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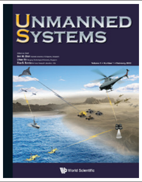

Review on Wind Resistance for Quadrotor UAVs: Modeling and Controller Design

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Micro-Unmanned Air Vehicles (Micro-UAVs), especially quadrotor UAVs, have been widely used in recent years because of their simple structure and convenient operation. However, due to under-actuated and strongly-coupled characteristics, their flight performance is not perfect when suffering external uncertainty such as wind disturbance. Therefore, in this paper, the literature is reviewed related to wind acting on UAVs and makes some conclusions. First, we review the wind field model of quadrotor operation and decompose it into wind turbulent model, wind shear model, and other typical wind field models. Then we focus on the mathematic model of wind disturbance on UAVs and divide it into effect on rotors and effect on the fuselage. Finally, various control laws are used to study the wind resistance of quadrotors. We review the promising works which have been done before and determine the research emphasis to be focused on in the future.

Keywords: Quadrotor; wind field model; wind resistance; control law.

Nomenclature

u, v, w :	Velocities along x, y, z axes of the aircraft (m/s)
Φ_u, Φ_v, Φ_w :	Power spectral densities of u, v, w (m^3/s^2)
$\sigma_u, \sigma_v, \sigma_w$:	Standard deviations of u, v, w (m/s)
L_u, L_v, L_w :	Scale lengths for u, v, w (m)
m :	Mass of aircraft (kg)
H_0 :	Roughness height, about 0.1 m
k :	Karman coefficient, about 0.4
u_{W0} :	Friction velocity, which is decided by ground shear stress τ_0 and air density ρ
v_i :	Induced velocity (m/s)
v :	Constant value over the whole disc (m/s)
R :	The radius of the disc (m)
r :	Distance from the center of the disc (m)
ψ :	The angular position of the rotor (rad)
K :	The ratio between v_i and v
ω :	Rotor angular velocity (rad/s)
a :	The rotational factor
ϕ :	The root blade angle (rad)
ρ :	Air density (kg/m^3)
A :	Area of the disc (m^2)
V_w :	Lateral wind speed (m/s)
F :	The force of the rotor (N)
N_b :	Number of blades
$R_{\min}$:	The minimum blade used in this study (m)
C_l :	Two-dimensional lift coefficient which is affected by wind disturbance
C_Q :	Torque coefficient which is affected by wind disturbance
λ :	Rotor inflow ratio
V_{tip} :	Rotor tip velocity (m/s)
$c(r)$:	Rotor chord distribution from hub to tip (m)
D_{bf} :	The force of the blade flapping (N)
D_i :	The induced drag of the fuselage (N)

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D_T : The translational drag of the fuselage (N)
D_p : The profile drag of the fuselage (N)
D_{par} : The parasitic drag of the fuselage (N)

1. Introduction

Unmanned Aerial Vehicles (UAVs) were first introduced in the 1910s during World War I (WWI). After more than a century of development, especially in recent years, with the vigorous development of Micro-Electro Mechanical Systems (MEMS), new materials, micro-inertial navigation and flight control technology, these vehicles have been widely used in many applications such as security and protection, management of natural risks, delivery transportation, industrial and agricultural production, military defense and so on. The utilization of UAVs makes it possible to gather information more quickly and effectively without risk to flight crews. Quadrotor UAV, as the representative of simple structure and convenient operation, is the most common structure style of UAVs in our daily life nowadays. Since its birth, the research on the quadrotor UAV has never stopped. Up to now, the research on the modeling and control of the quadrotor UAV has been quite abundant [1–3]. The general quadrotor can achieve automatic taking off and landing, fixed-point hovering, trajectory tracking and other capabilities. However, these techniques are usually subject to certain conditions in the working environment, such as keeping a certain distance from buildings or not taking off or landing under the condition of excessive wind speed. Most of these conditions are derived from the uncertainties of the flight environment, among which the influence of wind disturbance on UAVs is a part that can never be ignored. It is found that there are a few literature foci on quadrotor control under wind disturbance conditions. The reason may be that most researchers directly focus on the control system to improve the wind resistance performance of UAVs, instead of analyzing the wind disturbance model and its influence mechanism on the UAVs. Although their methods are generally feasible, we still want to improve the wind resistance of the quadrotor in principle. Micro-Unmanned Air Vehicle (Micro-UAV) weighing less than 7 kg is the most common in our daily life. Therefore, this paper is set as the wind resistance control of quadrotor aircraft, hoping to conduct in-depth research on the wind field model under the common working environment of micro-UAVs, the influence mechanism of wind disturbance on UAVs, and the controller design of quadrotor UAVs. For this reason, our studies are mainly divided into three categories: Wind field modeling of UAV working environment will be introduced in Sec. 2, Sec. 3 will present the influence mechanism of wind disturbance on UAVs and in Sec. 4 wind-resistance research and verification of flight control system will be introduced. Finally, conclusions will be discussed in Sec. 5.

