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Stable flight control of UAV under atmospheric turbulence

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Abstract. Unmanned aerial vehicles will be subjected to various environmental disturbances such as atmospheric turbulence during the execution of tasks, which will seriously affect the flight safety of UAV. By establishing UAV flight dynamics model and atmospheric turbulence model, and using PID algorithm to design controller, this paper studies the attitude and altitude control effect of UAV under atmospheric turbulence disturbance. The simulation results show that PID algorithm can effectively control the UAV's stable flight under atmospheric turbulence and ensure the safety of UAV.

Keywords: unmanned aerial vehicles, PID algorithm, atmospheric turbulence.

1. Introduction

In recent years, unmanned aerial vehicles (UAVs), also known as drones, have received widespread attention due to their advantages of low usage restrictions, high cost-effectiveness, and strong survivability. They have been applied in various fields such as search and rescue operations, aerial photography and videography, delivery and transportation, geographical mapping, and so on. As UAV technology continues to advance and mission requirements become more complex, the demands for their performance have also been increasing.

However, UAVs are inevitably subjected to various interferences during mission execution, such as turbulent airflow and disturbances from the natural environment. These factors can directly lead to unstable flight behavior of the UAVs, thereby reducing their mission effectiveness and even posing a threat to their safety. Therefore, designing controllers with strong robustness for UAVs is of paramount importance to enhance their overall performance.

In order to improve the robustness of the flight controller, various studies have been conducted [1][2][3]. In Reference [4], an adaptive non-singular terminal sliding mode control method was proposed for the quadrotor. The simulation results demonstrated that the proposed method can effectively control the aircraft to track the desired trajectory regardless of the disturbances. Prabhakar [5] presented a direct adaptive control laws in 2018, which is consisted of a disturbance accommodating control law and an adaptive controller. The results showed that this control scheme can provide disturbance rejection for the aircraft. In another study [6], an adaptive control strategy is applied to the UAV with the presence of gusty winds, whose effectiveness is demonstrated by the experimental results.

In order to explore the stable flight control of unmanned aerial vehicles (UAVs) under atmospheric turbulent disturbances, this paper first establishes a flight dynamics model for a fixed-wing UAV and a wind field disturbance model. Subsequently, a proportional-integral-derivative (PID) control algorithm is designed as the UAV's stable flight controller. Finally, simulation experiments are conducted using Matlab/Simulink to validate the effectiveness and reliability of the control algorithm.

The overall structure of this paper is arranged as follows: Chapter 2 presents the flight dynamics model of the fixed-wing unmanned aerial vehicle (UAV). Chapter 3 provides the atmospheric turbulent disturbance model. The design of the controller is described in Chapter 4. Chapter 5 presents the simulation results and analysis of the simulation experiments. Finally, the conclusion is given in Chapter 6.

2. Flight dynamic model

The fixed-wing unmanned aerial aircraft studied in this paper is equipped with elevator, aileron and rudder. And the flight dynamics model is given as follows:

First is the force equation:

$$\begin{aligned}\dot{u} &= rv - qw - g\sin\theta + (F_X + T_X)/m \\ \dot{v} &= -ru + pw - g\sin\phi\cos\theta + (F_Y + T_Y)/m \\ \dot{w} &= qu - pv + g\cos\phi\cos\theta + (F_Z + T_Z)/m\end{aligned} \tag{1}$$

where u, v, w represents the forward velocity, lateral velocity and the vertical velocity, respectively; F_X, F_Y, F_Z represents the aerodynamic forces along the body-fixed frame; T_X, T_Y, T_Z represents the thrust along the body-fixed frame

The moment equation is defined as follows:

$$\begin{aligned}\dot{p} &= I_1 pq + I_2 qr + I_3 L + I_4 N \\ \dot{q} &= I_5 pr - I_6 (p^2 - r^2) + I_7 M \\ \dot{r} &= I_8 pq - I_1 qr + I_4 L + I_9 N\end{aligned} \tag{2}$$

where L, M, N is the moments along the axis of the body-fixed frame.

