].

The quadcopter control system in this configuration must address the issue of synchronizing the thrust generated by the additional and main engines. Otherwise, the thrust generated by the APS will lead to loss of control, and the quadcopter may break up in mid-air.

To determine the design solutions that must be implemented in the quadcopter control system to eliminate negative consequences from the additional propulsion system, we use mathematical modeling methods.

We will consider the movement of the quadcopter in the fixed and moving coordinate systems shown in Figure **3** [43, 44].

The system of differential equations describing the dynamics of the quadcopter in the coordinate system shown in Figure **3** has the following form [45]:

$$\frac{d^2X}{dt^2} = \frac{(F_1+F_2+F_3+F_4)}{m}[cos(R)\cdot sin(T)\cdot cos(K) + sin(R)\cdot sin(K)] - \frac{A_x}{m}\frac{dX}{dt};$$

$$\frac{d^2Y}{dt^2} = \frac{(F_1+F_2+F_3+F_4)}{m}[sin(R)\cdot sin(T)\cdot cos(K) + cos(R)\cdot sin(K)] - \frac{A_y}{m}\frac{dY}{dt};$$

$$\frac{d^2Z}{dt^2} = \frac{(F_1+F_2+F_3+F_4)}{m}[cos(T)\cdot cos(K)] - \frac{A_z}{m}\frac{dZ}{dt} - \mathrm{g};$$

$$\frac{d^2T}{dt^2} = \frac{l}{J_{xx}}(F_4 - F_2); \qquad (1)$$

$$\frac{d^2K}{dt^2} = \frac{l}{J_{yy}}\times(F_3 - F_1);$$

$$\frac{d^2R}{dt^2} = \frac{l\times b}{J_{zz}\times \text{Кт}}(F_1 - F_2 + F_3 - F_4);$$

$$F_i = K_T(\omega_i)^2.$$

The following notations are used in it: F_i – propeller thrust forces (*i* = 1…4); J_{xx}, J_{yy}, J_{zz} – moments of inertia of the quadcopter around the corresponding axes; *m* – quadcopter mass; *l* – distance from the center of the quadcopter to the electric motor mounting points; *b* – technological coefficient; K_T - thrust coefficient; A_x, A_y, A_z - drag forces; ω_i - rotation frequency.

The equation system (1) is simplified if the quadcopter has smooth motion:

- with small roll and pitch angles, in which case: cos(T) ≈ cos(K) ≈ cos(R) ≈ 1, a sin(T) $\approx T, \sin(K) \approx K, \sin(R) \approx 0$;

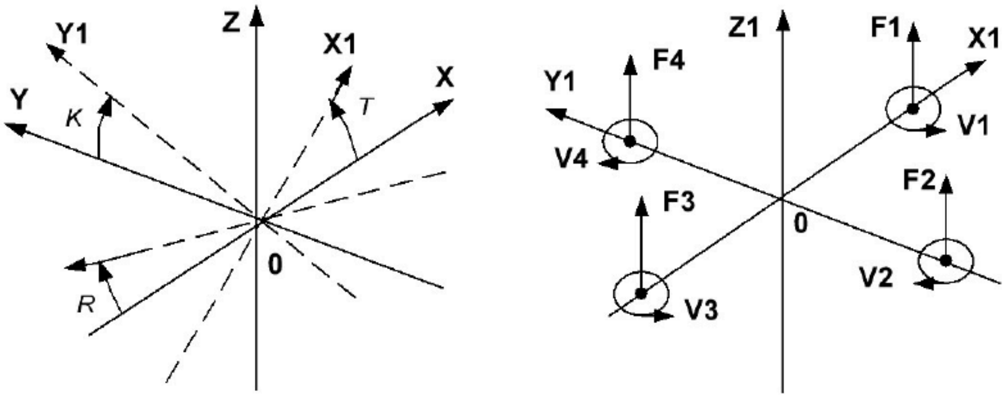
- in the XOY plane, *i.e.*, the condition $(F_1 + F_2 + F_3 + F_4) = m\mathrm{g}$.

To assess the impact of the additional propulsion system on the operation of the quadcopter control system, we will develop functional diagrams and mathematical models that take into account and exclude unauthorized external influences. We will pay particular attention to the control system components and the delays in receiving information from the corresponding quadcopter parameter sensors: coordinate position and velocity. These delays will be accounted for as time constants of the transfer functions of the corresponding sensors [46, 47].

Furthermore, when developing the functional diagram, we will pay attention to the speed and force limitations of the quadcopter's components and consider the significant nonlinearities that determine the energy capabilities of its power elements.