2. Wind Field Modeling

The study of wind field models was carried out very early, and it was mostly used in the military field in the early stage. In 1973, the National Aeronautics and Space Administration (NASA) and relative research institutions [4] began to study the wind disturbance model of the surface boundary layer and put forward wind field models under stable and unstable conditions respectively. They made progress in wind field modeling but their work was only focused on theoretical analysis and did not compare with the actual flight conditions adequately. Later in the 1980s, Schiess [5] discussed the feasibility of three statistical methods in combination to establish the wind gusts model which was used in aircraft flight simulation. They combined principal components analysis, time-series analysis and probability distribution methods to simulate and analyze wind gust components. Comparisons between wind gust components generated by this model and those measured onboard an aircraft showed that they were similar generally. Etkin [6] analyzed the basic model of turbulence and its influence on aircraft and Fleming *et al*. [7] studied the relationship between the average temperature, air pressure, wind field and the altitude and latitude of the location. Most of the wind field models established above were based on large-scale space and time conditions. Different from this, wind field research under small-scale space and time conditions was also being carried out as well. The US military first introduced Dryden and Von Karman turbulence models in its military specifications [8], and most of the turbulence wind field models used later came from these. These two algorithms are the most widely used expressions of the turbulence wind field. However, since the time spectrum function of the Von Karman model cannot be decomposed in conjugates, which is difficult to be realized in the time domain, the wind field turbulence generated by the Dryden model is more often used in numerical simulation. Its form of the power spectral densities for the turbulence velocities is as follows:

$$\begin{cases} \Phi_u(\omega) = \sigma_u^2 \dfrac{L_u}{\pi u} \dfrac{1}{1 + \left(L_u \frac{\omega}{u}\right)} \\ \Phi_v(\omega) = \sigma_v^2 \dfrac{L_v}{\pi v} \dfrac{1 + 12\left(L_v \frac{\omega}{v}\right)^2}{\left[1 + 4\left(L_v \frac{\omega}{v}\right)^2\right]^2} \\ \Phi_w(\omega) = \sigma_w^2 \dfrac{L_w}{\pi w} \dfrac{1 + 12\left(L_w \frac{\omega}{w}\right)^2}{\left[1 + 4\left(L_w \frac{\omega}{w}\right)^2\right]^2} \end{cases}, \tag{1}$$

$$\Phi(\omega) = |\,G(i\omega)\,|^2 = G^*(i\omega)G(i\omega), \tag{2}$$

where u, v, w are the velocities of the aircraft, Φ_u, Φ_v, Φ_w are the power spectral densities, L_u, L_v, L_w are scale lengths for u, v, w and $\sigma_u, \sigma_v, \sigma_w$ are the standard deviations of u, v, w.

Equation (2) is used to decompose the turbulent spectrum function equation (1), and the transfer function of the filter is obtained to generate the given spectrum. In 1986, Zhao *et al*. [9,10] proposed a strict and complete three-dimensional atmospheric turbulence signal including three linear velocity components and three angular velocity components in line with Dryden's model, and verified the reliability of the results with the correlation function. Later in 1993, T. R. Beal [11] presented two algorithms that can generate discrete-time histories of random atmospheric turbulence as prescribed by the Dryden and Von Karman model. Based on this, other researchers [12–14] proposed improved methods. Xiao [12] for example, generated a two-dimensional field of turbulent for special situations such as formation flight and aerial refueling. Since the correlation function of the Dryden model was not quite consistent with the theoretical value in some cases, Ma [13] theoretically analyzed the causes of the error and correct the white Gaussian noise. Besides, Qu *et al*. [14] proposed a form of improved turbulence model by optimizing its parameters. The simulation results in the time and frequency domain showed that the proposed new model was rational and the suggested simulation algorithm was valid. The above studies were aimed at the atmospheric turbulence as a typical wind field model acting on full-size aircraft, while the actual wind field often has other typical wind field models such as constant wind model, wind shear model and so on.

