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An autopilot-based method for unmanned aerial vehicles trajectories control and adjustment

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ABSTRACT

In today's world, the rapid development of aviation technologies, particularly unmanned aerial vehicles (UAVs), presents new challenges and opportunities. UAVs are utilized across various industries, including scientific research, military, robotics, surveying, logistics, and postal delivery. However, to ensure efficient and safe operation, UAVs require a reliable autopilot system that delivers precise navigation control and flight stability. This paper introduces a method for controlling and adjusting UAV trajectories, which enhances accuracy in environments and tasks corresponding to the first or second level of autonomy. It outperforms the linear-quadratic method and the unmodified predictive control method by 43% and 74%, respectively. The findings of this study can be applied to the development and modernization of new UAV, as well as the advancement of new UAV motion control systems, thereby enhancing their quality and efficiency.

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1. INTRODUCTION

In recent years, Unmanned aerial vehicles (UAVs) have gained significant popularity and have become an integral part not only of modern aviation but also of various sectors such as agriculture, energy, environmental monitoring, strategic infrastructure control, aerial photography, and rescue operations [1]–[3]. The use of UAVs provides many advantages compared to traditional manned aircraft. Since UAVs can perform tasks without human presence on board, they can be utilized in conditions that are dangerous or inaccessible to humans or when high precision and speed are required [4]. Such tasks fit the "three D" template, which stands for dangerous, dirty, and dull. Dangerous means that the life of a pilot can be at high risk during the flight. Dirty implies that the operational environment may be contaminated with chemical, biological, or radiation threats, making it unsafe for humans. Dull refers to long-duration, exhausting, and stressful operations that are undesirable for human performance [5], [6].

Hegde *et al.* [7] aim to characterize a quad-tilt rotor UAV using the Newton-Euler formulation. A mathematical representation of the vehicle's dynamic model is developed for horizontal, vertical, and transition flight modes. A resilient H-infinity control approach is suggested, assessed, and scrutinized through simulation to regulate the flight dynamics across various modes of the UAV. The simulation outcomes demonstrate the successful accomplishment of the transition phase by the tiltrotor UAV.

Creating a high-performance controller for a quadrotor poses a formidable challenge due to its inherent instability and the nonlinear nature of its under-controlled system. Basri and Noordin [8] challenges this by designing and optimizing an autonomous quadrotor controller. Initially, the dynamic model of the aircraft is introduced. Within the algorithm, the control parameters are computed using the integral absolute error to minimize the fitness function. Separately, the use of unmanned systems in the military domain stands out. The realities demonstrate that the utilization of unmanned systems is in high demand, as they are much cheaper than manned technology, more energy-efficient, and easier to operate. The small geometric dimensions and low noise allow for virtually unhindered collection of real-time intelligence information. However, a challenge remains: the UAV still relies on external control signals and data transmission. Regardless of how well it is encrypted, it can be jammed or even intercepted by an adversary [9], [10].

A fully autonomous vehicle can perform various missions even under electronic warfare attacks, as it does not depend on external control signals. Therefore, for the execution of such tasks, it is necessary to plan an optimal trajectory for the UAV's flight route, considering constraints such as range, flight duration, and the design limitations of the vehicle itself. The development of a control system will address the challenges of optimal UAV control. This paper analyzes the existing methods of controlling and regulating the trajectory of unmanned vehicles. In particular, Hoffmann *et al.* [11] consider the use of a proportional-integral-derivative (PID) controller in the example of four the Stanford Testbed of autonomous rotorcraft for multi-agent control (STARMAC) rotary UAVs. The authors emphasize the need to create a detailed mathematical modeling of the quad rotor to ensure accurate control of the flight path. The authors note that the use of a PID controller gives good results on simple trajectories and low speeds, but is not suitable for accurate trajectory tracking at high speeds and in an uncontrolled environment.

Ameen and Humod [12] introduces a novel PID controller designed to enhance both the transient and steady-state properties of a dynamic system. A non-linear proportional-derivative (PD) controller is proposed by incorporating a nonlinear function into a traditional PID controller, with the optimal gains determined through the use of particle swarm optimization (PSO). Simulation results demonstrate that the suggested controller, utilizing a nonlinear PD approach with PSO-derived gains, outperforms a conventional PID controller designed through symmetrical optimum criterion with pole assignment technique in terms of transient response and robustness.

Sabikan *et al.* [13] introduces a technique for constructing a mathematical time-to-collision (TTC) model tailored for outdoor UAVs using PSO. This model offers forecasts of the time remaining before a UAV encounters an obstacle along its trajectory, relying on parameters such as current speed and payload. The primary emphasis of this paper lies in detailing the procedural approach of employing PSO to formulate the TTC model, particularly for five distinct payload configurations.

A combined control system is presented in [14]. It consists of two parts: a predictive state space controller for translational movements and a nonlinear $H\infty$ control strategy for stabilization. The proposed control strategy was modeled and confirmed its ability to cope with significant disturbances affecting all degrees of freedom at different times. In [15]–[19], the authors present a new control method for a quad-rotor UAV using neural networks. This structure allows for better adaptation to environmental conditions, thus improving efficiency. Simulation results suggest that the proposed method outperforms the conventional PID controller. Overall, the paper presents a promising approach to controlling a multi-rotor UAV. However, since the results are based on modeling, it is not known how the proposed method will work in real conditions.

