Optimization of Counterwind Disturbance Compensation Control Algorithm for UAV Flight

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Abstract. The mechanical parameters of UAV in the headwind flight are easily disturbed by nonlinear variation of the wind force, so the optimal control design is needed. A counterwind disturbance compensation control algorithm for UAV flight based on static anti-saturation yaw suppression is proposed. The dynamic parameter model and control constraint parameter model of UAV flight is constructed under the action of headwind disturbance to realize the optimal configuration of UAV flight dynamics in uncertain environment. The vector velocity and radial acceleration of UAV flight are optimized and matched in the vortex center polar coordinate system. The static anti-saturation yaw suppression method is used to compensate the disturbance and correct the yaw in the headwind flight environment of UAV. Under the optimal control law, the UAV carrier is guided to fly headwind along the predetermined flight trajectory, and the stability control of UAV flight is realized. The simulation results show that the proposed algorithm has good output stability and accurate tracking ability, reduces the flight control error and improves the control quality.

1. Introduction

With the development of unmanned aerial vehicle (UAV) design technology, the research of UAV has been strengthened all over the world. UAV plays a great role in carrying out combat mission and high-risk mission in special environment. The flight stability of UAV is the key technology to guarantee the survivability and autonomous navigation ability of UAV. It is of great significance to study the autonomous control technology of UAV in promoting the development of UAV technology. When UAVs carry a variety of mission equipment to carry out tasks such as military, meteorological, mapping and so on, because of the heavy load, they are vulnerable to the influence of uncertain disturbance factors during the headwind flight, which affects flight stability. The research on the headwind disturbance control method of UAV has become the hotspot of UAV flight control design [1].

On the basis of optimal design and information fusion of control parameters established for headwind disturbance control design of UAV, local parameter fitting and information fusion tracking method are adopted in complex environment. The complex motion control of UAV flight [2],
according to the change of environment and independent planning, decision-making, improve flight stability, in the traditional methods, the method of counterwind disturbance compensation for UAV flight is mainly based on sensor information fusion tracking and fuzzy control methods. In the paper [5], a robust control model based on dynamic inverse feedback for UAV low altitude penetration is proposed. According to the random robustness index, the feedback compensation of parameter perturbation is carried out to realize the robust dynamic stability enhancement control of UAV at low altitude penetration, but the convergence of the control method is not good. In reference [6], a steepest gliding trajectory control method based on Terminal sliding mode surface is proposed to realize the gliding trajectory correction and adaptive control of UAV. The real-time performance of the control method is poor and the global stability of the control output is poor. In reference [7], the anti-disturbance control model of UAV based on flight inertial attitude fusion filtering and accelerated robust fusion is proposed to improve the anti-perturbation ability of the control model. The anti-disturbance performance of the control model is not good when the UAV flies headwind.

In view of the disadvantages of the traditional methods, this paper presents a counterwind disturbance compensation control algorithm for UAV flight based on static anti-saturation yaw suppression. Firstly, the dynamic parameter model and control constraint parameter model of UAV flight are constructed to realize the optimal configuration of UAV flight dynamics in uncertain environment. In the polar coordinate system of vortex center, the vehicle velocity and radial acceleration of UAV flight are optimized and matched, and then the disturbance compensation and yaw correction in the headwind flight environment of UAV are carried out by using static anti-saturation yaw suppression method. Under the optimal control law, the UAV carrier is guided to fly headwind along the predetermined flight trajectory, and the stability control of UAV flight is realized. Finally, the simulation results show the superiority of the proposed method in improving the control capability of counterwind disturbance compensation for UAV.

2. Flight dynamics parameter model and control constraint parameter model

2.1. A dynamic parameter model for UAV flight
In order to realize the counterwind disturbance compensation control of UAV flight, the dynamic parameter model of UAV flight is first constructed. Let \( I \) be a finite domain driving force model, under good anti-saturation model. The linear extension model is obtained as: \( u: I \times IR^d \rightarrow IR \). The perturbation equation of UAV flight attitude control is obtained as:

\[
\begin{align*}
\dot{u} - \Delta \alpha + F &= 0, \\
(u, \alpha) = (u_0, u_1) \in \mathcal{H}_u \times \mathcal{H}_\alpha,
\end{align*}
\]

by using the dual integral control method, the control object model of counterwind saturation compensation for UAV is obtained as follows:

\[
\| \nabla u \|_{\mathcal{V}_L} + \| \nabla^{-1} u \|_{\mathcal{V}_L} + \| \nabla u \|_{\mathcal{V}_L} + \| \nabla^{-1} u \|_{\mathcal{V}_L} \leq C(\|u_0, u_1\|_{\mathcal{H}_u}, \|u_\alpha\|_{\mathcal{H}_\alpha})
\]