To improve the precision of the wind field model compared with the actual environment, other typical wind models had been proposed besides the turbulence wind model such as the Dryden wind field model. Cole *et al*. [15] introduced a statistical wind model over water which was different from traditional gust wind models such as Dryden models. Watkins *et al*. [16,17] mainly focused on the problem of how to establish the disturbance atmosphere boundary layer, particularly disturbance a few meters above the ground. They considered the temporal and spatial characteristics of the atmospheric boundary layer near the ground, as well as the relative disturbance experienced by the moving aircraft. The wind speed they studied varies from 1.5 to 9.5 m/s, which is the most typical wind speed that UAVs subjected. Mann [18,19] developed a model of the spectral velocity-tensor in neutral flow over complex terrain by measuring the real-time changing wind speed and direction. Compared with Sandia's method [20], this method is more efficient, simpler to be implemented, and more meaningful physically in some respects. Branlard [21] proposed a time series wind model based on the Kaimal spectrum and the Fast Fourier Transform (FFT) results of the wind speed generated by the model were in good agreement with the Kaimal spectrum. The result generated from this method is displayed in Fig. 1. Its mean value is

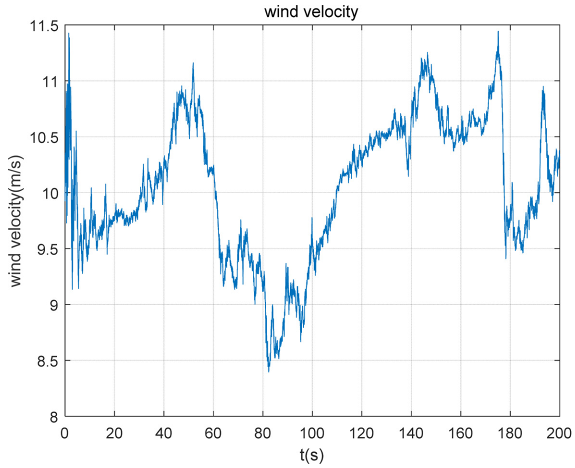

Fig. 1. Four examples of time series generated from the Kaimal spectrum[21].

exactly 20 m/s, and the standard deviation varies between 0.90 and 1.23 m/s. The samples resemble quite well with real wind time series. This wind field model was then used by Gavrilovic [22] for the simulation of UAVs under the influence of wind disturbance, and relatively ideal results were obtained.

The actual wind field model of UAV is usually not a single wind field, but the superposition of many typical wind fields. In 2009, Yu [23] introduced the model of wind shear and atmosphere turbulent in his academic dissertation. He described in detail the mechanism of these two wind fields and tested the corresponding action of aircraft under wind disturbance. Simulation results showed that the wind models introduced were ideal and valid. In addition to the turbulent model, we introduced above, there are also a variety of wind shear models such as wind shear logarithm model, wind shear index model and microburst model. The wind shear logarithm model is taken as an example, and its expression is shown in Eq. (3), indicating that the wind speed is related to flight altitude. Similarly, Waslander [24] also considered the wind disturbance as a superposition of the wind shear model and Dryden turbulent model. It was verified by the simulation results that the wind disturbance data generated by the above wind field model was in good agreement with the actual wind disturbance. Later Wang [25] and Mansson [26] pointed out that the usual wind field where UAV works is a superposition of constant wind model, wind shear model and Dryden turbulent model. Furthermore, Wang [27] considered the wind field model as a combination of constant wind, turbulent wind, many kinds of wind shear and the propeller vortex. Except for the fourth wind model, which is generally considered in UAV formation flight, the other three wind types are all typical wind field models. Behdad Davoudi *et al*. [28] tried to combine large-scale spatiotemporal wind field model with small-scale Spatio-temporal wind field model. Large-scale spatial and temporal wind field models include Large-eddy simulation, the approximate solution of the Navier–Stokes equations, and its reduced-order wind representations, while the Dryden turbulence model belongs to small-scale spatial and temporal model. MATLAB simulation results showed that the models were consistent with the actual environment, but there were still some difficulties in modeling the large-scale spatiotemporal wind field.