Based on equations (1), a functional diagram of the quadcopter was developed (Figure **4**), taking into account both its main nonlinearities and information delays.

The following designations are used on it: RPz, RPx, RPy, RPr, RPт, RPк - position controllers for coordinates Z, X, Y, T, K, R; ED1-D4 – four speed-controlled electric drives; RSr, RSт, RSк – speed controllers for coordinates T, K and R; SPz, SPx, SPy, SPr, SPт, SPк - position sensors for coordinates



a) **b**)

Figure 3: Fixed and mobile coordinate systems (**a**), quadcopter coordinate system (**b**): X, Y, Z – fixed coordinate system, X1, Y1, Z1 – mobile coordinate system, R – yaw angle; T – pitch angle; K – roll angle.

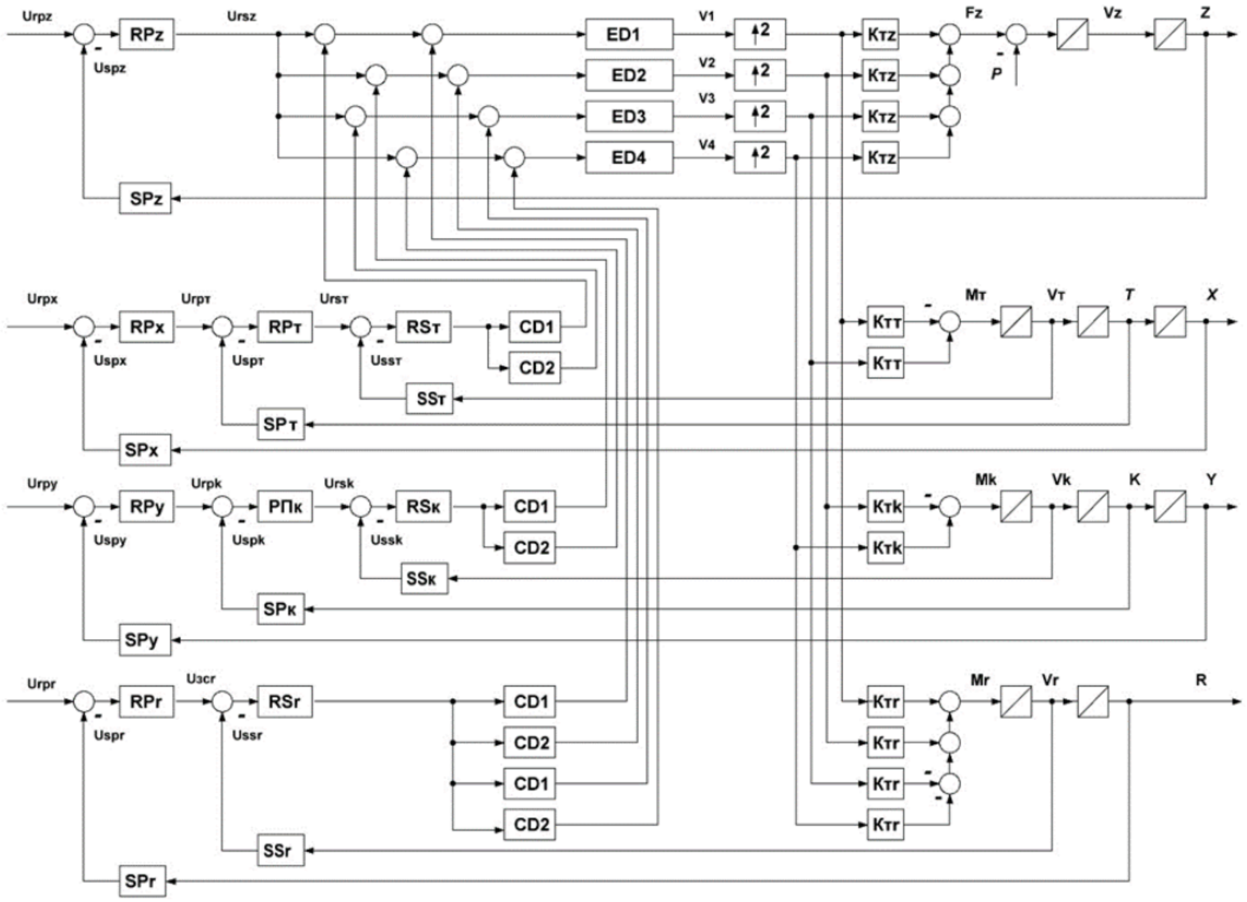


Figure 4: Functional diagram of the quadcopter.

