Robust Control Design for Quadcopter for Path Following in Monitoring Tasks

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***Abstract*—The control system design plays a critical role in unmanned aerial vehicles to perform pre-planned tasks such as fire exploration and monitoring operations. The UAV encounters various interferences when carrying out outdoor missions. Therefore, it is very important to work on the development of a robust control algorithm that is resistant to external disturbances and changes in parameters. This article proposes the structure of the robust UAV control design by setting their parameters using the example of a quadcopter, a robotic device that is perfect for monitoring tasks. The results of modeling and experiments confirm the good performance of the system in tracking trajectories even in the presence of disturbances.**

Keywords—UAV, quadcopter, robust controller, PID controller, path tracking.

I. INTRODUCTION

In recent years, there has been a steady increase in interest in autonomous air vehicles, especially the most common type, the quadcopter, a four-engine UAV. The advantages of quadcopters are low cost, simplicity, few movement restrictions, and the ability to carry large payloads. Their use has increased due to their easy access to remote areas for wide applications such as monitoring, agricultural services, mapping and photography, combat damage assessment, border interception prevention, and others [1]. The drones' promising applications are exploration and fire monitoring [2, 3]. Environmental factors, such as gusts of wind, affect the quality of data collection (photos) during reconnaissance flights. From this point of view, it is essential to obtain reliable data. Therefore, a reliable controller with trajectory control algorithms is required for high-quality flight performance. For autonomous UAV navigation, the controller must include trajectory planning and path tracking [4]. There are several control laws to stabilize the quadrocopter during flight (nonlinear, linear, robust, etc.). Many control laws have been developed using a simplified nonlinear system or linear models [5], [6]. In [7], a linear and nonlinear model predictive control scheme was presented for controlling a quadcopter to track various reference trajectories. The authors also presented an analysis of the stability of linear and nonlinear feedback control schemes. In [8], the authors proposed a unified motion control scheme for quadcopters, which solves the problems of stabilization, trajectory tracking, and the problem of path following. In a later paper [9], researchers proposed a trajectory generation algorithm, which allows you to quickly calculate high-performance flight trajectories for moving a quadcopter from a large class of initial states to a given target location. Thus, the actual task is to develop a controller for a quadrocopter control system that allows autonomous flight along a given route with minor deviations and is resistant to external influences. This work proposes a simple quadrocopter controller structure and a trajectory control algorithm.

II. SYSTEM DESCRIPTION

This section describes the dynamic quadcopter model and controller circuit used in the experiments. The dynamic model of a quadcopter is obtained by representing the vehicle as a 3D rigid body driven by forces and torques generated by the propellers, see Fig. 1.

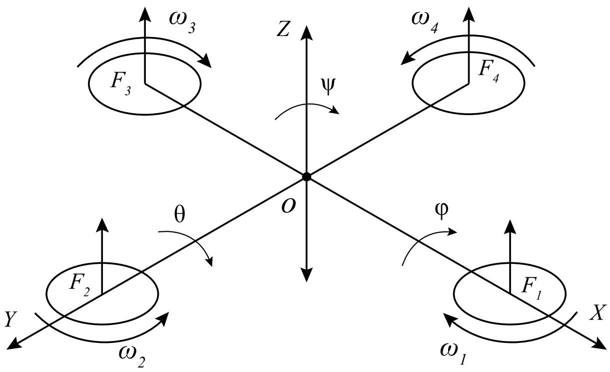

Fig. 1 Dynamic model of a quadcopter

A widely used simplified quadcopter model is shown below. [10]:

$$\begin{aligned} m\ddot{x} &= -u\sin\theta, \quad I_\psi\ddot{\psi} = \tilde{\tau}_\psi \\ m\ddot{y} &= u\cos\theta\sin\phi, \quad I_\theta\ddot{\theta} = \tilde{\tau}_\theta \\ m\ddot{z} &= u\cos\theta\cos\phi - mg, \quad I_\phi\ddot{\phi} = \tilde{\tau}_\phi \end{aligned} \tag{1}$$

where x and y — horizontal coordinates, z — vertical position, g — acceleration of gravity, ψ , θ and φ — yaw, pitch and roll angles respectively, m — device weight, I_i — moment of inertia about the i - axis, and $\tilde{\tau}_i$ — torque acting on the i - axis.