$$\begin{cases} V_w = \dfrac{u_{W0}}{k} \ln \dfrac{H}{H_0} \\ u_{W0} = \sqrt{\dfrac{\tau_0}{\rho}} \end{cases}, \tag{3}$$

where V_w is the lateral wind speed, τ_0 is ground shear stress and H is the height of aircraft. As can be seen from the above literature, the wind field modeling for the working environment of the UAV has been relatively complete. Many different wind field models have been proposed and applied. In general, they can be divided into wind shear model, turbulent wind model, propeller vortex model, Navier–Stokes equation generated model and other typical wind field models. Considering the computation and performance requirements, it is generally sufficient to combine the wind shear model and turbulent wind model as the simulation wind model. In order to facilitate users to apply wind disturbance to the simulation, MATLAB, one of the most used software for numerical simulation, has packaged several typical wind field models like the wind shear model and the turbulent wind model into modules according to relevant standards. Users can call them directly from the library, just need to adjust some parameters in the set interface.

3. Research about Influence Mechanism of Wind

Understanding the intrinsic mechanism of wind acting on aircraft helps to build accurate mathematical models and a simulation environment which helps to verify the disturbance rejection performance of the controller proposed. Considering the influence of wind disturbance on UAVs, it can be divided into two parts: One is the effect of wind disturbance on the rotors and the other is the effect on the fuselage. The former mainly discussed the influence of wind disturbance on a single rotor and extend to multi-rotor as well. Due to the influence of wind disturbance on speed and downwash airflow, the force and torque generated by the rotating blade will change, so as changing the overall stress condition of UAVs. The latter usually treated the UAV as an entity and analyze the drag and torque effect of wind disturbance on its fuselage.

3.1. *The effect of wind on rotors*

To fully understand the influence of wind disturbance on rotors, we need to introduce the induced velocity generated by the rotating rotor. As early as 1926, to solve the difference between experimental observation and theoretical calculation of rotor lateral forces caused by uniform inflow, Glauert [29] proposed a first-order harmonic inhomogeneous inflow model that generated the induced velocity field which was shown in Eq. (4). The theory was developed on the assumption that the angles of the blade elements were small, that the interference flow was similar to that caused by an ordinary airfoil. With the comparison of calculated and experimented results, Wheatly *et al*. [30] also proposed an induced velocity expression like Eq. (5) and made a conclusion that most of the rotor characteristics could be calculated with reasonable accuracy, and that the type of induced flow assumed had a secondary effect upon the net rotor forces, although the flapping motion was influenced appreciably. In 1947, Brotherhood [31] measured the induced velocity distribution of UAV in a hovering state and proposed the expression as Eq. (6). Results showed that the measured value of the induced velocity had a great correlation with the calculated value of blade element theory. Later, experiments had been made to determine the flow conditions through a helicopter rotor in forwarding flight using the smoke filament technique by Brotherhood and Steward [32]. However, the induced velocity measured by them was quite different from the results obtained by Mangler and Square [33] based on potential theory. Before the 1950s, the influence of static and time-invariant incoming flow on the induced velocity of the rotor was mainly concerned. Till 1953, an experimental determination of the response of the thrust and induced velocity of a helicopter rotor to various rates of collective blade-pitch increase had been conducted on the helicopter test tower by Carpenter and Fridovich [34]. The calculated and experimental results were in agreement generally, although, the former was about 10% greater than the latter.