Z, X, Y, T, K, R; SSr, SSт, SSк – speed sensors for coordinates T, K and R; CD1, CD2 – correcting elements; Urpz, Urpx, Urpy, Urpt, Urpк, Urpr – signals for setting positions for coordinates Z, X, Y, T, K, R; Ursz, Ursr – output signals from the position controllers of coordinates Z and R; Urpt, Urpк – signals for setting coordinates T and K; Urst, Ursk, Ursr – signals for setting the speeds of coordinates T, K and R; Fz – thrust force along the Z coordinate; P – quadcopter weight; Vz – speed of movement along the Z coordinate; M_T, V_T – torque and speed along the T coordinate; M_K, V_K – torque and speed along the K coordinate; Mr, Vr – torque and speed along the R coordinate; Кτz, Кττ, Кτк, Кτr – physical coefficients.

The developed functional diagram of the quadcopter is original, displaying four main control loops for the quadcopter coordinates (X, Y, Z, R), constructed according to the hierarchical principle with subordinate regulation of parameters (for example, the control loop for the X coordinate includes the control loop for the T coordinate, which includes the control loop for the Vт coordinate). This diagram is not widespread and described in the literature (except for the author's), since other approaches to the construction of quadcopter systems with other parameter sensors and controllers are possible [48, 49].

The quadcopter's coordinate control loops are tuned to technical and symmetrical optima [50].

The developed functional diagram of the quadcopter allows for the analysis of various operating modes. However, we are interested in the issue of changing the quadcopter's trajectory in the event of danger in the vertical plane. Therefore, further analysis of the quadcopter's behavior was carried out with its part responsible for ascent and descent - with the control loop along the Z coordinate (altitude).

To do this, from the functional diagram of the quadcopter shown in Figure **4**, we select the diagram shown in Figure **5**.

The circuit operates as follows. The position reference signal Urpz along the Z coordinate is algebraically summed with the signal from the position sensor Uspz. The difference is processed in the position controller RPz according to a specific law (*e.g.*, proportional-integral or proportional-differential). The output signal from the position controller Ursz sets the rotation speeds of the adjustable electric drives V1–V4

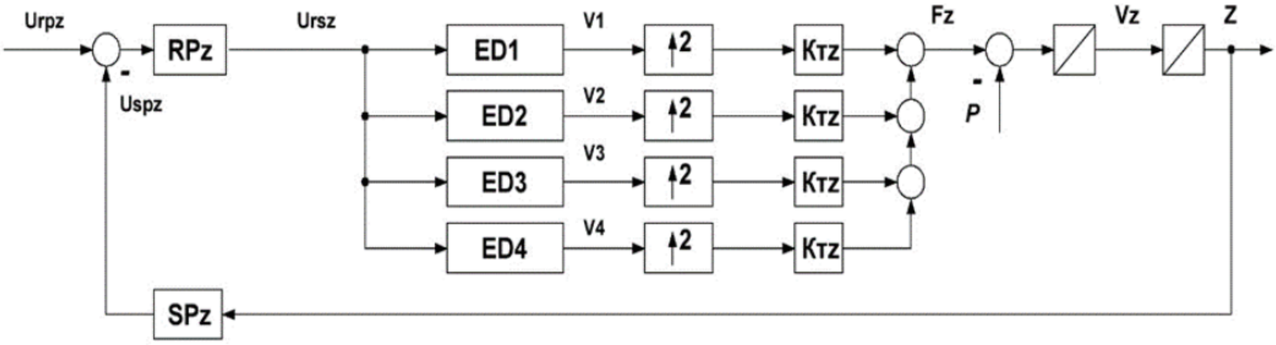


Figure 5: Functional diagram of the control loop of a quadcopter without an additional propulsion system along the Z coordinate.

(consisting of electric motors and control systems), on whose shafts the propellers are located, creating a thrust force Fz proportional to the squares of the shaft velocities and the thrust coefficient Kтz. The quadcopter acceleration is proportional to the difference between the thrust force Fz, the weight P, and the air resistance force, which depends on the velocity Vz. The quadcopter velocity Vz is the integral of the acceleration, and the position Z is the integral of the velocity Vz. Thus, a linear correspondence is established between the position reference signal Urpz along the Z coordinate and the quadcopter position Z.

This functional diagram corresponds to the structural diagram shown in Figure **6** (for greater clarity, the structural diagram is shown with a single feedback [51] – in this case Zr = Urpz/Kspz, where Kspz is the transmission coefficient of the position sensor along the Z coordinate).