(1)

Assuming that the shell model of UAV is a symmetric rigid body model with six degrees of freedom, the trajectory model of dynamic primitive satisfies \( C(a^4 + 2a^3b) < 1 \), at the flight attitude equilibrium point \( P_\ell(x^l_0, x^l_0) \), and the iterative formulas of the moving trend boundary solution vector \( W \) and \( Z \) of UAV's headwind flight are obtained:

\[
w_{\mu}(k + 1) = w_{\mu}(k) - \alpha \frac{\partial F}{\partial w_{\mu}}
\]

(2)

\[
z_{\mu}(k + 1) = z_{\mu}(k) - \alpha \frac{\partial F}{\partial z_{\mu}}
\]

(3)
The Jacobian matrix for constructing dynamic motion primitives can be written as:

\[
J(x) = \begin{pmatrix}
\frac{\partial e_{11}}{\partial w_1} & \frac{\partial e_{11}}{\partial w_2} & \cdots & \frac{\partial e_{11}}{\partial z_{w_m}} \\
\frac{\partial e_{12}}{\partial w_1} & \frac{\partial e_{12}}{\partial w_2} & \cdots & \frac{\partial e_{12}}{\partial z_{w_m}} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{\partial e_{m0}}{\partial w_1} & \frac{\partial e_{m0}}{\partial w_2} & \cdots & \frac{\partial e_{m0}}{\partial z_{w_m}}
\end{pmatrix}_{m \times m}
\]

(4)

When the vehicle deviates from the predetermined trajectory, the inertial attitude parameter is adjusted by minimizing the energy function [8], and the weighted parameter \( w \in (a, a_s) \) is taken as the constraint parameter. The heading angular control boundary conditions of the unmanned aerial vehicle flying against the wind disturbance control are obtained as follows:

\[
\begin{aligned}
\frac{\partial e_{x}}{\partial z_{ij}} &= -\frac{\partial Y_{ij}}{\partial z_{ij}} = -g'(o_{ij}) \sum_{i,j} z_{ij} a_{ij} = -g'(o_{ij}) \frac{\partial \sum_{i,j} z_{ij} a_{ij}}{\partial z_{ij}} = \begin{cases} -g'(o_{ij}) a_{ij}, & d = k \\ 0, & d \neq k \end{cases} \\
\frac{\partial e_{\mu}}{\partial w_{ji}} &= -\frac{\partial Y_{ji}}{\partial w_{ji}} = -g'(o_{ji}) \frac{\partial a_{ij}}{\partial w_{ji}} = -g'(o_{ji}) \frac{\partial a_{ij}}{\partial a_{ij}} \frac{\partial a_{ij}}{\partial w_{ji}} = -g'(o_{ji}) \frac{\partial \text{net}_{ji}}{\partial w_{ji}} = -z_{ij} x_{ij} g'(o_{ij}) f'(\text{net}_{ji})
\end{aligned}
\]

(5)

(6)

The flight dynamic parameter model and the control constraint parameter model of UAV flight are constructed under the predetermined deviation trajectory to realize the optimal configuration of UAV flight dynamics in uncertain environment and to improve the stability of flight control and the resistance to headwind disturbance.

2.2. Optimal configuration of UAV flight dynamics

On the basis of constructing dynamic parameter model and control constraint parameter model of UAV flight, the optimal configuration of UAV flight dynamics is carried out under uncertain environment [9], and the continuous solution vector \( f(x) \) of UAV flight dynamics configuration is obtained.

\[
f(x) = \begin{cases} f(x), x \in \text{Lev}_f \\ a, x \in \text{Lev}_f \end{cases}
\]

(7)

\[
G(x) = \begin{cases} \frac{\partial f(x)}{\partial C(x)}, x \in \text{Lev}_f \\ a, x \in \text{Lev}_f \end{cases}
\]

(8)

The state space parameters of the yaw system can be obtained for \( b > a \), UAV flight attitude transfer joint parameters can be satisfied:

\[
\text{Lev}_a f \subseteq \{ x \mid f(x) < b \}
\]

(9)
Under the condition of global stability, when the $\exists x, p > 0, u > 0$ condition is established, the fuzzy function of counterwind disturbance compensation control for UAV flight is obtained as follows:

$$u(t) = w(t)(u_o, u_i) + \frac{\int_0^r \sin((t-t')||u||)F(u(t'))dt'}{||u||}$$  \hspace{1cm} (10)