$$v_i = v + v_1 \frac{r}{R} \cos\psi, \tag{4}$$

$$v_i = Kv \frac{r}{R} \cos\psi, \tag{5}$$

$$v_i = \omega r(1 - a') \tan\phi. \tag{6}$$

Later with the emergence of electronic computers and the improvement of computational performance, researchers have been able to obtain abundant experimental data and analyze complex mathematical formulas and verify them. For example, in 2015, Khan [35, 36] analyzed the magnitude and distribution of induced velocity generated by rotor rotation in detail from the perspective of Blade Element Momentum Theory (BEMT) and established corresponding mathematical models respectively for the conditions with or without wind disturbance. The simulation results showed that the model can well reproduce the wind effect of a single rotor. Munoz [37], Wu [38] and He *et al*. [39] supposed that the airflow generated by the lateral wind affects the induced velocity generated by the propellers introducing additional force, F_w, on the aircraft like Eq. (7). Due to the over-simplification of the calculation method, there is a big error between the result and the actual situation. Behdad Davoudi *et al*. [28] established the model of rotor force and torque and the quadrotor mode under wind disturbance effect based on the momentum and blade element theories introduced by Leishman [40]. This model analyzes the effects of rotor action and wind disturbance on the quadrotor from a theoretical point of view, which requires higher knowledge of aerodynamics and mechanical structure. In the process of modeling, it is necessary to accurately measure the object and process a large amount of data to ensure the accuracy of the model. The final expression is shown in formula (8). In 2019 and 2020, Wang *et al*. [27,41] also researched the impact of wind disturbance on UAVs. Compared with the former literature which mostly only considered the speed triangle theory, this paper analyzed the impact of wind disturbance on UAVs from the perspective of energy transfer referring to other literature [42]. Based on the conservation of energy and momentum theory, the velocity variation of UAVs under wind disturbance can be deduced which is shown in formula (9). With this simple and understandable analysis method, its simulation results showed that the results obtained from the perspective of energy transfer are more consistent with the actual situation than other analysis methods.

$$\begin{cases} F_w = 2\rho A v_i V_w \\ \|v_i\| = \sqrt{\dfrac{F}{2\rho A}} \end{cases}, \tag{7}$$

$$\begin{cases} F_w = N_b \displaystyle\int_{R_{\min}}^{R} \frac{1}{2}\rho C_l\left[(r\omega)^2 + (\lambda V_{tip})^2\right]c(r)dr \\ Q = C_Q \rho \pi R^5 \omega^2 \end{cases}, \tag{8}$$

$$\begin{cases} v_w^2 S\rho + m v_{lat} = v_w'^2 S\rho + m v_{lat}' \\ \dfrac{v_w^3 S\rho}{2} + \dfrac{m v_{lon}^2}{2} = \dfrac{v_w'^3 S\rho}{2} + \dfrac{m(v_{lat}'^2 + v_{lon}^2)}{2} \end{cases}, \tag{9}$$

where F_w is the force of the rotor under wind disturbance, v_w and v_w' are the forward and backward changes of wind speed.

The traditional aerodynamic model of the quadrotor is almost entirely based on the modeling of a single rotor, ignoring the wake interference among the four rotors nearby. Considering that not all the propellers were directly exposed to the wind, Tran [36] introduced the shielding effect, which is represented by a weighting function. Similarly, Luo *et al*. [43] proposed a quadrotor forward-flight mathematical model considering rotor wake mutual interference. To validate the precision of the model, a series of computational fluid dynamics (CFD) analyses were conducted. An integral quadrotor model and an isolated rotor were analyzed under the same conditions. The mathematical model and results of the CFD analyses provided consistent trends and demonstrated the suitability of the proposed model for high-speed forward flight. In Lei's paper [44], the aerodynamic characteristics of a quadrotor aircraft considering the wind disturbance were studied by both simulations and experiments. The comparison of simulation and experimental results showed that the distribution of flow field becomes more complicated with mutual interferences resulting from the distortion of rotor wake and crash of the downwash flow from the front rotors along with the wind direction. However, they only considered the constant horizontal wind disturbance, ignoring the role of the turbulent wind field, so the model was limited.

3.2. *The effect of wind on the fuselage*

The above references mainly talk about the influence of wind disturbance on a single rotor and extend this effect to multi-rotor as well. However, in addition to the impact of this aspect, there is also the impact of wind disturbance on the whole fuselage that can never be ignored.

In 2007, Hoffmann *et al*. [45] investigated the aerodynamic effects of airframe design, which pertain to quadrotor flight. Although they did not propose a specific expression, they still proved that wind disturbance would have a great impact on the fuselage, so it should be considered in the airframe design. Later, Bangura and Mahony [46] along with Silva *et al*. [47] tried to give a detailed explanation of the aerodynamic effects. They considered in detail several aspects, such as blade flapping (Eq. (10)), induced drag (Eq. (11)), translational drag (Eq. (12)), profile drag (Eq. (13)), parasitic drag (Eq. (14)) and others such as ground effect and vertical descent. Based on this work, Allibert *et al*. [48] retained translational drag and blade flapping because other aerodynamic effects were tiny and could be ignored. Tran [36] and Tang *et al*. [49] mentioned that the fuselage drag of the quadrotor can be described by the following Eq. (15), where C_d is the drag coefficient, V is the relative airspeed. They also calculated the drag coefficient by measuring the drag force acting on a quadrotor in the given cross airflow. In 2014, Mansson and Stenberg [26] introduced a simple method about how to calculate the projected surface area of the aircraft from an arbitrary point of view. In their work, Eq. (15) is more convenient to use.