This functional diagram corresponds to the structural diagram shown in Figure **6** (for greater clarity, the structural diagram is shown with a single feedback [51] – in this case Zr = Urpz/Kspz, where Kspz is the transmission coefficient of the position sensor along the Z coordinate).

The following notations are used on it: Wrпz(S), transfer function of the position controller along the Z coordinate; Ked, Ted – transfer coefficient and time constant of the speed-controlled electric drive; Kvz – transfer coefficient of the speed node along the Z coordinate; Kтz – traction coefficient; Zr – displacement task along the Z coordinate; Frp – nonlinearity of the position controller along the Z coordinate, characterized by nonlinearity parameters a1, b1; S – Laplace operator.

The developed structural diagram takes into account the most important nonlinearities of the control loop—the asymmetric limitation of the position controller signal and the quadratic dependence of the thrust force on the electric motor speed. Analysis of the impact of nonlinearities on quadcopter operation using traditional methods (harmonic linearization, fitting, energy linearization, etc.) is uninformative. Therefore, in this paper, the controllers are synthesized for a linearized mathematical model of the control loop, followed by mathematical modeling that takes all nonlinearities into account.

For a quadcopter with an auxiliary propulsion system, the developed functional diagram of the Z-coordinate control loop is presented as shown in Figure **7**. In the primary operating mode, the Z-coordinate control loop operates identically to the previous one. The peculiarity of the circuit is that the additional propulsion unit generates a traction force Pp equal to 50 N for Tp~1 s, while at the signal Up the adjustable electric drives stop working for a time to. For this purpose, a switching device is included in the diagram, disabling the electric drives during auxiliary propulsion system operation.

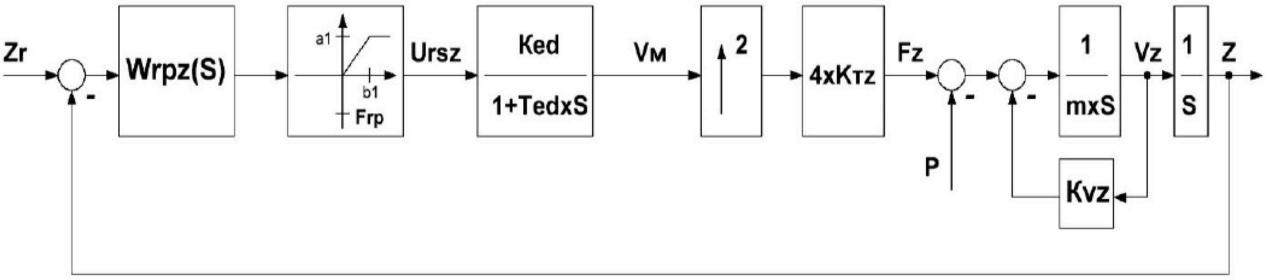


Figure 6: Structural diagram of the control loop of a quadcopter without an additional propulsion system along the Z coordinate.

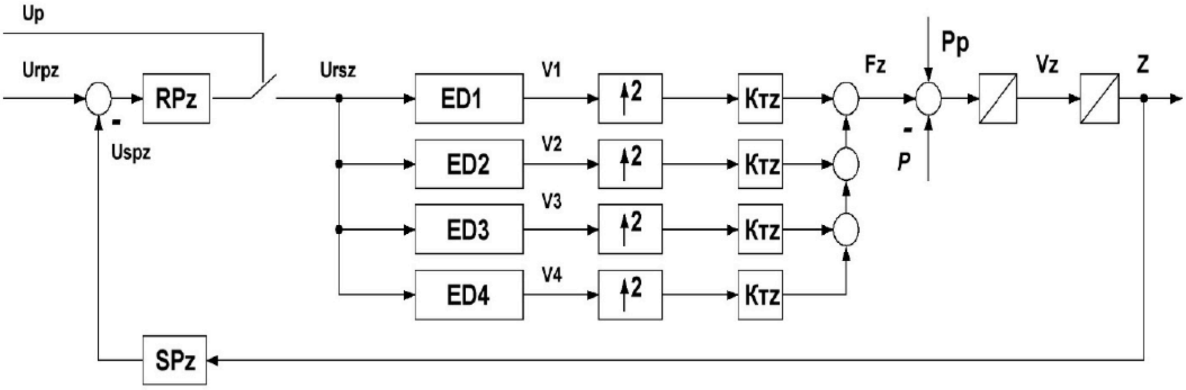


Figure 7: Functional diagram of the control loop along the Z coordinate with an additional propulsion system.

