Algorithm of UAV flight disturbance control based on dynamic trajectory learning

Xiaoli Liu[1, *], Xinghua Lu[2]

[1]Guangzhou Huali Science and Technology Vocational College, Guangzhou, China
[2]Huali College Guangdong University of Technology, Guangdong Guangzhou, China

*Corresponding author E-mail: xhlu@gdut.edu.cn

Abstract. UAV is prone to yaw due to disturbance in dynamic flight with load, in order to improve the anti-disturbance ability of UAV, a flight disturbance control algorithm for UAV based on dynamic trajectory learning is proposed. The constraint parameter model of UAV flight control is constructed by time-delay tracking compensation model in homogeneous space, and the time-frequency decomposition of inertial constraint parameters of UAV flight rejection control is carried out by using Laplace transform. Adaptive weighted learning algorithm is used to deal with the dynamic trajectory of UAV under external disturbance. The disturbance error is compensated by adding a post integral at the end point of the learning trajectory. Combined with dynamic trajectory learning and dynamic motion primitive real-time feedback method, the real-time deviation correction of UAV flight trajectory is realized, and the adaptive optimal control of UAV flight disturbance is realized. The simulation results show that the proposed method can correct the error of UAV flight disturbance and improve the stability of UAV flight control.

1. Introduction

With the development of aircraft design and control technology, various kinds of UAV equipment have shown good application value in military, meteorological, surveying and mapping fields. UAV is suitable for environment to perform special tasks instead of manned aircraft. The robustness and stability of flight control is the key to the maneuverability of UAV. The UAV control system plays an important role in the realization of large-scale high-precision positioning and navigation control, the relevant control algorithms have attracted much attention [1].

The design of autonomous control of UAV is mainly to optimize the design of control law, which is the core problem of UAV flight safety. Because of the poor stability of UAV flight control, the anti-disturbance control methods of UAV include nonlinear H ∞ robust control method and fuzzy PID control method [1, 2]. Dynamic inverse control method and multi-mode control are used to improve the stability of flight control by optimizing estimation of flight state parameters and optimization design of multi-mode control law. In reference [4], a flight anti-disturbance stability control law for UAV based on inverse steady-state error compensation is proposed. The controlled object model and control constraint parameters of UAV anti-disturbance control is analyzed, and the flight dynamic parameter model of UAV is constructed. The adaptive steady-state error compensation method is used to realize the optimal control of UAV flight process, the configuration of mechanical parameters, the configuration of characteristic structure, and the improvement of control stability, but the real-time performance of UAV flight control by this method is not good. In reference [5], a method of UAV flight disturbance control based on extended Kalman filter is proposed, which realizes UAV attitude angle correction and parameter fusion, which is not adaptive to UAV disturbance angle compensation. In reference [6], a UAV flight control algorithm based on inverse integral compensation is proposed, which combines the unscented Kalman filter (UKF) information fusion method to realize the UAV steady-state control and improve the control accuracy. This method is not good for UAV yaw correction ability.

In order to solve the above problems, this paper presents a flight disturbance control algorithm for UAV based on dynamic trajectory learning. Firstly, the constraint parameter model of UAV flight control is constructed, and the time-frequency decomposition of inertial constraint parameters of UAV flight rejection control is carried out by using Laplace transform. Adaptive weighted learning algorithm is used to deal with the dynamic trajectory of UAV. Then the control law is designed and the disturbance error is compensated by adding the post integral item at the end point of the learning trajectory. The real-time error correction of UAV flight trajectory is realized by combining the dynamic trajectory learning and the dynamic motion primitive real-time feedback method. Adaptive optimal control of UAV flight disturbance is realized. Finally, the application performance of the proposed method in UAV flight disturbance control optimization is demonstrated by simulation experiments.