Papers [20], [21] describe a modified predictive control model and demonstrate it on the example of aircraft, and the results show that it works effectively under the constraints of vehicle maneuvering programs. So, the study [22] considers a strategy for controlling several multi-rotor unmanned vehicles using a predictive control model and a Kalman filter. The simulation results show the effectiveness of this approach, since the use of the Kalman filter allows suppressing interference and thus improving flight stability in difficult conditions. Two control methods are considered in [23]: PID and linear quadratic regulator (LQR). Experimental results show that the use of LQR provides similar results compared to the PID method, although the LQR method provides a smoother trajectory and is less susceptible to disturbances.

The study [24] presents the use of linear and nonlinear models of predictive controllers to regulate the trajectory of unmanned vehicles. The controllers were evaluated in the following possible situations: hovering, movement, and abrupt change of trajectory in the presence of disturbances. In the comparison, both controllers showed similar results, but the nonlinear controller demonstrated a slightly better ability to filter out disturbances. Although the authors suggest that the nonlinear controller improves performance, it also requires more computation.

The studies [25]–[28] present various PID control strategies for multi-rotor systems. The modeling results demonstrate promising opportunities for the use of PID controllers in the construction of a high-quality mathematical model of an aircraft, or in conjunction with additional regulators. So, the study [29] focuses on developing an optimal PID controller for the camera gimbal on UAVs, achieved through three improvements using PSO. The PSO algorithm is integrated with the PID controller to manage the DC motor gimbal. The study explores the impact of iteration numbers before comparing the performance of the PSO-PID-controlled DC motor with a Zeigler-Nichols controller. Bode analysis is conducted to confirm the stability of the proposed PSO-PID controller. Simulation results in MATLAB demonstrate that the PSO-PID controller surpasses the Zeigler-Nichols controller in terms of overshoot and rise time, with future research considering the integration of other optimization methodologies like fuzzy logic for enhanced performance.

The scientific article [30] describes the development and tuning of a modified PID controller for autopilot in micro-aircraft. The authors of the article used a modeling methodology and experimental verification to evaluate the performance of the controller. In particular, they propose a new model of micro-aircraft dynamics that allows for more accurate modeling of its movement. The authors also used genetic algorithms and optimization methods to tune the PID controller parameters. The results of the study showed that the proposed modified PID controller has better performance compared to the standard PID controller, in particular, it provides more accurate and stable operation of the autopilot in different conditions. As for the stabilization error, the use of the modified PID controller reduced the stabilization error by 30% compared to the standard PID controller. The navigation accuracy of the modified PID controller provided more accurate navigation by the specified trajectories with an error of less than 5%. The stability of the modified PID controller allowed for achieving stable operation of the autopilot even under variable conditions, such as wind, turbulence, and the response time of the modified PID controller allowed to reduce the response time of the autopilot system by 20%, which improved the response to unforeseen disturbances. This article may be useful for those involved in the development and tuning of autopilot systems for micro-aircraft. Similarly, to improve the gain of the PID controller of transient flight control systems for the model of an aerial UAV, the authors of the work [31] applied a genetic algorithm. The MATLAB/Simulink environment is often used as a platform for modeling a quadcopter. In particular, in the previous article in [32], [33]. However, the disadvantage of these works is the unexplored issue of time costs for the decision.

The study [34] investigates the possibility of using graphics processing units (GPUs) to improve the performance of parallel computing in modeling the behavior of a cluster of drones during air combat operations. The authors propose to use a mixture of open multi-processing and compute unified device architecture (CUDA) technologies to optimize computational processes on the Central Processing Unit and GPU, respectively. As a result, a system has been developed that allows parallel modeling of UAV cluster behavior, providing high performance and accuracy of computations. The article may be useful for researchers involved in the development of parallel computing systems for modeling the behavior of unmanned vehicles. Roberge and Tarbouchi [35] describe the development of a parallel algorithm on the GPU for wireless data collection from sensors using a team of UAVs. To maximize the efficiency and speed of data collection, the authors use parallel computing on a GPU using CUDA technology.

In [36] presents an algorithm and constructs an automated system aimed at addressing the issue of tracking and identifying drones. It utilizes data from both a radar station and a photo or video camera. In this context, a Kalman filter was implemented to improve the localization of "noisy" radar measurements, and a convolutional neural network (CNN) was employed for the binary classification of input images. Consequently, the achieved results were more than ten times closer to the true measurements compared to the initial noisy data. Materials on classification using CNN for various areas of computer vision are analyzed in detail by the authors in [37]. After reviewing various articles, we can draw conclusions:

a. Using a PID controller has its advantages, especially for simple trajectories and low speeds. It can provide stable control and respond quickly to changes in the system. However, the PID controller has its limitations, especially when tracking trajectories accurately at high speeds and in uncontrolled environments.
b. The use of nonlinear controllers can be effective at high speeds and in disturbance conditions, but require more computing power.
c. The model predictive control (MPC) method can be effective for following a given trajectory exactly. By using optimization and prediction, it can provide optimal control in complex environments. However, an MPC controller can be more computationally demanding.