The angular velocity function is given as follows:

$$\begin{aligned}\dot{\phi} &= p + \tan\theta(q\sin\phi + r\cos\phi) \\ \dot{\theta} &= q\cos\phi - r\sin\phi \\ \dot{\psi} &= \frac{q\sin\phi + r\cos\phi}{\cos\theta}\end{aligned} \tag{3}$$

where p, q, r represents the angular rates in the body-fixed frame; ϕ, θ, ψ represents the roll angle, pitch angle and yaw angle, respectively.

3. Atmospheric turbulence model

During the flight of unmanned aerial vehicles (UAVs), they are susceptible to atmospheric turbulent disturbances, which can impact their safe operation. Atmospheric turbulence is a random fluctuation superimposed on the mean wind field, and it is commonly modeled using the Dryden model and the Von Karman model. Among these, the Von Karman model is preferred in this paper due to its more complex spectral function, which better captures the realistic characteristics of atmospheric turbulence. Therefore, in this research, the Von Karman model is adopted to simulate atmospheric turbulence and investigate its effects on the stable flight of UAVs.

Based on actual measurement data, the energy spectral function of the Von Karman model is given by [7]:

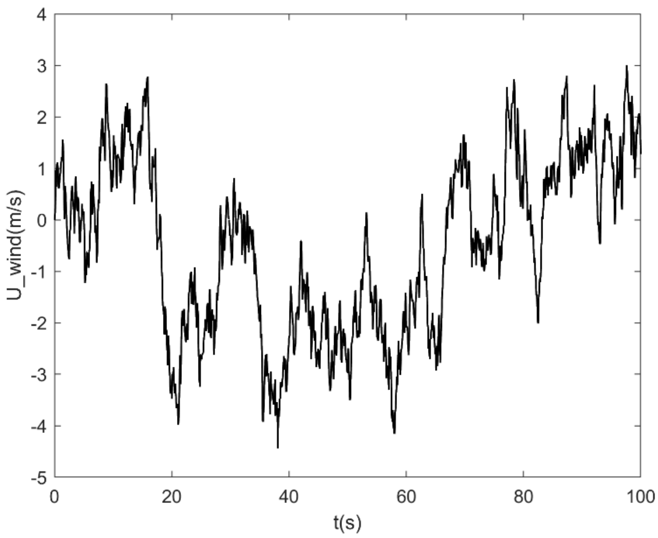
$$E(\Omega)=\sigma^2 \frac{55L}{9\pi}\frac{(aL\Omega)^4}{\left[1+\left(aL\Omega^2\right)^{17/6}\right]} \tag{4}$$

where $a=1.34$, L is the scale length, Ω is spatial frequency， σ is turbulence intensity.

Therefore, the correlation function of the spectrum of the Von Karmon turbulence model can be obtained as follow：

$$\left.\begin{aligned}
R_{UU}\left(\xi_1,\xi_2,\xi_3\right)&=\sigma_{\mathrm{n}}^2\frac{2^{2/3}}{\Gamma(1/3)}\zeta^{1/3}\left[K_{1/3}(\zeta)-K_{2/3}(\zeta)\frac{\xi_2^2+\xi_3^2}{2aL\xi}\right]\\
R_{WV}\left(\xi_1,\xi_2,\xi_3\right)&=\sigma_{\mathrm{n}}^2\frac{2^{2/3}}{\Gamma(1/3)}\zeta^{1/3}\left[K_{1/3}(\zeta)-K_{2/3}(\zeta)\frac{\xi_1^2+\xi_3^2}{2aL\xi}\right]\\
R_{WW}\left(\xi_1,\xi_2,\xi_3\right)&=\sigma_{\mathrm{n}}^2\frac{2^{2/3}}{\Gamma(1/3)^{1/3}}\left[K_{1/3}(\zeta)-K_{2/3}(\zeta)\frac{\xi_1^2+\xi_2^2}{2aL\xi}\right]
\end{aligned}\right\} \tag{5}$$

Based on the above equations, the simulation of atmospheric turbulence was carried out in Matlab/Simulink, and the forward wind speed, lateral wind speed and longitudinal wind speed of atmospheric turbulence were obtained as shown in the Figure 1:



(a) Forward wind speed.