The yaw model of UAV flight is obtained as follows:

$$\| f \|_{C^{2}(t, \mathbb{R}^n)} = \left\{ \int_{t}^{t'} \left( \int_{t}^{t'} f(t,x) d\theta \right) d\theta \right\}^{1/2}$$  \hspace{1cm} (11)

Where

$$\frac{1}{r} + \frac{1}{r'} = \frac{1}{q} + \frac{1}{q'} = 1$$  \hspace{1cm} (12)

Based on the pseudo inverse matrix, the stable boundary value solution is obtained as follows:

$$f^*(x,v) = \lim_{s \to \infty} \sup(f(y+sv) - f(y))/t$$  \hspace{1cm} (13)

3. Control algorithm optimization

3.1. Static anti-saturation yaw suppression

On the basis of constructing the dynamic parameter model and control constraint parameter model of UAV flight, and realizing the optimal configuration of UAV flight dynamics under uncertain environment, the optimal design of control algorithm is carried out. This paper presents a counterwind disturbance compensation control algorithm for UAV flight based on static anti-saturation yaw suppression. The static anti-saturation yaw suppression method is used to control the local convergence of disturbance [10]:

$$\dot{V}(t) \leq \varphi^2(t)\Psi(d_i(t), d_j(t))\xi(t) < 0$$  \hspace{1cm} (14)

Set $E_{i} = \inf f_i(x), E_{i} = \sup f_i(x)$, the convex combination model of UAV flight control is obtained:

$$V(a_1, \ldots, a_m) = \left( \begin{array}{c} a_i \\
\vdots \\
\vdots \\
\end{array} \right)_{i=1}^{m} = \left( \begin{array}{cccc} 1 & 1 & \cdots & 1 \\
\vdots & \vdots & & \vdots \\
\vdots & \vdots & & \vdots \\
\end{array} \right)_{i=1}^{m} = \left( \begin{array}{cccc} a_0 & a_2 & \cdots & a_m \\
\vdots & \vdots & & \vdots \\
\vdots & \vdots & & \vdots \\
\end{array} \right)$$  \hspace{1cm} (15)

If $\frac{1}{p} = \frac{1}{q} + \frac{s}{d}, 1 < p < q < \infty, s > 0$, then the steady state convergence solution vector of the UAV carrier flying headwind along the predetermined flight trajectory meets the requirements $\| f \|_{L^{\infty}(\mathbb{R})} \leq C \| \nabla f \|_{L^{\infty}(\mathbb{R})}$. The attitude parameter matrix of flight dynamics configuration is constructed as:
\[ A = \left( a_{i,j}^{-1} \right)_{i,j=1}^m = \begin{pmatrix} 1 & a_1 & \cdots & a_{m-1} \\ 1 & a_2 & \cdots & a_m \\ \vdots & \vdots & \ddots & \vdots \\ 1 & a_{m} & \cdots & a_{m-1} \end{pmatrix} \]  
(16)

\[ B = \left( b_{i,j}^{-1} \right)_{i,j=1}^m = \begin{pmatrix} 1 & b_1 & \cdots & b_{m-1} \\ 1 & b_2 & \cdots & b_m \\ \vdots & \vdots & \ddots & \vdots \\ 1 & b_{m} & \cdots & b_{m-1} \end{pmatrix} \]  
(17)

For \( \forall \varepsilon > 0, \exists N > 0 \), while \( N > N \), by adjusting the output attitude parameters of the observer and combining the multisensor fusion filter\(^{[11-13]}\), the linearized NLSEF stability condition is obtained as \( x^{(k)} < x^{(0)} \), which makes the desired yaw angle meet the desired yaw angle:

\[ \inf F(x^{(k)}, q_k) = \min_{1 \leq i \leq N} \{ \inf F(x^{(i)}, q_i) = \alpha^N \} \]  
(18)

The perturbation conditions of Schur are constructed and the perturbation estimates are obtained:

\[ 0 \leq \min_{x \in X^{(0)}} |f(x, q_k) - a^N| = \min_{x \in X^{(0)}} (f(x, q_k) - F(x^{(k)}, q_k) - \inf F(x^{(k)}, q_k)) \leq k \|X^{(k)}\| \]  
(19)

According to the global convergence condition, the linear compensation output of the upwind disturbance is obtained as follows:

\[ \min_{x \in X^{(0)}} |f(x, q_k) - a^N| \rightarrow 0 \]  
(20)

Where, \( \forall \varepsilon > 0, \exists N > 0 \), the static anti-saturation yaw suppression method is used to compensate the disturbance and yaw in the headwind flight environment of UAV \(^{[14]}\), and the output inertial compensation parameters are obtained:

\[ \min_{x \in X^{(0)}} |f(x, q_k) - a^N| < \frac{\varepsilon}{2} \]  
(21)

According to convex combinatorial optimization theorem, adaptive weighted learning method is used to compensate the upwind disturbance.