Based on the analytical review of scientific publications, we can conclude that MPC is a powerful control method used to optimize the control, regulation, and measurement of trajectory parameters of unmanned aerial vehicles. The main advantage of MPC is that it takes into account the system dynamics and constraint conditions, which allows for optimal control in real-time. Since the MPC method requires more computing resources, the use of a less resource-intensive controller in conjunction with the MPC method to distribute functions can help reduce their use. Such an auxiliary controller can be a P controller. Compared to other controllers, it has a simple structure and low computational complexity. However, it has limited capabilities to solve the problem of constant error and stability compared to other more complex controllers. However, using a combination of MPC and proportional controllers, it is possible to realize the advantages of both controllers, namely the flexibility and accuracy of MPC and the speed of response of the proportional controller, and reduce the impact of constant error on the system motion. Therefore, the optimization method is described as follows: a proportional link is used to generate a basic control signal. This signal is transmitted to the MPC controller and is further processed to determine the angular movements of the machine. The P controller is responsible for rapid flight path corrections, while the MPC controller solves flight planning tasks within a given planning horizon. Thus, the described combination allows for a computationally simpler control system that can provide optimal motion in a simple environment without large external disturbances.

The goal of this work is to optimize the methods of controlling and regulating the UAV's trajectory, namely, to improve the accuracy of trajectory following. To achieve this goal, the following tasks were set: i) analysis of existing methods for controlling and regulating the trajectory of unmanned vehicles; ii) development of a combined control system to realize the advantages of proportional control and predictive control, which will improve the accuracy of trajectory following; and iii) testing the improved method and comparing it with existing analogs.

The originality and novelty of this paper are summarized as follows: i) We propose a method for controlling and adjusting the UAV trajectory, which allowed us to improve accuracy in environments and tasks corresponding to the first or second level of autonomy. ii) We have implemented an aircraft simulation system, namely a mathematical model of a quadcopter, a flight controller, and a flight path generator. This provides a reasonable and feasible reference and guide for further research in areas of human activity where it is necessary to conduct aerial surveys in controlled environments or premises. And iii) through large-scale testing, we confirm the effectiveness of the proposed algorithm and its advantages over LQR, MPC methods.

2. METHOD

There are two coordinate systems used to describe the state of a UAV: the inertial (absolute) and the moving system. The inertial coordinate system allows for the analysis of external forces acting on the quadcopter and determines its motion dynamics, while the moving system enables control of its orientation and stabilization processes. Since we are investigating a quad-rotor aircraft, let's consider how the rotors make the aircraft move.

The direction of the rotor blades' movement for rotors one and three is counterclockwise, while for rotors two and four, it is clockwise. This is because, according to Newton's third law, "forces acting on objects are directed along the same line, equal in magnitude and opposite in direction". Thus, the opposite directions of rotor pairs' movement compensate for each other's moments and allow the quadcopter to remain stationary around the *Oz*-axis. Now let's examine the control signals that govern the motion of the aircraft. Thrust is the resultant force of the individual rotor thrusts and is directed along the *Oz*-axis, where Ω represents the angular velocity of rotor blade rotation as shown in Figure 1(a). Roll is the force created by the difference in torque between the rotors R_2 and R_4, while the angular velocity of the rotors R_1 and R_3 (located along the *Ox*-axis) is the same to maintain balance as shown in Figure 1(b). Thus, the thrust force of the rotors R_2 and R_4 creates a moment of force and makes the quadcopter rotate around the *Ox*-axis.

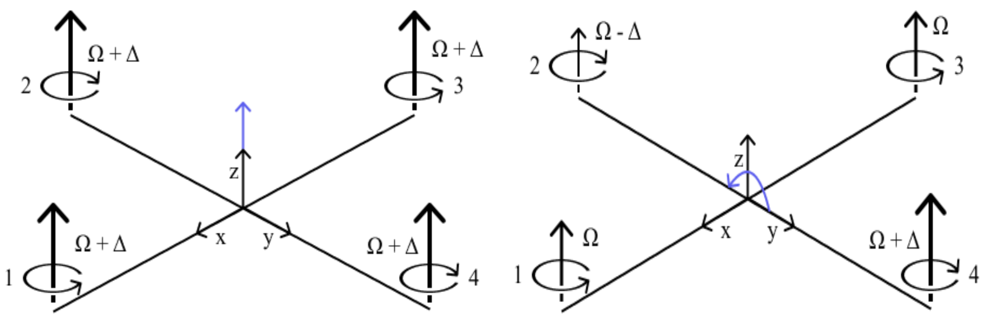

Figure 1. Ratio of angular velocities: (a) to thrust generation (along the *Oz*-axis) and (b) to pitch (located along the *Ox*-axis)

Pitch is the force created by the difference in torques between the rotors R_1 and R_3, while for balance, the angular velocity of the rotors R_2 and R_4 (located along the *Oy*-axis) is the same as shown in Figure 2(a). Thus, the thrust force of the rotors R_1 and R_3 creates a moment of force and makes the UAV rotate around the *Oy*-axis. Yaw is the force created by the total torque around the *Oz*-axis from all rotors. Due to the uniform rotation of opposite rotors, provided that the rotation of these pairs differs, a greater angular velocity of the rotors whose blades rotate clockwise, according to Newton's third law, causes the quadcopter to rotate counterclockwise as shown in Figure 2(b).