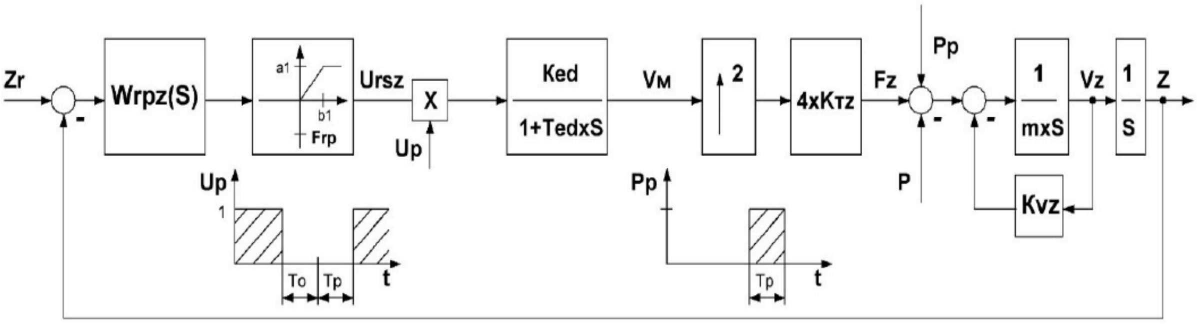


Figure 8: Structural diagram of the control loop along the Z coordinate with an additional propulsion system.

The structural diagram corresponding to this functional diagram is shown in Figure **8**.

3. RESEARCH RESULTS

We will conduct a mathematical modeling of the developed Z-axis control loops based on the system of differential equations (1).

We will evaluate the quality of transient processes and the accelerations, speeds, and errors obtained by the quadcopter for a range of its movement along the Z coordinate of up to 10 m.

The algorithm for modeling the operation of the quadcopter's Z-axis control loop without an additional power plant is shown in Figure **9**.

The controller synthesis was carried out for a linear model based on the conditions of the standard setting (technical or symmetric optima), ensuring the required quality of transient processes.

The control loop along the Z coordinate is tuned to the technical optimum. For this purpose, the transfer function of the position controller is selected based on the condition [47]

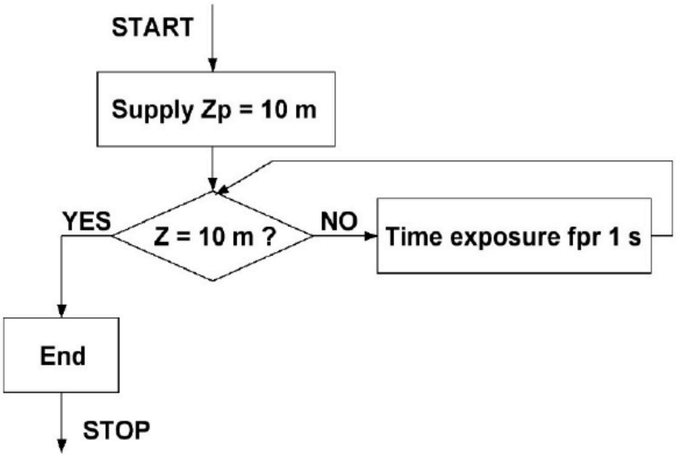


Figure 9: Algorithm for modeling processes in the control loop for the Z coordinates of a quadcopter without an additional propulsion system.

$$4\times \mathrm{Wrpz(S)}\times \mathrm{K\tau z}\,\frac{\mathrm{Ked}}{1+\mathrm{Ted}\times \mathrm{S}}\times\frac{\mathrm{Kvz}}{1+\mathrm{Kvz}\times \mathrm{S}}\times\frac{1}{\mathrm{S}}=\frac{1}{2\times \mathrm{Ted}\times \mathrm{S}\times(1+\mathrm{Ted}\times \mathrm{S})}. \qquad (2)$$

The coefficients Kτz and Kvz included in expression (2) depend on the quadcopter's configuration, area, and volume, as well as the propeller shape; Ked and Ted depend on the motor parameters, the internal design of the speed controllers, and the speed sensors. If these parameters are known, the controller's transfer function can be easily determined. The key feature of tuning for the technical optimum is the virtual absence of exceeding the output coordinates during control and the virtual absence of overshoot in the output coordinate (Z-height) during control.

The analysis of the influence of nonlinearities (asymmetric Frp of the “limitation” type and quadratic) on the operation of the control loop using various analytical methods is ineffective, therefore, in the work, mathematical modeling of the control loop is carried out taking into account these nonlinearities.