The quadcopter control system can be divided into sub-controllers such as position controller (to control x and y), height controller (to control z), and attitude controller (to control the three Euler angles φ , θ , and ψ) (see Fig. 2).

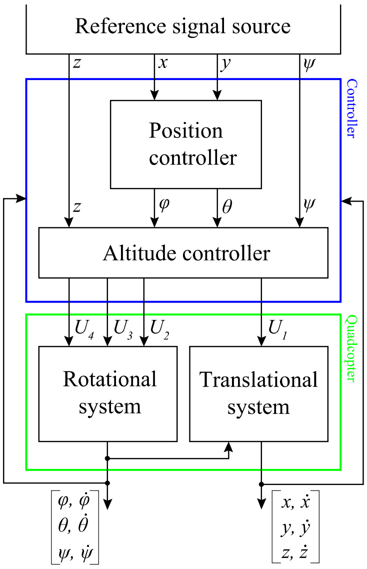

Fig. 2 Basic controller system structure for quadcopter

It is worth noting that in the system described above, the angles and their time derivatives are independent of the translation components. Ideally, we can imagine the structure described above consisting of two subsystems: angular rotations and linear displacements, as shown in Fig. 3.

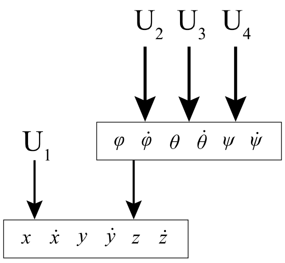

Fig. 3 Relationship between the rotational and translational subsystems of the quadcopter

III. METHODOLOGY

A. Control system for quadcopter

The mathematical equations of the quadcopter model without perturbations can be written as follows:

$$\ddot{x} = \left(\cos\varphi \sin\theta \cos\psi + \sin\varphi \sin\psi\right)\frac{U_1}{m} \tag{2.1}$$

$$\ddot{y} = \left(\cos\varphi \sin\theta \sin\psi - \sin\varphi \cos\psi\right)\frac{U_1}{m} \tag{2.2}$$

$$\ddot{z} = \left(\cos\varphi \cos\theta\right)\frac{U_1}{m} - g \tag{2.3}$$

$$\ddot{\varphi} = \frac{I_y - I_z}{I_x}\dot{\theta}\dot{\psi} - \frac{J_r}{I_x}\Omega_r\dot{\theta} + \frac{1}{I_x}U_2 \tag{2.4}$$

$$\ddot{\theta} = \frac{I_z - I_x}{I_y}\dot{\varphi}\dot{\psi} + \frac{J_r}{I_y}\Omega_r\dot{\varphi} + \frac{1}{I_y}U_3 \tag{2.5}$$

$$\ddot{\psi} = \frac{I_x - I_y}{I_z}\dot{\varphi}\dot{\psi} + \frac{1}{I_z}U_4 \tag{2.6}$$

The system can be rewritten in state space form:

$$\dot{X} = f(\mathrm{X}, \mathrm{U}) \tag{3}$$

where U – input vector, and X - state vector chosen as follows:

$$X = \begin{bmatrix} x & y & z & \varphi & \theta & \psi & \dot{x} & \dot{y} & \dot{z} & \dot{\varphi} & \dot{\theta} & \dot{\psi} \end{bmatrix}^T \tag{4.1}$$