Therefore, the control system receives the control signals U_1, U_2, U_3, U_4, which activate the UAV's rotors. Thus, the control signals are related to the angular velocities of the rotors. They also depend on certain aerodynamic coefficients, such as thrust and drag, as well as the distance from the rotor to the center of mass of the aircraft. A body moving freely in space has six degrees of freedom. Its motion can be considered as rotation around the *Ox*, *Oy*, *Oz* axes and sliding along these axes. Thus, the body will have six types of independent possible motions: three rotational motions (φ, θ, ψ) and three translational motions (x, y, z).

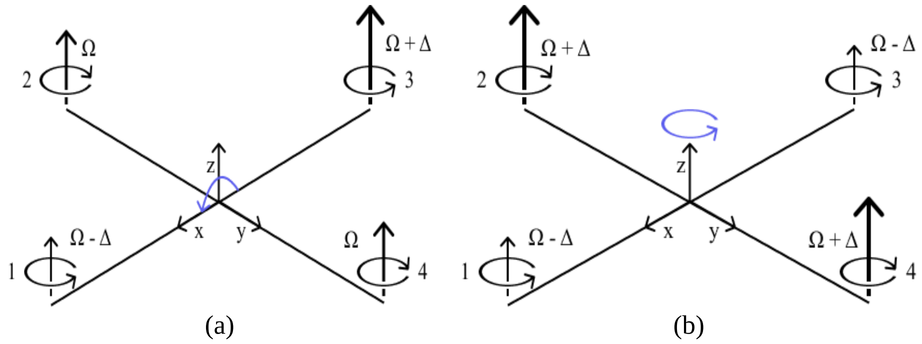

Figure 2. Ratio of angular velocities: (a) to pitching (located along the *Oy*-axis) and (b) to thrust generation (around the *Oz*-axis)

To determine the orientation of an object in an inertial system, a rotation matrix is used to convert values from a moving coordinate system to an inertial (1).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = R \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix}. \tag{1}$$

This matrix, denoted as R, relates the coordinates of vectors in the vector space when changing coordinate systems. Any orientation in space can be achieved by combining three elementary rotations, so the rotation matrix R can be decomposed into the product of three elementary rotation matrices. Multiplying these matrices yields the rotation matrix for the *X-Y-Z* sequence (2).

$$R_{xyz}(\varphi, \theta, \psi) == \begin{bmatrix} cos\psi cos\theta & cos\psi sin\theta - sin\psi cos\varphi & cos\psi sin\theta cos\varphi + sin\psi sin\varphi \\ sin\psi cos\theta & sin\psi sin\theta + cos\psi cos\varphi & sin\psi sin\theta cos\varphi - cos\psi sin\varphi \\ -sin\theta & cos\theta sin\varphi & cos\theta cos\varphi \end{bmatrix} \tag{2}$$

The rotation matrix is an orthogonal matrix, since vector lengths are preserved during the rotation operation. This matrix is also used to convert the velocities u, v, w of an object from the moving coordinate system to the inertial system. To convert the angular velocities p, q, r a linear transformation matrix (3) is used, as represented in (4). This matrix is not orthogonal, so to perform the inverse transformation, the inverse matrix needs to be found (5).

$$\begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = T \cdot \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{3}$$

$$T = \begin{bmatrix} 1 & 0 & -sin\theta \\ 0 & cos\varphi & sin\varphi cos\theta \\ 0 & -sin\varphi & cos\varphi cos\theta \end{bmatrix}, \tag{4}$$

$$T = \begin{bmatrix} 1 & sin\varphi tan\theta & cos\varphi tan\theta \\ 0 & cos\varphi & -sin\varphi \\ 0 & sin\varphi / cos\theta & cos\varphi / cos\theta \end{bmatrix}. \tag{5}$$

Therefore, taking into account the forces and moments acting on the object, we will rewrite the Newton-Euler equation [38]. We will find the acceleration matrix from the Newton-Euler formula and rewrite the obtained equation using the found matrices. By multiplying these matrices, we obtain the final equation. The resulting (6) is a mathematical model of a quadcopter in the form of a state equation in a moving coordinate system.

Where I_{xx}, I_{yy}, I_{zz} are the moments of inertia around the corresponding axis. Since the dynamics of the aircraft are described by a system of differential-equations (6), numerical integration methods such as the Runge-Kutta method [39] allow us to approximate the solution of these equations with the required accuracy. Here, $\dot{x}_{k,wa}$ represents the weighted average of four coefficients, and T is the time step.

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} -wq + vr + gsin\theta \\ wp - ur - gcos\theta sin\varphi \\ -vp + uq - gcos\theta cos\varphi + U_1/m \\ -\frac{I_{zz}rq}{I_{xx}} + \frac{I_{yy}qr}{I_{xx}} - qI_p\Omega/I_{xx} + U_2/I_{xx} \\ I_{zz}rp/I_{yy} - I_{xx}pr/I_{yy} + pI_p\Omega/I_{yy} + U_3/I_{yy} \\ -I_{yy}qp/I_{zz} + I_{xx}pq/I_{zz} + U_4/I_{zz} \end{bmatrix} \quad (6)$$

The value of $\dot{x}_{k,wa}$ is calculated using four computations (7).

$$\dot{x}_{k,wa} = \frac{1}{6}\left(\dot{x_{k_1}} + 2\dot{x_{k_2}} + 2\dot{x_{k_3}} + \dot{x_{k_4}}\right). \quad (7)$$

By finding the weighted sum of the derivative values of the intermediate states of the system, we obtain the differential of the system, $\dot{x}_{k,wa}$ which can be used to determine the next state of the system at time $t + T$. This process is repeated until the flight is completed. Therefore, the predicted state values should be as close as possible, in accordance with the requirements, to the real state values. The aircraft itself determines its state using sensors. If the control object accurately predicts future system states, meaning they are close to the real values, the controller can effectively manage the quadcopter.