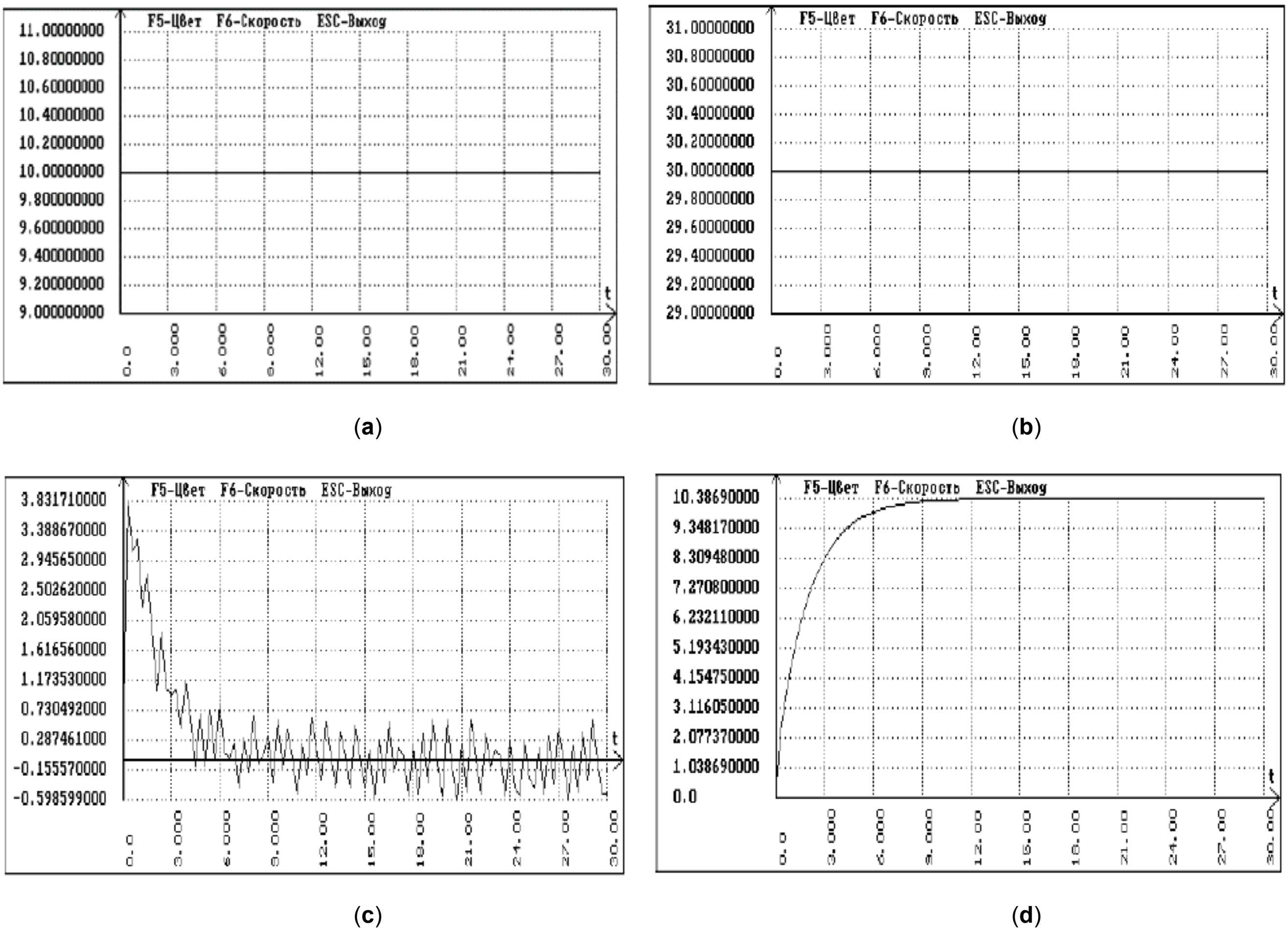
Let us carry out mathematical modeling with the following parameters of the studied quadcopter sample: a1 = 10 m; b1 = 400 rad/s; Ked = 2; Ted = 0.008 s; Ktz = 0.001 (N·s^2)/rad^2; Kvz = 0.1 (N·s)/m; Wpпz(S) = 2·10^4·(1+0,3·S)/(1+0,01·S).

The results of mathematical modeling of processes in the control loop for the Z coordinates of a quadcopter (m = 3 kg) without an additional propulsion system are shown in Figure **10**. It shows the dependencies on time t: a) the input signal Zr, b) the weight of the quadcopter P, c) the speed Vz, d) the Z coordinates of the quadcopter.