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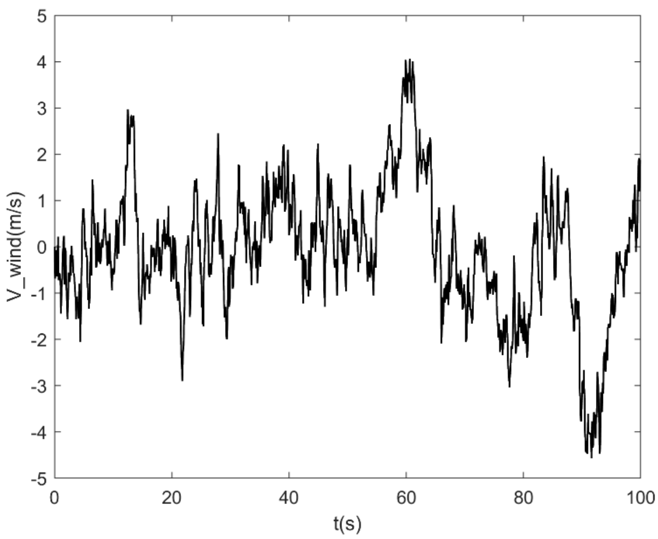
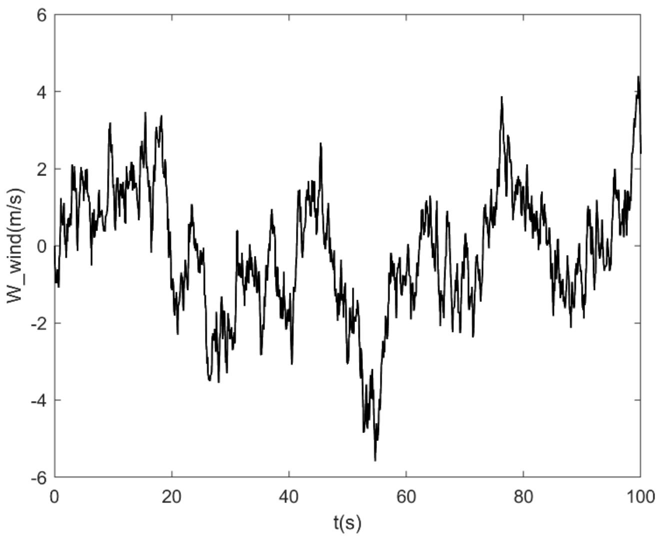


(b) Lateral wind speed.



(c) Longitudinal wind speed.

Figure 1. Simulation results of atmospheric turbulence.

As can be seen from the Figure 1, the atmospheric turbulence has obvious wind speed in all directions, among which the forward wind speed ranges between [-5m/s,3m/s], the lateral wind speed ranges between [-5m/s,4m/s], and the longitudinal wind speed ranges between [-6m/s,4m/s]. Therefore, it will have a significant impact on the flight of UAVs.

4. Controller model

To achieve stable flight of the fixed-wing unmanned aerial vehicle (UAV) under atmospheric turbulent disturbances, this paper employs both the PID control algorithm and the cascaded PID control algorithm to design the attitude controller and altitude controller for the UAV, respectively.

The PID control algorithm is a closed-loop control method that consists of three control units: Proportional, Integral, and Derivative. Due to its simplicity in design, clear theoretical understanding, and low requirements on the system model, the PID control algorithm is currently the most widely used control method. Utilizing the PID control algorithm allows the design of a controller with excellent control capabilities, and the characteristics of its three components are as follows:

(1) Proportional component: It reflects the error in proportion to the error value. When the proportional coefficient is small, the controlled system adjusts slowly, resulting in relative stability. On the other hand, a large proportional coefficient allows the controlled system to reach the target rapidly, but it may become unstable and prone to oscillations.

(2) Integral component: It remembers the historical errors and can eliminate the steady-state error of the controlled system. However, a large integral coefficient may lead to oscillations and worsen stability.

(3) Derivative component: It reduces the oscillations caused by the proportional component when the target value is reached, effectively reducing the overshoot of the system. The derivative component also provides proactive adjustment, but obtaining the derivative value of the system state variables is often challenging in practical applications.