Based on the literature above, in 2020, Jeremie *et al*. [50] tried to establish an accurate quadrotor model under wind disturbance filling the gap between simple models that ignore important aerodynamic effects and other more comprehensive but computationally expensive models. Results showed that the simulation results and the experimental data were in good agreement, which proved the rationality of the quadrotor model under the influence of wind disturbance. However, the wind disturbance added in the simulation and tunnel test was constant, which is different from the actual outdoor environment.

$$D_{\mathrm{bf}} = T\left(A_{\mathrm{flap}}\frac{V_p}{\varpi} + B_{\mathrm{flap}}\frac{\Omega}{\varpi}\right), \tag{10}$$

$$D_i = K_i V_p, \quad V_p = (u, v, 0)^T, \tag{11}$$

$$D_T = K_T V_p, \tag{12}$$

$$D_p = K_p V_p, \tag{13}$$

$$D_{\mathrm{par}} = K_{\mathrm{par}} \left| V_{\mathrm{par}} \right| V_{\mathrm{par}}, \quad V_{\mathrm{par}} = (u, v, w)^T, \tag{14}$$

$$D_{\mathrm{drag}} = \frac{1}{2} C_d \rho A V^2, \tag{15}$$

where $D_{\mathrm{bf}}, D_i, D_T, D_p, D_{\mathrm{par}}$ and D_{drag} are various methods for calculating fuselage resistance and they are influenced by different factors.

3.3. *Brief summary*

We classify the influence of wind disturbance on the quadrotor, as shown in Table 1. In general, the influence of wind disturbance in the mathematical model of the quadrotor is derived from Eqs. (7) and (15) and is sufficient. But other influences need to be considered if a more accurate mathematical model is needed. For instance, if the down washing airflow generated by rotor rotation is affected by the horizontal wind disturbance, the additional force will be generated, and if the direction of this force does not pass through the quadrotor center of gravity, the torque effect will occur, which is also a non-negligible factor to be considered. Additionally, when considering the influence of wind disturbance on the whole fuselage, the torque generated by the wind cannot be ignored. Besides, the wind shielding effect is common in multirotor UAVs and needs further research.

Table 1. Influence mechanism of wind disturbance and corresponding references.

Influence mechanism of wind disturbance	Corresponding references
Influence on rotors	[27,42]
Influence on fuselage	[26,36,50]
Wind shielding effect	

To sum up, it is not simple to establish a mathematical model of quadrotor under wind disturbance, and there are a lot of uncertainties. To solve this problem, it is necessary to research various aspects, compare the theoretical results, simulation results, and actual experimental results together, and get the accurate mathematical quadrotor model under wind disturbance finally.

4. Research on Controller Design for Wind Resistance

The controller design is the most important step in the wind resistance process of the quadrotor. A well-designed controller can achieve a good control performance, undoubtedly. There are lots of literature about flight control design for quadrotor aircraft, which can be divided into two parts. We named the first one as passive wind resistance control strategy. In other words, when the wind disturbance has a great influence on the position and attitude of the UAV and deviates from its reference position and attitude, the corresponding control value is calculated accordingly to suppress the wind disturbance effect. Another one is the active wind resistance control strategy which can estimate the wind disturbance in real-time and compensate in the controller.

4.1. *Passive control strategy*

In the actual flight condition, quadrotor flying at low altitude is more susceptible to wind field that could significantly affect the aerodynamic performance and its stability. Therefore, it is necessary to take the impact of the wind field into account in the study of the quadrotor system's modeling and control [51]. As we introduced before, the passive control strategy works when wind disturbance affects the quadrotor and deviates from its reference pose. In general, because of its simple principle, most controllers adopt this control strategy.