2.1. Description of the proposed algorithm

The controller itself consists of two parts: a proportional link and an MPC component. Additionally, there will be a trajectory generator in the system, which the aircraft is supposed to follow. These data will serve as inputs for the proportional link. Let's consider a situation where the quadcopter needs to change its position from point A to point B. To achieve this goal, it is necessary to adjust the orientation values of the aircraft, φ and θ, so that the thrust vector points towards point B. In other words, by extending the thrust vector, it should intersect point B. This allows determining the necessary value of the control variable, thrust U_1, and the orientation values φ and θ. These values will be the outputs transmitted to the MPC as the desired orientation values. The yaw angle ψ is determined by the trajectory generator and directly passed to the MPC. Thus, the MPC controller will determine the control signals U_2, U_3, and U_4 to achieve the desired motion.

However, using this architecture introduces a problem since the values of φ and θ typically change each time, while the MPC controller iteratively tries to minimize the error between the real and desired orientation values. To address this issue, the MPC controller will be used multiple times per one usage of the proportional link. The research will employ a ratio of 5 to 1 for this purpose.

MPC method [40] calculates future states for a discrete system over a defined planning horizon, using constant matrix values. Equation (8) represents the state equation for the discrete system with a specified horizon value ($N = 5$), which computes future states of the system.

$$\begin{bmatrix} \vec{x}_1 \\ \vec{x}_2 \\ \vec{x}_3 \\ \vec{x}_4 \\ \vec{x}_5 \end{bmatrix} = \begin{bmatrix} B & 0 & 0 & 0 & 0 \\ AB & B & 0 & 0 & 0 \\ A^2B & AB & B & 0 & 0 \\ A^3B & A^2B & AB & B & 0 \\ A^4B & A^3B & A^2B & AB & B \end{bmatrix} \begin{bmatrix} \vec{u}_1 \\ \vec{u}_2 \\ \vec{u}_2 \\ \vec{u}_3 \\ \vec{u}_4 \end{bmatrix} + \begin{bmatrix} A \\ A^2 \\ A^3 \\ A^4 \\ A^5 \end{bmatrix} \vec{x}_0. \quad (8)$$

Since the MPC controller is an optimization algorithm, it minimizes a cost function. The cost function consists of two parts, which are explained in (9).

$$J = \frac{1}{2}\vec{e}_{k+N}^T S \vec{e}_{k+N} + \frac{1}{2}\sum_{i=0}^{N-1}[\vec{e}_{k+i}^T Q \vec{e}_{k+i} + \vec{u}_{k+i}^T R \vec{u}_{k+i}], \quad (9)$$

where,

$$\vec{e}_{k+N}=\begin{bmatrix}e_{\varphi_{k+N}}\\ e_{\theta_{k+N}}\\ e_{\psi_{k+N}}\end{bmatrix}=\begin{bmatrix}\varphi_{R_{k+N}}-\varphi_{k+N}\\ \theta_{R_{k+N}}-\theta_{k+N}\\ \psi_{R_{k+N}}-\psi_{k+N}\end{bmatrix},\quad S=\begin{bmatrix}S_1&0&0\\0&S_2&0\\0&0&S_3\end{bmatrix},\quad Q=\begin{bmatrix}Q_1&0&0\\0&Q_2&0\\0&0&Q_3\end{bmatrix},\quad R=\begin{bmatrix}R_1&0&0\\0&R_2&0\\0&0&R_3\end{bmatrix},\quad \vec{u}_{k+i}=\begin{bmatrix}u_{2_{k+N}}\\ u_{3_{k+N}}\\ u_{4_{k+N}}\end{bmatrix},$$

N – planning horizon.

The first part is the sum of weighted squared errors at each time step. Where the number of time steps depends on the length of the planning horizon. This yields a vector of error values (dependent on control variables) for which the cost function is minimized.

The second part is the sum of weighted squared control variables at each time step. Weights determine the importance given to each element for optimization. A higher weight indicates a higher priority for optimization. In summary, the MPC controller predicts future states using (8) and minimizes the cost function, which is composed of weighted error terms and weighted control variable terms. The weights determine the priority of optimization for each element.

To find the object's position in an inertial coordinate system, we use Newton's second law. The total force F is decomposed into three components: gyroscopic effect, gravitational force, and the influence of control signals. The matrices for these forces have been previously calculated in the moving coordinate system. However, since we need to determine the position, we only consider the first three rows of each matrix that describe the object's position. To transform these matrices into the inertial system, a rotation matrix is applied. This yields the motion equations for position control in the inertial coordinate system (10).

$$\begin{bmatrix}\ddot{X}\\ \ddot{Y}\\ \ddot{Z}\end{bmatrix}=\begin{bmatrix}(cos\varphi cos\theta cos\psi+sin\varphi sin\psi)\frac{U_1}{m}\\ (cos\varphi sin\theta sin\psi-sin\varphi cos\psi\,)\frac{U_1}{m}\\ cos\varphi cos\theta\frac{U_1}{m}-g\end{bmatrix} \tag{10}$$