The control principle diagram of PID is shown in Figure 2:

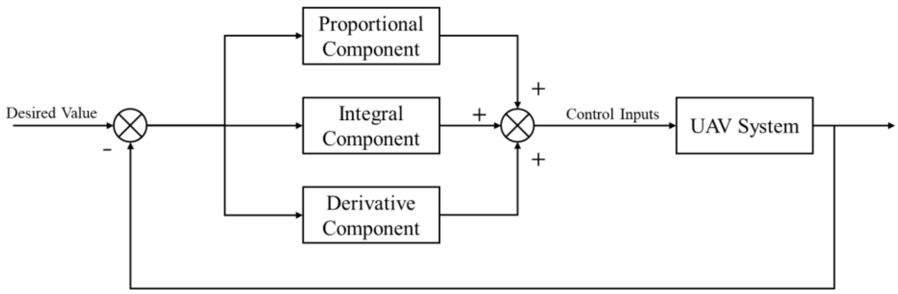


Figure 2. Control principle diagram of PI.

The mathematical formula of PID control algorithm can be obtained from the figure, as follows:

$$u(t) = K_p \mathrm{e}(t) + K_i \int_0^t \mathrm{e}(\tau) \mathrm{d}\tau + K_\mathrm{d} \frac{\mathrm{de}(t)}{\mathrm{d}t} \tag{6}$$

where K_p, K_i, K_d denotes the proportional coefficient, the integral coefficient and the derivative coefficient, respectively.

However, in some cases, due to the high complexity of the system, using a single-layer PID control may not yield the desired control performance. In such situations, a cascaded PID control method is required. The cascaded PID control achieves better control performance by nesting multiple PID controllers in a series, allowing for a more refined and precise control. The fundamental principle lies in first stabilizing the controlled system through an inner-loop PID control to optimize the system's dynamic characteristics. Then, an outer-loop PID control is further nested to achieve a more sophisticated and accurate control.

Based on the above discussions, this paper employs both the PID controller and the cascaded PID controller to achieve attitude control and altitude control of the unmanned aerial vehicle under atmospheric turbulent disturbances. The control framework is illustrated in Figure 3 and Figure 4, as follows:

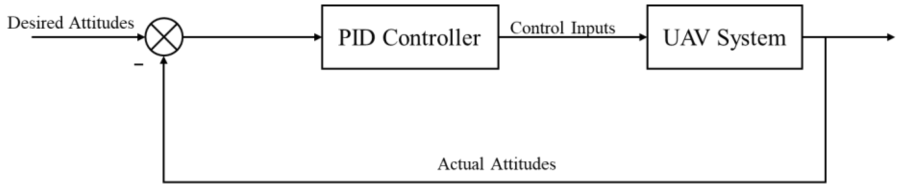


Figure 3. Control framework of Attitude control.

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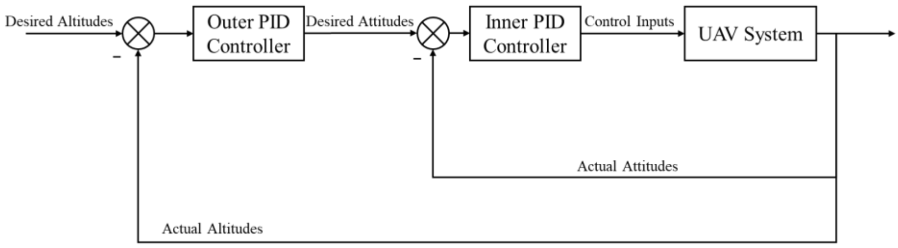


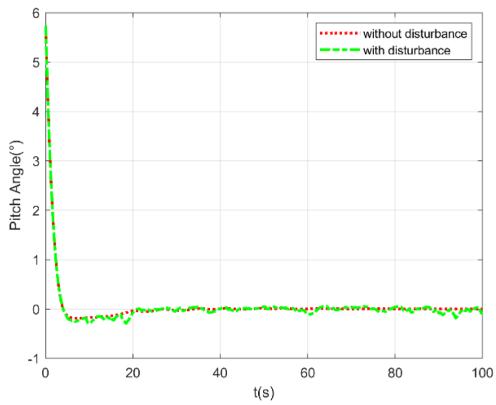
Figure 4. Control framework of altitude control.