The results of the simulation are clear. From Figure **10** it is evident that the quadcopter has smooth transient processes, a small static error (0.1 m), and acceptable speed (a height of 10 m is reached in 10 s).

The algorithm for simulating the operation of the control loop along the Z coordinate of a quadcopter with an additional propulsion system is presented in Figure **11**.

The results of mathematical modeling of the control loop of a quadcopter (m = 3 kg) with an additional propulsion system along the Z coordinate, generating a traction force Pp equal to 50 N for Tp = 2 s, are presented in Figure **12** in the form of dependencies on



(**a**) (**b**)

(**c**) (**d**)

Figure 10: Transient processes along the Z coordinates of a quadcopter without an additional propulsion system.

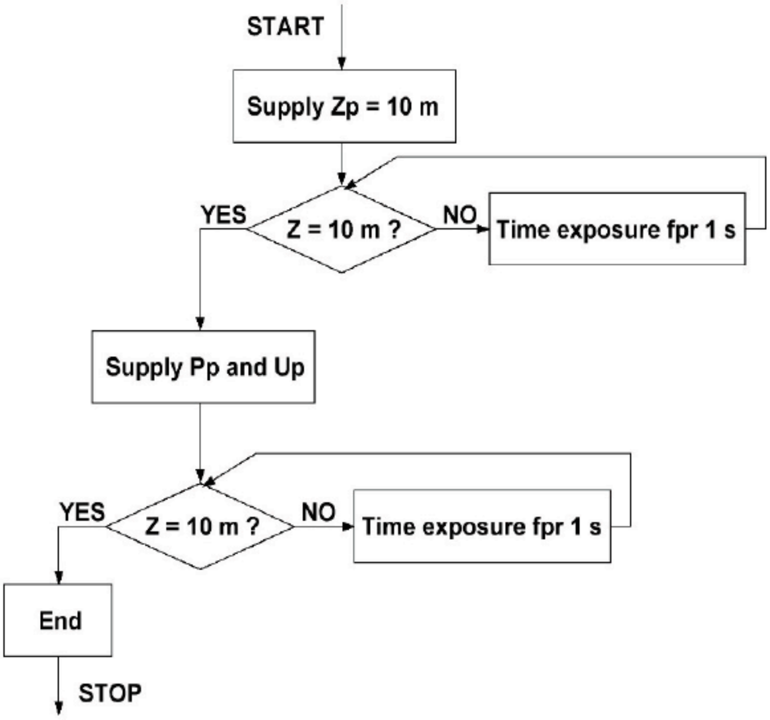


Figure 11: Algorithm for modeling processes in the control loop for the Z coordinates of a quadcopter with an additional propulsion system and a switching device.

time t: a) the input signal Zr; b) the weight of the quadcopter P; c) the speed Vz; d) the Z coordinate; e) the force impulse generated by the additional propulsion system Pp; f) the control impulse Up.

Figure **12** shows that the circuit has a smooth transition process, a small static error (0.1 m), and good response speed (average speed of 1.4 m/s, boost speed of 40 m/s). An altitude of Z = 10 m is reached in 1.5 seconds.

Based on a series of experiments conducted using mathematical modeling, the following approximate empirical formula was determined for calculating the quadcopter's deviation from the intended trajectory when using the additional propulsion system:

$$\mathrm{Z}_{\text{доп}} \approx 6{,}3\times \frac{\mathrm{Pp}\times \mathrm{Tp}^{3/2}}{\mathrm{m}^3}. \qquad (4)$$

4. CONCLUSION

Modern quadcopters are complex electromechanical devices with microprocessor control units that use neural controllers, PID controllers, and fuzzy controllers, built according to various principles and circuits.

An innovative functional diagram and mathematical model have been developed for the control system of a quadcopter with a total mass of 3 kg, equipped with an additional propulsion system, which increases the quadcopter's survivability in the event of unauthorized external influences such as elevated electromagnetic fields, flocks of birds, physical objects.