The controller minimizes the error between desired flight trajectory values and actual values using proportional coefficients. Thus, we obtain a differential equation of second order representation (11).

$$\ddot{e}-k_2\dot{e}-k_1e=0. \tag{11}$$

We need to find the values of k_1 and k_2 that minimize the error between desired and actual values. In our research, we will select λ_1 and λ_2 to determine k_1 and k_2. Therefore, with the given values of λ, we can find the coefficients. Thus, the values of φ, θ, and U_1 are determined according to formulas (12), (13), and (14), respectively.

$$\theta=arctan\left(\frac{\ddot{X}\cdot\cos(\psi_r)+\ddot{Y}\cdot\sin(\psi_r)}{\ddot{Z}+g}\right) \tag{12}$$

$$\varphi=acrtan\left(\sin(\theta)\cdot\tan(\psi_r)-\frac{\ddot{Y}\cos(\theta)}{\cos(\psi_r)\cdot(\ddot{Z}+g)}\right) \tag{13}$$

$$U_1=\frac{m(\ddot{Z}+g)}{\cos(\varphi)\cdot\cos(\theta)} \tag{14}$$

2.2. Description of the software implementation

Let's describe the sequence of steps in the algorithm of the implemented control system in the software product as shown in Figure 3. The controller receives the desired values of position and orientation to be achieved, and it also receives the output of the control system. The system contains a model of the object in the state equations relative to the values of which the values of the next states of the object are found by integration, which go to the output of the system and, as a result, to the input of the controller. The same values are returned to the control system as inputs to the state model, since the value of future states is determined in the model relative to the value of previous states, that is, $k+1$ will be determined by the value of k. The controller outputs the values of the control signals (U_1, U_2, U_3, U_4) to achieve the desired values given to its input. These values are transmitted to the system input. From these values, the value of the angular velocity of rotation of the rotors (Ω_1, Ω_2, Ω_3, Ω_4) is found, which is also transmitted to the object model. The total value of the angular velocities is transmitted to the controller, as it is necessary for calculations.

To find the next states, the current state must be used, so the output value of the control system must be passed to the integrator. Since the values of the desired values that are transmitted to the controller are in the inertial coordinate system, the states that are the output of the control system must also be in the inertial coordinate system, since they were previously in the moving coordinate system. This is necessary to compare the obtained values (the output of the control system) with the required values (the controller input, i.e., the desired values) and to find an error to correct it. The code structure consists of four blocks as shown in Figure 3.

- Trajectory generator: constructs points along which the aerial vehicle needs to fly and provides the controller with the coordinate values of these points in space.
- Controller: consists of two sub-controllers (MPC and proportional control) that determine the optimal control signal values to optimize the flight of the aerial vehicle. These values are then passed to the plant.
- System: contains the mathematical model of the aerial vehicle and applies the calculated control signal values to determine the next state.
- Control system: the main file that manages the operation of the previous blocks and the execution frequency of the controllers.

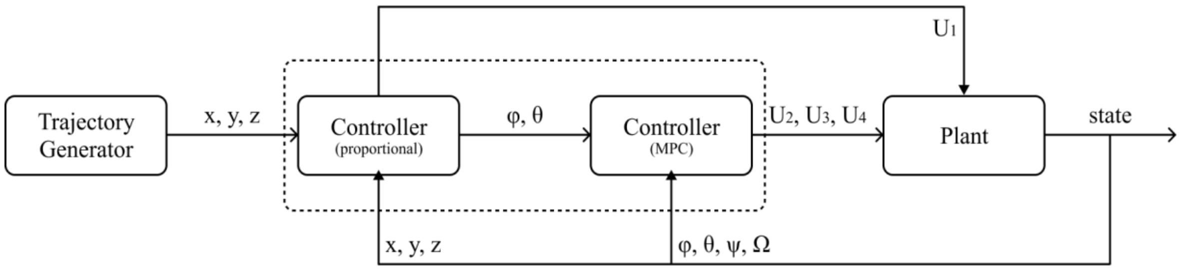

Figure 3. Flowchart of the implemented control system

3. RESULTS AND DISCUSSION

The quad rotor control system was implemented for simulation using the Python programming language. The values of the parameters used in the simulation are presented in Table 1. The duration of the simulation was 60 seconds. The simulation was conducted on two trajectories to test the hypotheses regarding the extreme values of the turning angles in the desired trajectory and the extreme values of the distance from the desired trajectory.

Table 1. Values of the simulation parameters

Parameter	g	m	ρ	l	I_{xx}	I_{yy}	I_{zz}	J_p	C_L	C_D	Horizon planning
Value	9.81	0.468	1.29	0.225	$3.856 \cdot 10^{-3}$	$3.856 \cdot 10^{-3}$	$8.801 \cdot 10^{-3}$	$3.357 \cdot 10^{-5}$	$2.980 \cdot 10^{-6}$	$1.140 \cdot 10^{-7}$	5

The aerial vehicle is located on the ground with initial coordinates x, y, z at the point (0, 0, 0) in a stationary state with zero thrust. The implemented method was tested on a flight trajectory called a "cylindrical helical line" in Figure 4.