In 2004, Bouabdallah *et al*. [52,53] designed quadrotor controllers, respectively based on proportional-integral-derivative (PID, Eq. (16)), linear quadratic regulator (LQR, (17)), backstepping (Eq. (18)) and sliding-mode (Eq. (19)) algorithms, and compared them with each other. Later, in order to improve the anti-disturbance performance of the control system, some improvements were made based on the traditional LQR control law adding an integration element by Tran *et al*. [36] The simulation results showed that the improved LQR control law enhances the disturbance resistance performance of the quadrotor, but the LQR control law needs an accurate mathematical model of the controlled object, and it is difficult to obtain the corresponding model of the quadrotor. Because the quadrotor model was dynamically unstable and nonlinear, so nonlinear control strategy was used by Mian *et al*. [54] The control structure included feedback linearization (Eq. (20)) coupled with a PD controller for the translational subsystem and a backstepping-based PID nonlinear controller for the rotational subsystem of the quadrotor. Similarly, a quadrotor position controller was designed by He *et al*. [39] included an integral backstepping controller for the inner loop and a PID controller for the outer loop. The dynamic performance and control ability under the effect of turbulent wind were studied with numerical simulation. The results showed the controller had good robustness and disturbance resistance in the effect of wind disturbance. Besides, Daewon *et al*. [55] presented two types of nonlinear controllers for an autonomous quadrotor helicopter. One is a feedback linearization controller that involved high-order derivative terms and turned out to be quite sensitive to sensor noise as well as model uncertainty. The second type involved an adaptive sliding mode controller using input augmentation to account for the under-actuated property of the quadrotor, sensor noise, and uncertainty. Similarly, a nonlinear PID controller was proposed to control the quadrotor UAV by Milhim [1]. A series of trajectories were used to demonstrate the effectiveness of the designed controller.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d e(t)/dt, \tag{16}$$

$$\begin{cases} PA + A^T P - PBR^{-1}B^T P + Q = 0 \\ K_c = R^{-1}B^T P \\ u(t) = -K_c x(t) \end{cases}, \tag{17}$$

$$u(t) = -cx(t) - \frac{\rho^2(x,t)}{2\varepsilon}x(t), \tag{18}$$

$$u(t) = -cx(t) - \varepsilon sgn(s(t)), \tag{19}$$

$$u = \frac{1}{g'(x)}(-f'(x) + v). \tag{20}$$

In 2009, Cai *et al*. [56] designed and implemented a robust automatic flight control system for a small-scale unmanned helicopter. Based on the helicopter's linearized model, this flight control system was designed by employing H_∞ control and dynamic inversion techniques. Chen [51] and Azinheir [57] adopted the improved form of backstepping to design the quadrotor controller and validate the stability of the system by Lyapunov theory. Simulation results showed the excellent performance of the proposed controllers and proved their capability of disturbance rejection in the face of wind disturbance. In 2009, in order to solve the path following problem for a quadrotor helicopter, Raffo *et al*. [58] introduced an integral predictive and nonlinear robust control strategy. The proposed control structure was a hierarchical scheme consisting of a model predictive controller (MPC) to track the reference trajectory together with a nonlinear H_∞ controller to stabilize the quadrotor helicopter. Alexi *et al*. [59,60] studied the attitude and position control of the quadrotor UAV affected by wind disturbance with a constrained finite time optimal controller (CFTOC). Simulation and real flight experiment results showed that this scheme was an effective control approach, capable of effectively attenuating strong wind disturbance. To enhance the wind rejection ability of UAVs to achieve safe and precision control, a wind disturbance rejection control method based on acceleration feedback (AF) was proposed for multirotor UAVs by Dai *et al*. [61] in 2020. By introducing linear and angular acceleration information feedback into the original controller, a faster and more accurate attitude and position tracking performance can be obtained without changing the structure of the original controller. The experimental results demonstrated that the acceleration feedback enhanced controller can suppress the turbulent wind effectively and the accuracy of the UAV flight control system was greatly improved.

4.2. *Active control strategy*

In the above literature, the passive control strategies were adopted to resist the wind effect for the UAVs. Objectively, this control strategy will cause a time delay and may appear the phenomenon of oscillation, so some experts wonder if the controller could include the wind influence, instead of only considering it as a disturbance to be further rejected. We call this type of approach an active wind resistance strategy, which may be a better choice to resist wind interference for quadrotor UAVs.