2. Description of controlled object and construction of UAV kinematics model

2.1. Controlled object description

Firstly, the overall structure model of UAV control is constructed. The stability control of UAV flight anti-disturbance is based on parameter information collection and characteristic analysis of control constraint parameters. The accelerometer and magnetic force sensor are used to collect the flight position and dynamic parameters of UAV. The flight dynamic parameters of UAV are input into the control command system. Combining information fusion and adaptive weighted learning method to control UAV flight disturbance [7]. The constrained parameter model of UAV flight control is constructed by time-delay tracking compensation model in homogeneous space. The controlled object model of UAV flight disturbance control is shown in figure 1.

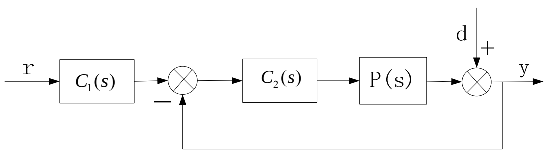


Figure 1. Controlled object model of UAV flight disturbance control

In the disturbance control object model of UAV shown in Fig. 1, the inertia constraint parameter model of UAV flight control is established by using the lateral offset correction and adaptive linear ADRC method:

$$\begin{cases} Q_1(s) = M_{-}^{-1}(s)\, f_1(s) \\ Q_2(s) = M_{-}^{-1}(s)\, f_2(s) \end{cases} \tag{1}$$

Where, $f_1(s)$ and $f_2(s)$ are static anti-saturation terms and time-delay terms representing linear active disturbance rejection. The error compensation terms of flight control are obtained by using yaw control and static anti-saturation compensation method:

$$\begin{cases} f_1(s) = \dfrac{1}{\lambda_1 s + 1} \\ f_2(s) = \dfrac{1}{\lambda_2 s + 1} \end{cases} \tag{2}$$

Where, $C_1(s)$ is the constrained function with load control, $C_2(s)$ is the flight error compensation function. According to the yaw motion performance of the actuator and the fuzzy control method, the terminal position of UAV flight control is adjusted [8]. The control object model is described as follows:

$$Y(s) = \frac{C_1(s)C_2(s)P(s)}{1+C_2(s)P(s)}R(s) + \frac{1}{1+C_2(s)P(s)}D(s) \tag{3}$$

Weakening the effect of saturation on the system, the disturbance term of UAV is studied with adaptive weighted learning, and the dynamic characteristic parameters of mass center rotation of UAV are obtained as follows:

$$\begin{cases} C_1(s) = \dfrac{Q_1(s)}{Q_2(s)} \\ C_2(s) = \dfrac{Q_2(s)}{1 - M(s)Q_2(s)} \end{cases} \tag{4}$$

The constrained parameter model of UAV anti-disturbance control is constructed, and the adaptive weighted learning algorithm is used to deal with the dynamic trajectory of UAV by using adaptive weighted learning algorithm to improve the stability and self-adaptability of UAV [9].

2.2. *Steady-state kinematics model for UAV control*

Under the condition of continuous boundedness, the inertial confinement motion parameters of UAV steady-state flight meet the control vector set of $0 < \eta \le \eta_0$, I relative to the airframe coordinate system. Using the fine observation data to construct the initial characteristic value of flight control, $(u_0, u_1) \in \dot{H}_x^{s_c} \times \dot{H}_x^{s_c - 1}$, is used to reconstruct the flight trajectory in the flight kinematics phase trajectory. The control characteristic equation of UAV flight control composed of polar diameter and polar angle is obtained. The control characteristic equation of UAV flight control meets the requirement: $\begin{matrix} \| (u_0, u_1) \|_{\dot{H}_x^{s_c} \times \dot{H}_x^{s_c-1}} \le A \\ \| w(t)(u_0, u_1) \|_{L_{t,x}^{10}(I \times IR^4)} \le \eta \end{matrix}$. In homogeneous space $I \times IR^4$, the center motion fuzzification fusion method is adopted. When the eigenvalue solution vector has a unique solution, the prediction function of UAV motion trajectory is obtained as:

$$\begin{aligned} &\| u \|_{L_{t,x}^{10}(I \times IR^4)} \le 2\eta \\ &\| |\nabla|^{\frac{5}{4}} u \|_{S_{\frac{1}{4}}} + \| |\nabla|^{\frac{1}{4}} u_t \|_{S_{\frac{1}{4}}} < \infty \end{aligned} \tag{5}$$