5. Simulation results and discussions

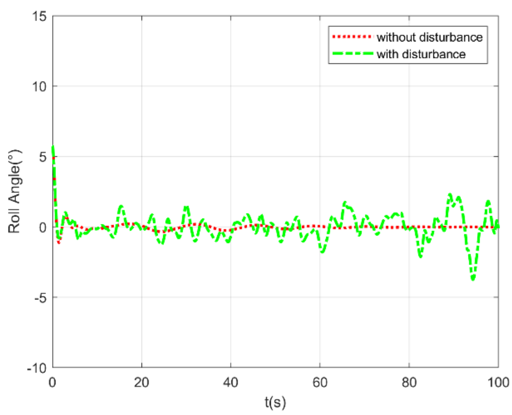
In the previous section, the flight dynamics model, atmospheric turbulence model, and controller model were introduced. In this section, the simulation and analysis of unmanned aerial vehicle (UAV) stable flight control under atmospheric turbulence perturbations will be conducted using Matlab/Simulink software.

5.1. Attitude control under atmospheric turbulence disturbances

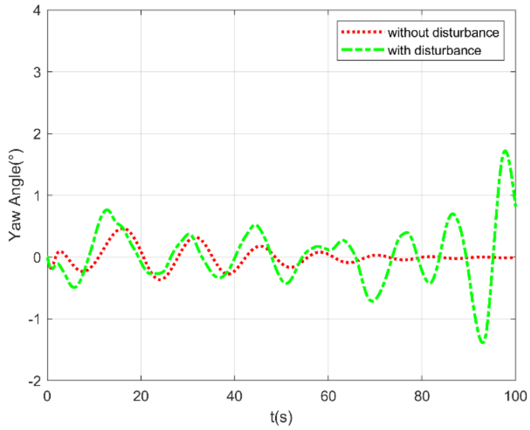
This section presents the implementation of attitude control for the UAV under the influence of atmospheric turbulence using a PID controller. Initially, the UAV's initial roll angle is set to 0.1 rad, the initial pitch angle is set to 0.1 rad, and the initial yaw angle is set to 0 rad. Through the PID control, the objective is to stabilize the UAV's three-axis attitude angles to 0 rad. A comparison will also be made to assess the effectiveness of attitude control in the presence of atmospheric turbulence. The simulated variations of the three-axis attitude angles are depicted in Figure 5.



(a) Variation of pitch angle.



(b) Variation of roll angle.



(c) Variation of yaw angle.

Figure 5. Variations of attitude angle.

From Figure 5(a), it can be observed that without disturbance, the designed PID control algorithm enables the UAV to reach the desired pitch angle of 0° in a short period. Even when atmospheric turbulence perturbations are introduced, the control algorithm remains effective in rapidly achieving the control objective. Figure 5(b) displays the variations in roll angle, showing that under atmospheric turbulence perturbations, the control of roll angle is significantly affected. However, the designed control algorithm still manages to maintain the roll angle fluctuating near the target value of 0°. On the other hand, Figure 5(c) indicates that the control of yaw angle becomes more challenging under atmospheric turbulence disturbances, and the designed algorithm struggles to achieve the ideal value.

5.2. Altitude control under atmospheric turbulence disturbances

This section demonstrates the use of a cascade PID controller to achieve altitude control for the UAV under the influence of atmospheric turbulence. Initially, the UAV's initial altitude is set to 2000 meters, and through the cascade PID control, the objective is to descend to an altitude of 1800 meters. A comparison will also be made to assess the effectiveness of altitude control in the presence of atmospheric turbulence. The simulated variations of UAV altitude are illustrated in Figure 6, and the variations in pitch angle are shown in Figure 7.

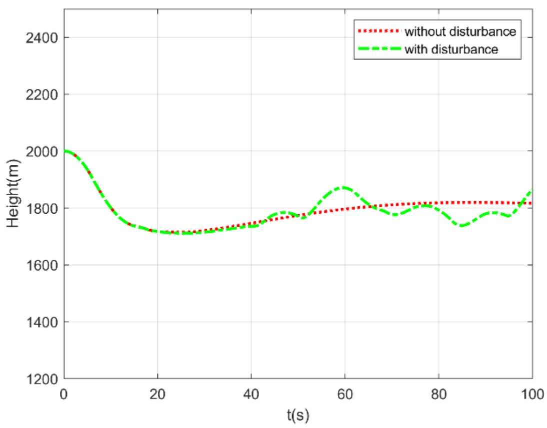


Figure 6. Variation of height.