The modeled case is described as follows. During the first step, from time 0 to 0.1, the rotors abruptly generate high thrust by increasing the angular velocity of blade rotation. Sharp changes in the control signals are observed during each step within time intervals of 0–8 seconds for pitch, 0–6 seconds for roll, and 0–2 seconds for yaw. These changes are explained by the significant distance between the aerial vehicle and the defined trajectory, resulting in a large error that the system tries to minimize. Approximately at the 8th second, the motion of the aerial vehicle stabilizes and smoothly follows the desired trajectory without abrupt angular movements or thrust changes throughout the simulation.

From this experiment, it can be concluded that to optimize the flight trajectory, it is necessary to minimize the distance from the initial position of the aerial vehicle to the starting point of the desired flight trajectory. In other words, the takeoff point should be the initial point of the trajectory. In the presence of significant disturbances, the quadcopter control system may generate extreme thrust values and angles, which can lead to damage to the rotors and propellers, as well as loss of stability and accidents.

The second experiment takes into account the problem of large angles in the desired trajectory. The simulation was performed on a trajectory with a discontinuity as shown in Figure 5. The simulation shows two regions of high-frequency changes in velocity values, angular velocities, and control signals. The first region occurs at the beginning of the simulation, between 0–10 seconds, and is caused by a significant distance between the object and the desired trajectory. This leads to a substantial generation of thrust and angular movements.

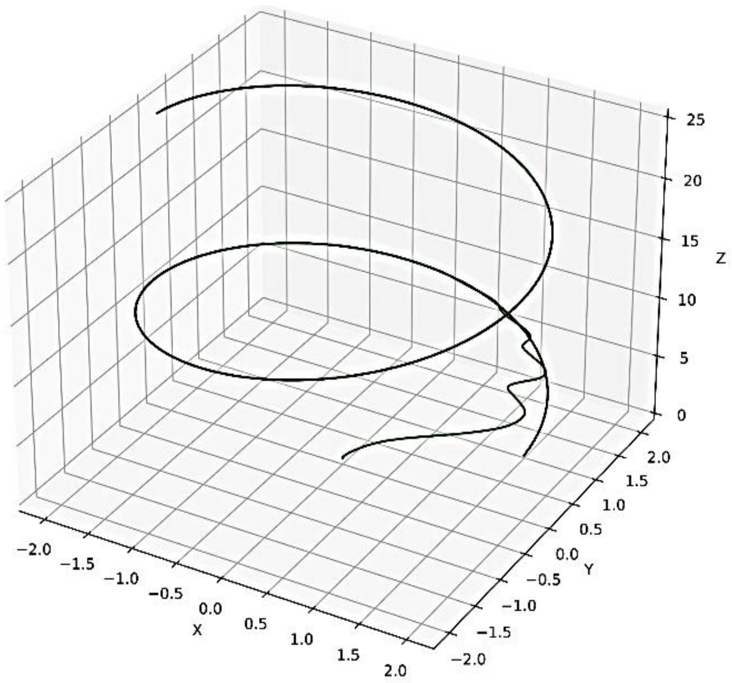

Figure 4. Planned and optimal flight trajectory

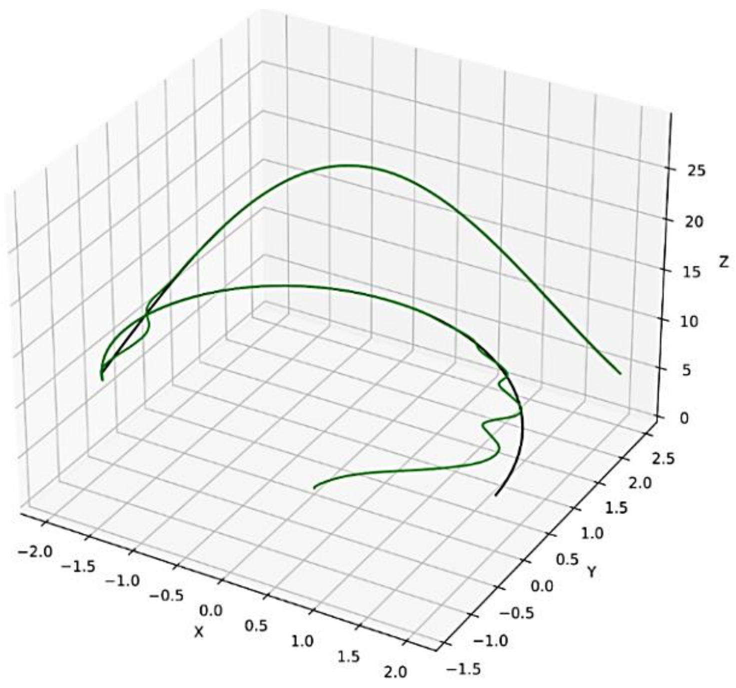

Figure 5. Planned and optimal flight trajectory

The second region occurs at 24 seconds, at the location of the trajectory discontinuity. In this area, relatively large angles occur, resulting in high values of control signals and orientation angles. After minimizing the error using the algorithm, approximately 5 seconds on average, and the aerial vehicle gradually stabilizes and accurately follows the desired trajectory. Therefore, it can be concluded that for optimal and stable motion of the aerial vehicle, a smooth flight trajectory is desirable. This experiment aims to compare the trajectory tracking accuracy of the control system against existing controllers. The comparison will be performed with PD, LQR, and MPC controllers in an environment without additional external disturbances [41]. The implemented method was compared to a "cylindrical helical line" flight trajectory as shown in Figure 6.