$$U = \begin{bmatrix} U_1 & U_2 & U_3 & U_4 \end{bmatrix}^T \tag{4.2}$$

Let us present the equations of connection of control channels U_1 , U_2 , U_3 , and U_4 with the rotation speeds of the quadcopter propellers. The quadcopter altitude changes with U_1, steer angle changes with U_2, pitch angle depends on U_3 and U_4 controls yaw angle. These input forces will help the operator move the quadcopter in all directions. Each input force is calculated by the equation shown below. Inputs are displayed as follows:

$$U_1 = k_f\left(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2\right) \tag{5.1}$$

$$U_2 = k_f\left(-\omega_2^2 + \omega_4^2\right) \tag{5.2}$$

$$U_3 = k_f\left(\omega_1^2 - \omega_3^2\right) \tag{5.3}$$

$$U_4 = k_z\left(-\omega_1^2 + \omega_2^2 - \omega_3^2 + \omega_4^2\right) \tag{5.4}$$

and

$$\Omega_r = \omega_1 - \omega_2 + \omega_3 - \omega_{41} \tag{6}$$

where ω_i for $i = 1, 2, 3, 4$ denotes the speed of the i-th rotor, and T_i for $i = 1, 2, 3, 4$ - thrust generated by the i-th rotor, and the thrust $T_i(t)$ is equal to the function of the rotor speed, determined by the expression:

$$T_i(t) = k_f\omega_i^2 \tag{7}$$

where k_f and k_z - constant coefficients, and

$$f(X,U) = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \\ u_x\frac{U_1}{m} \\ u_y\frac{U_1}{m} \\ \left(\cos\varphi\cos\theta\right)\frac{U_1}{m} - g \\ \frac{I_y - I_z}{I_x}\dot{\theta}\dot{\psi} - \frac{J_r\Omega_r}{I_x}\dot{\theta} + \frac{l}{I_x}U_2 \\ \frac{I_y - I_x}{I_y}\dot{\varphi}\dot{\psi} + \frac{J_r\Omega_r}{I_y}\dot{\varphi} + \frac{l}{I_y}U_3 \\ \frac{I_x - I_y}{I_z}\dot{\varphi}\dot{\theta} + \frac{1}{I_z}U_4 \end{bmatrix} \tag{8}$$

where

$$u_x = \cos\varphi \sin\theta \cos\psi + \sin\varphi \sin\psi \quad (9.1)$$

$$u_y = \cos\varphi \sin\theta \sin\psi - \sin\varphi \cos\psi \quad (9.2)$$

B. *Trajectory control algorithm*

The critical element of the quadrocopter control system (as an unstable system) is the stabilizing PID controller, which is a component capable of fixing the course of the control deviation, its cumulative value, and change over time. The PID controller calculates the "error" value as the difference between the measured and desired values. The deviation value is multiplied by the P factor (proportional term), the accumulated value is multiplied by the I factor (integral term), and the difference is multiplied by the D factor (differential term). The sum of the individual products gives us the amount of regulation [11]:

$$u_t = P \cdot E_t + I \cdot \sum_{i=0}^{t} E_t + D \cdot \left(E_t - E_{t-1}\right) \quad (10)$$

where u - amount of regulation, P - proportional coefficient, E - deviation size, I - integral coefficient, D - derivative coefficient.

The projections of the horizontal force, without resistance of the non-load-bearing part of the device, according to the dynamics equations have the form below:

$$U_x = P\left(-\cos\gamma \cos\psi \sin\upsilon + \sin\gamma \sin\psi\right) \quad (11.1)$$

$$U_z = P\left(\cos\gamma \sin\psi \sin\upsilon + \sin\gamma \cos\psi\right) \quad (11.2)$$

from where it is possible to determine the roll and pitch angles at which the required effects are created with a known total thrust P:

$$\gamma_d = \arcsin\frac{U_{zd}\cos\psi_d + U_{xd}\sin\psi_d}{P} \quad (12.1)$$

$$\vartheta_d = \arccos\frac{U_{zd}\sin\psi_d - U_{xd}\cos\psi_d}{P} \quad (12.2)$$