Waslander [24] and Qu *et al*. [62] used the improved PID controller to improve the precision of position control of the quadrotor under wind disturbance. The control system estimated the wind disturbance of the environment and took the initiative to resist the wind according to the wind speed and direction information. Simulation results showed that the improved PID controller has better robustness under wind disturbance. Similarly, Sydney *et al*. [63] designed the quadrotor controller based on wind field estimation as well. They used the recursive Bayesian filter to estimate the wind field, which was incorporated into an input/output feedback linearization controller that included aerodynamic effects on the vehicle such as blade flapping and induced drag. It was evident through simulation results that the inclusion of the airflow compensation in the controller design enhances the ability of quadrotors. Lee *et al*. [64] presented a robust attitude tracking controller for quadrotors based on the nonlinear disturbance observer. It is shown that the proposed controller recovers the performance of the nominal closed-loop system under parameter uncertainties and disturbance torques. In 2019, Tang *et al*.

[49] designed a position controller for the quadrotor under the impact of wind disturbance. In the process controller designed, the Extended State Observer (ESO) was used to estimate and compensate the total disturbance in real-time and combined the double power reaching law for sliding mode control (DSMC) with small chattering and fast response speed. The simulation results proved that the position optimization law of the proposed control law can reach about 90% under wind disturbance, which improved the anti-interference ability and robustness of the system. Wu [38] and Yang [65] also designed the quadrotor flight controllers based on PD and ADRC control laws. It can be seen from the results that compared with the PD controller, the ADRC-based controller has better control performance and can effectively control the influence of the disturbance of the turbulent wind field. However, the ADRC controller also has the problem of too many parameters to be tuned. To simplify parameter tuning of ADRC controller, the linear active disturbance rejection controller (LADRC) and fuzzy active disturbance rejection controller (Fuzzy-ADRC) were proposed in Bao's master's thesis [66], which refer to Han and Gao's [67–69] literature. Furthermore, Wang [70] combined fuzzy control, neural network control and nonlinear ADRC to design the fuzzy ADRC flight control system and neural network ADRC flight control system. The feasibility of the control method was verified by an indoor semi-physical simulation platform and an outdoor flight platform.

4.3. *Brief summary*

To sum up, there are lots of literature research on the wind resistance control system design of quadrotor UAVs. Some typical literature is classified according to control law, as shown in Table 2. The results of simulation and actual flight show that the performance of active wind resistance control strategy is better than passive control strategy generally. Therefore, in recent years, most studies have focused on the design and application of active wind resistance control strategies. Compared with the passive method, it has more advantages, such as timely estimation and compensation of disturbance, strong disturbance resistance performance, etc., but it also has disadvantages, such as more complex control structure, more parameters to be tuned, greater computational power requirement.

Table 2. Control laws and their improvements and corresponding references.

Control laws and their improvements	Corresponding references
PID	[1,24,36,39,52,54,66]
Backstepping	[39,51,53,57,72,73]
LQR	[36,52,66,71,74,76]
Sliding-mode	[49,53,55,72,77,79]
Feedback Linearization	[54,55,63,74,80]
H_∞ control	[56,58,81]
Dynamic Inversion	[56,82,83]
CFTOC	[59,60]
Acceleration Feedback	[61,84]
ADRC	[38,66,70]
Fuzzy Control	[70,78]
Machine Learning	[70,82,85,86]

5. Conclusion

Research on wind resistance of quadrotor UAVs originates from practical flight needs. Since its birth, great progress has been made in wind field modeling, mechanism of wind disturbance influence research and wind resistance controller design. In general, it is sufficient to combine the wind shear model and turbulent wind model such as the Dryden model. But if a more accurate wind field model is needed, other typical wind models should be considered. Given the complex influence of wind disturbance on quadrotor UAVs, we divide this influence into two parts, one is the influence on rotors and the other is the influence on the fuselage. Besides, the wind shielding effect should also be taken into consideration due to the symmetrical structure of the quadrotor. Finally, various wind resistance control laws are divided into passive control strategy (such as traditional PID, backstepping etc.) and active control strategy (such as ADRC). Simulation and flight test results show that the wind resistance of the latter is generally better than the former. Therefore, to improve the anti-disturbance performance of the control system, the design of the rejection wind disturbance controller changed from the passive strategy to the active strategy adopted by the mainstream.

To summarize, great progress has been made in the study of wind resistance of quadrotor UAVs. The main follow-up work should focus on building more refined models and conducting the flight test from simulation to the actual physical flight platform.

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