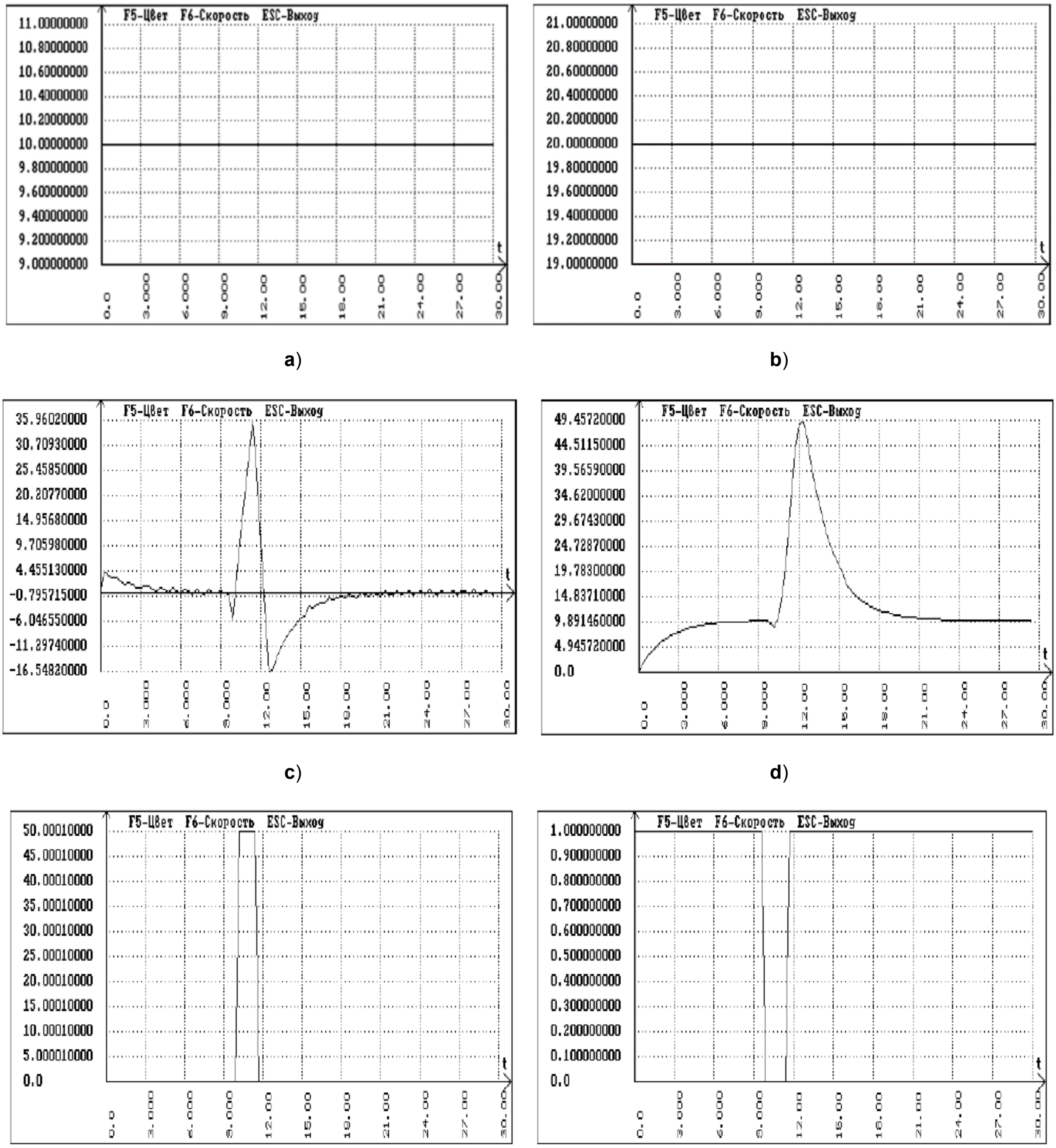
This control system has a hierarchical structure built according to a subordinate parameter control scheme, with control loops tuned to technical and symmetrical optima. This approach combines scientific and engineering approaches.

The developed innovative functional diagram and mathematical model of the control system enable the analysis of virtually any quadcopter operating mode and situation.

The control system synchronizes the short-term thrust generated by the additional propulsion system upon activation with the lift forces generated by the quadcopter's main engines. This prevents damage and ensures the quadcopter remains controllable after exiting the zone of unauthorized external influence.

The resulting static error between the quadcopter control systems with and without the additional propulsion system is virtually identical, while maintaining the same response speed. Furthermore, the addition of an additional propulsion system to the quadcopter design significantly reduces the time the quadcopter spends in the danger zone.

Currently, a quadcopter design is being developed that ensures that the thrust vector of the APS passes through its geometric center of mass.



a) **b**)

c) **d**)

e) **f**)

Figure 12: Transient processes in the control loop along the Z coordinate of a quadcopter with an additional propulsion system.

The described control scheme increases the quadcopter's survivability under operating conditions exposed to various unexpected factors.

CONFLICT OF INTEREST

No conflict of interest.

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