Controlling influences U_{xd} and U_{zd}, and also $U_{yd} = U_1$ for the height control channel can be obtained by considering the trajectory control subsystem as a control system that tracks the required coordinates of the center of mass, in particular, as the output signals of the PID controller according to deviations of the center of mass coordinates from the required ones:

$$\begin{aligned} U_{xd} &= K_{px}(x_d - x) + K_{ix}\int(x_d - x)dt + K_{dx}(\dot{x}_d - \dot{x}) \\ U_{yd} &= \frac{m}{\cos\gamma\cos\vartheta}K_{py}(y_d - y) + K_{iy}\int(y_d - y)dt + K_{dy}(\dot{y}_d - \dot{y}) + mg \\ U_{zd} &= K_{pz}(z_d - z) + K_{iz}\int(z_d - z)dt + K_{dz}(\dot{z}_d - \dot{z}) \end{aligned} \quad (13)$$

The values of the coefficients of the regulators for the relevant variables, selected by the Ziegler-Nichols method [12], are shown in Table 1.

TABLE I. VALUES OF THE PID CONTROLLER COEFFICIENTS

	K_p	K_i	K_d
x	8.5	0.02	8.1
y	24	10	28
z	4.9	0.015	5.1

IV. EXPERIMENTAL RESULTS

In this section, we show the effectiveness of the proposed UAV trajectory tracking control for various trajectory curvatures. We tested the control algorithm, which stabilizes the flight coordinates of a quadrocopter and tracks a given trajectory. The simulation for an arbitrary curvature path to show that the proposed design provides satisfactory performance under multiple scenarios is shown in Fig. 4. The quadcopter flew at a fixed altitude of 30 meters and pass through ten waypoints, where at the top points the UAV stops to take some photos. And Fig. 5 shows changes in *x*, *y* and *z* coordinates.

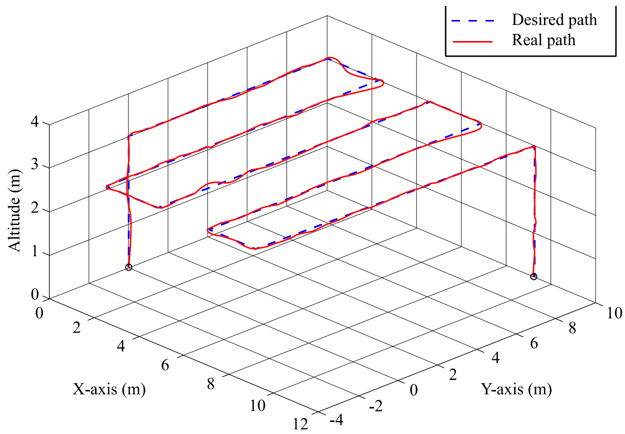

Fig. 4 Trajectory tracking test when the quadcopter follows the path in presence of wind and manual disturbances