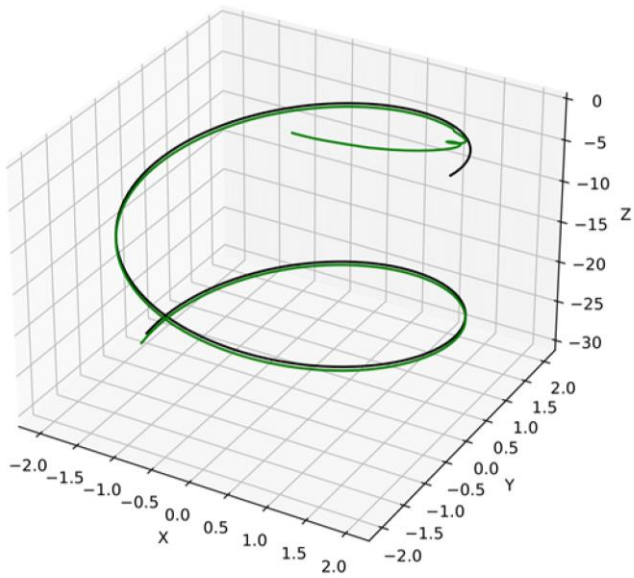

Figure 6. Planned and optimal flight trajectory

Similar to previous experiments, at the beginning of the flight trajectory, there is a high frequency of changes due to a large distance from the trajectory. It is worth noting that unlike the first experiment where the trajectory stabilized after some time, in this experiment, it is slightly offset. This behavior of the system can be attributed to the change in simulation parameters.

In the study, the comparison was conducted using the root-mean-square error (RMSE) [42] for position values along the *Ox*, *Oy*, and *Oz* axes, and the comparative values are presented in Table 2. Overall, by finding the RMSE values resulting from the execution of the PD, LQR, MPC, and combined methods, their accuracy can be compared percentage-wise, and the comparative values are presented in Table 3.

Table 2. RMSE for helix

Controller	RMSE along the X-axis	RMSE along the Y-axis	RMSE along the Z-axis
PD	0.5393	0.8615	1.0474
LQR	0.8388	2.1771	2.3180
MPC	0.8445	3.9009	2.9437
Combined MPC	0.4736	0.7946	1.7721

Table 3. Percentage improvement value

Controller	Combined MPC
PD	-32%
LQR	+43%
MPC	+74%

As a result, our combined method will have higher accuracy compared to LQR and MPC but lower than PD, as shown in Table 3. These results can be explained by the simulation environment, as it did not include the presence of disturbances. Therefore, the created control system fully utilizes the advantages of both controllers. Additionally, it can be assumed that the proposed system will exhibit more stable behavior in the presence of minor disturbances due to the inclusion of an MPC controller.

During the execution of this work on optimizing control, regulation, and measurement methods for the trajectory of UAV, the method of optimal control for a quadrotor UAV was improved to enhance trajectory tracking accuracy. To test the method, an emulation system of the UAV was implemented, consisting of a mathematical model of the quadcopter, flight controller, and trajectory generator. A combination of an MPC sub-controller and a proportional sub-controller was used as the controller to distribute the system's functions and improve trajectory tracking accuracy relative to the specified design constraints of the UAV. A proportional controller was also employed for responsiveness and computational simplification. The mathematical model was linearized for additional controller optimization. The use of different MPC controller planning horizons was also considered.

The emulation system was tested on various trajectories using the Python programming language. The result graphs demonstrate that the system can optimize the UAV's movement and enable autonomous flight in uncomplicated environments. The obtained results are of practical value as they can be applied in areas of human activity where aerial inspections are required in controlled environments or premises. The system itself can be further improved by constructing a more accurate mathematical model [43], [44]. As noted in [45], [46] today a system of several UAVs is of particular interest due to the ability to coordinate simultaneous coverage of large areas and cooperate to achieve common goals/tasks. Therefore, it will be important to further investigate the proposed method for controlling and optimizing the UAV flight path using the example of a multi-UAV system.

4. CONCLUSION

In this paper, we have improved a method for controlling and optimizing the flight path of a UAV. The system was implemented and tested on several trajectories, and the following results were obtained: i) the proposed algorithm allows for maintaining the accuracy of the quad-rotor on trajectories that do not involve movement along sections of the path with extreme values of angular motions. And ii) external disturbances will significantly affect flight stability.

Comparison of the system with existing controllers suggests that it is capable of optimizing the flight path of a quadcopter in a simple environment without additional disturbances, i.e., indoors or other controlled environments, so it can theoretically be used in real-world conditions. It is worth noting that the system can operate outside the described situations, but in this case, the system will generate high values of rotor angular velocities, which may adversely affect the technical condition of the aircraft, which does not guarantee the aircraft's serviceability, or even lead to a loss of stability.

Through experiments and comparisons with other methods such as PD, LQR, and unmodified linear MPC, improvements in trajectory accuracy of 43% and 74%, respectively, were confirmed on a helicopter trajectory without disturbances. This demonstrates the effectiveness and advantages of the proposed control method for enhancing accuracy and reducing motion errors in the system. Therefore, the combination of MPC and P-controller enables optimal motion of unmanned aerial vehicles in a simplified environment, reducing the influence of steady-state errors and requiring fewer computational resources.

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