From Figure 6, it can be observed that without disturbances, the designed cascade PID control algorithm effectively guides the UAV from an altitude of 2000 meters to the desired altitude of 1800 meters. However, in the presence of atmospheric turbulence perturbations, the control performance is relatively less optimal. After 40 seconds, noticeable fluctuations in altitude occur. Despite this, the control algorithm still manages to meet the basic control requirements.

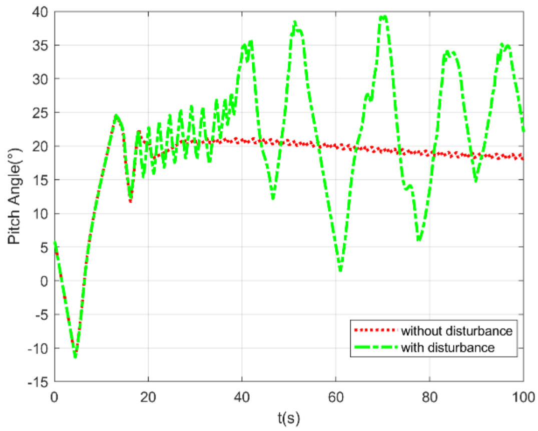


Figure 7. Variation of pitch angle.

From Figure 7, it can be observed that under the influence of atmospheric turbulence disturbances, the UAV's pitch angle exhibits noticeable fluctuations. This phenomenon can be attributed to two main factors. Firstly, the irregular atmospheric turbulence perturbations have an impact on the UAV, resulting in fluctuations in the pitch angle. Secondly, the UAV needs to adjust its pitch angle to achieve the objective of descending from an altitude of 2000 meters to 1800 meters. This further contributes to the observed pitch angle fluctuations.

6. Conclusion

Unmanned aerial vehicles (UAVs) are susceptible to various disturbances during mission execution, with atmospheric turbulence disturbances being one of the most common types. Therefore, studying UAV flight control under atmospheric disturbances is of significant importance. This paper first establishes a simulation experimental platform by developing a six-degree-of-freedom dynamic model of the UAV and an atmospheric turbulence model using Matlab/Simulink. Subsequently, PID controllers and cascade PID controllers are designed for attitude control and altitude control of the UAV under atmospheric turbulence perturbations, respectively, followed by conducting simulation experiments.

The simulation results demonstrate that even in the presence of atmospheric turbulence disturbances, the designed control algorithms effectively steer the UAV to achieve the desired attitude angles and flight altitude. This verifies the control capabilities of the PID control algorithm for UAVs under perturbed conditions. The conclusions drawn in this study provide valuable insights for the design of UAVs and lay the foundation for exploring the application of other control algorithms in UAV robust flight control in future research.

References

[1] Wang F., Gao H., Wang K., et al. Disturbance observer-based finite-time control design for a quadrotor UAV with external disturbance. IEEE Transactions on Aerospace and Electronic Systems, 2021, 57(2): 834-847.
[2] Islam S., Liu P., El Saddik A. Robust control of four-rotor unmanned aerial vehicle with disturbance uncertainty. IEEE Transactions on Industrial Electronics, 2015, 62(3): 1563-1571.
[3] Yang J., Liu C., Coombes M., et al. Optimal Path Following for Small Fixed-Wing UAVs Under Wind Disturbances. IEEE Transactions on Control Systems Technology, 2021, 29(3): 996-1008.

DOI: 10.54254/2755-2721/37/20230513

[4] Ghadiri H., Emami M., Khodadadi H. Adaptive super-twisting non-singular terminal sliding mode control for tracking of quadrotor with bounded disturbances. Aerospace Science and Technology, 2021, 112(1):106616.

[5] Prabhakar N., Painter A., Prazenica R., et al. Trajectory-driven adaptive control of autonomous unmanned aerial vehicles with disturbance accommodation. Journal of Guidance Control and Dynamics, 2018, 41(9): 1976-1989.

[6] Cui L., Zhang R., Yang H., et al. Adaptive super-twisting trajectory tracking control for an unmanned aerial vehicle under gust winds. Aerospace Science and Technology, 2021, 115: 106833.

[7] Liu W., Zhao S., Zhu Z., et al. Estimation of lateral flight technical error based on Von Karman atmospheric turbulence model. Public House of Electronics Industry, 2018: 873-878.