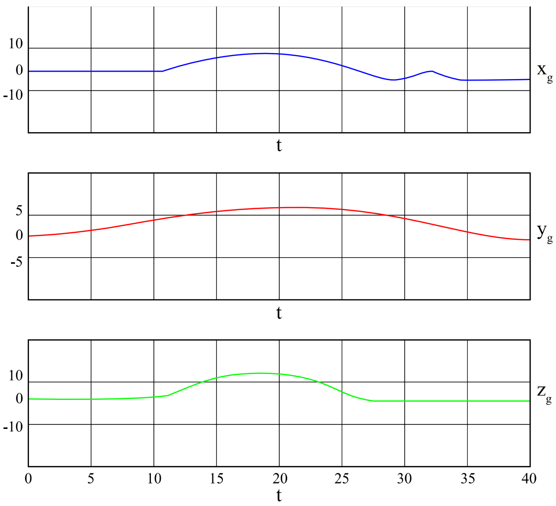

Fig. 5 Coordinate changes (x_g , y_g , z_g) of the PID controller

V. DISCUSSION

During experimental studies on a quadrocopter, the following effect was noticed. When adjusting the parameters of the stabilizing PID controller directly during the flight according to the above algorithm based on telemetry data, the most difficult process is to adjust the differential component of the controller, a slight change in this parameter leads to overshoot. At the same time, dosed overshoot, which does not lead to loss of control and is poorly distinguishable visually, has a positive effect on the stability of the quadcopter to external influences. The stabilization of the quadcopter occurs much faster, and with an increase in the payload of the apparatus, the growth of the component D generally has a positive effect on the actual controllability of the quadcopter.

Conclusion

This article proposes a robust controller scheme for path tracking of a quadcopter for automatic monitoring of a target area. The control structure is based on a simple non-linear controller with sub-controllers. The control scheme has been verified in flight tests to track the trajectory, considering external disturbances. The simulation results demonstrate the proposed method's good performance and show the algorithm's efficiency in its implementation.

References

[1] H. N. Lashari, H. Mansoor Ali, S.-U.-R. Massan, “Applications of unmanned aerial vehicles: a review”, 3C Technology. Special Edition, 2019. doi: 10.17993/3ctecno.2019.specialissue3.85-105.

[2] D. Kaliyev, O. Shvets. “Application of robotic systems for fire exploration”. AIS 2019: 14th International Symposium on Applied Informatics and Related Areas organized in the frame of Hungarian Science Festival 2019 by Óbuda University. Székesfehérvár, pp. 91-92.

[3] D. Kaliyev, O. Shvets, G. Györök. “UAV based navigation system for forest fires monitoring”. AIS 2021: 16th International Symposium on Applied Informatics and Related Areas organized in the frame of Hungarian Science Festival 2021 by Óbuda University, Székesfehérvár, 2021, pp. 47-50.

[4] I. D. Cowling, O. A. Yakimenko, J. F. Whidborne, A. K. Cooke. "A prototype of an autonomous controller for a quadrotor UAV," 2007 European Control Conference (ECC), 2007, pp. 4001-4008, doi: 10.23919/ECC.2007.7068316.

[5] H. Mo, G. Farid. “Nonlinear and adaptive intelligent control techniques for quadrotor uav–a survey”. Asian Journal of Control, 2019. Vol. 21, №. 2, pp. 989-1008.

[6] S. H. Derrouaoui, Y. Bouzid, M. Guiatni. “Nonlinear robust control of a new reconfigurable unmanned aerial vehicle”. Robotics, 2021, Vol 10. № 2, p. 76.

[7] P. Ru, K. Subbarao. “Nonlinear Model Predictive Control for Unmanned Aerial Vehicles,” MDPI aerospace, 2017, pp. 1–26. doi: 10.3390/aerospace4020031.

[8] V. H. Andaluz, H. Víctor, Gallardo, M. Cristian, Chicaiza, A. Fernando, Carvajal, P. Christian. “Robot nonlinear control for Unmanned Aerial Vehicles’ multitasking”. Assembly Automation. 2018. doi: 10.1108/AA-02-2018-036.

[9] Y. Al Younes, M. Barczyk. “Nonlinear model predictive horizon for optimal trajectory generation”. Robotics, 2021. Vol. 10, № 3, p. 90.

[10] P. Castillo, L. E. Munoz, P. Garcia. “Indoor Navigation Strategies for Aerial Autonomous Systems”. Elsevier, Feb. 2017 ISBN:9780128051894.

[11] A. A. Najm, I. K. Ibraheem. “Nonlinear PID controller design for a 6-DOF UAV quadrotor system”. Engineering Science and Technology, an International Journal, 2019, Vol. 22, № 4, pp. 1087-1097.

[12] V. V. Patel. Ziegler-Nichols tuning method. Resonance, 2020, Vol. 25, № 10, pp. 1385-1397.