3.2. Counterwind disturbance compensation control
Under Laplace transform, the state space solution vector of UAV yaw system is satisfied:

\[ \Psi(h, 0) = \Psi + hK(Z_1 + Z_2 + Z_3)^{-1}K^TL(Z_2 + Z_3)^{-1}L^T < 0 \]  
(22)

\[ \Psi(0, h) = \Psi + hWZ_1^{-1}W^TL(Z_1 + Z_3)^{-1}L^T + h_2M(Z_2 + Z_3)^{-1}M^T < 0 \]  
(23)
Combined with dynamic trajectory learning and dynamic motion primitive real-time feedback method, the flight trajectory of UAV can be rectified in real time [15]. The delay link of UAV control is introduced as follows:

$$\Phi(u(t)) := w(t)(u_0, u_1) + \int_0^t \frac{\sin((t-s)\|\nabla\|)}{\|\nabla\|} F(u(s))ds$$

(24)

The open loop transfer function of linear active disturbance rejection in headwind flight is:

$$B = \{u : \|u\|_{\infty} \leq \alpha, \|\nabla [\|S(u)\|] \|u\|_{\infty} + \|\nabla [\|S(u)\|] \|u\|_{\infty} \leq b\}$$

(25)

Set $\max\{N_1, N_2\} = N$, while $N > \bar{N}$, then:

$$\min_{n=\bar{N}}(\epsilon) - (f(x) - \alpha_N) = \min_{n=\bar{N}}(f(x_1, q_k) - (f(x, q_k) - f(x))) < \frac{\epsilon}{2} + \frac{\epsilon}{2}$$

(26)

According to the convex optimal stability condition, the asymptotic convergence and stability of the proposed control law for UAV flight headwind disturbance compensation are obtained.

4. Simulation experiment and performance analysis

In order to test the application performance of this method in the control of flight headwind disturbance compensation for UAV, the simulation experiment is carried out. Matlab 7 is used in the experiment. The prototype model of UAV is UAV2017 8 rotor prototype. Setting the no-load mass of the prototype at 2.4 kg, in the headwind flight, the flight time of 12 min, three-axis magnetometer is 12 min, the bandwidth of the acquisition of flight mechanics parameters is 2.4 dB, the sampling frequency is 1 200 kHz, and the UAV is expected to be stable in hovering state. The set value of the eigenvalue $(x_1, x_2)$ is:

$$X_1 = [0.4301597103476526, -0.4301596991717815]$$

(27)

$$X_2 = [-0.5698403045535088, -0.5698402933776378]$$

(28)

The expected yaw angle is calculated as:

$$K_{x^{(I)}} = \{k \in {1, 2, \cdots, n} | u(x^{(I)}_k) \neq 0\}$$

(29)

The optimal solution vector of the control objective parameter is set as follows:

$$f(X) = [1.071539141671495, 1.071539141671497]$$

(30)

According to the above simulation environment and parameter setting, the simulation experiment is carried out, and the time domain output and frequency domain output of UAV flight attitude parameters are obtained as shown in figure 1.
Taking the attitude data of headwind flight of UAV in figure 1 as the research object, compensation control of headwind disturbance is carried out, and the convergence curve of control parameters is obtained as shown in Fig. 2.

Figure 2 shows that the error compensation performance of this method is good, and the control accuracy of different methods is tested. The comparison results are shown in figure 3. The static anti-saturation yaw suppression method is used to compensate the disturbance and correct the yaw in the headwind flight environment of UAV. The accurate tracking ability of the flight trajectory is stronger and the flight control error is reduced and the control precision is better.
5. Conclusion
UAVs are liable to be affected by uncertain disturbance factors during headwind flight, which affects flight stability. In this paper, a counterwind disturbance compensation control algorithm for UAV flight based on static anti-saturation yaw suppression is proposed. The dynamic parameter model and control constraint parameter model of UAV flight are constructed under the action of headwind disturbance. The optimal configuration of UAV flight dynamics under uncertain environment is realized, and the UAV is carried out in the polar coordinate system of vortex center. The optimal matching of carrier velocity and radial acceleration of the flight is carried out. The static anti-saturation yaw suppression method is used to compensate the disturbance and correct the yaw in the headwind flight environment of the UAV. Under the optimal control law, the carrier edge of the UAV is guided. The flight stability of the UAV is controlled by the flight trajectory of the UAV against the wind. The results show that the disturbance compensation and control accuracy of this method are good and the flight stability is improved.

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