In the course of trajectory learning, a continuous bounded integral compensation control method is adopted [10], and a closed-loop control function is introduced to correct the error. The closed-loop control function is described as follows:

$$\boldsymbol{J} = \sum_{k=0}^{\infty}[\boldsymbol{z}^{\mathrm{T}}(k)\boldsymbol{z}(k) - \gamma^2\boldsymbol{w}^{\mathrm{T}}(k)\boldsymbol{w}(k)] \tag{6}$$

Where, $\gamma > 0$ is a constant, the weighted control vector of the learning trajectory satisfies the $w(k) \neq 0$, and the basis function of the $w(k) \in L_2[0,\infty)$, dynamic moving primitive is satisfied with the dynamic primitive learning:

$$\boldsymbol{J} \leq \sum_{k=0}^{\infty}[\boldsymbol{z}^{\mathrm{T}}(k)\boldsymbol{z}(k) - \gamma^2\boldsymbol{w}^{\mathrm{T}}(k)\boldsymbol{w}(k) + \Delta\boldsymbol{V}_k] \tag{7}$$

The learning locus position is calculated and the *j* component converges to:

$$\boldsymbol{J} \leq \boldsymbol{\Phi}_2(k)\boldsymbol{U}\boldsymbol{\Phi}_2^T(k) \tag{8}$$

In any trajectory, the weight vectors of UAV flight trajectory are obtained by recombination of primitive vectors:

$$U = \begin{bmatrix} \bar{A}^T P \bar{A} - P + K^T RK + C^T C & \bar{A}^T P \bar{B} + C^T D & \bar{A}^T PF_1 + C^T F_2 \\ \bar{B}^T P \bar{A} + D^T C & \bar{B}^T P \bar{B} - R + D^T D & \bar{B}^T PF_1 + D^T F_2 \\ F_1^T P \bar{A} + F_2^T C & F_1^T P \bar{B} + F_2^T D & F_1^T PF_1 + F_2^T F_2 - \gamma^2 I \end{bmatrix} \tag{9}$$

In the time-delay finite field IR^d of UAV attitude gyroscope, the driving function of UAV flight control is obtained by using the discrete linear combination method of attitude measurement value:

$$\hat{f}(\xi) = (2\pi)^{-d/2} \int_{IR^d} \mathrm{e}^{-\mathrm{i}x\cdot\xi} f(x)dx \tag{10}$$

The kinematics model of attitude stability control for high UAV flight is obtained by using Lipschitz continuous regularization decomposition method:

$$\dot{H}_x^s(IR^d) := \{ f : \| f \|_{\dot{H}_x^s(IR^d)} := \| |\nabla|^s f \|_{L_x^2(IR^d)} = \| |\xi|^s \hat{f} \|_{L_\xi^2(IR^d)} < \infty \} \tag{11}$$

The space-time norm of flight anti-disturbance control is defined as:

$$\| f \|_{L_t^q L_x^r(I\times IR^d)} = (\int_I (\int_{IR} | f(t,x)|^r dx)^{q/r} dt)^{1/q} \tag{12}$$

The Laplace transform is used to decompose the time-frequency characteristic of the constrained parameters of flight anti-disturbance control. The disturbance control capability of UAV is improved by combining the adaptive adjustment method of the constrained parameters with the control object model established by $I \times IR^d$ mapping.

3. Optimization of control Law

3.1. Elementary coupling processing of UAV dynamic trajectory

On the basis of constructing the constraint parameter model and kinematics of UAV flight control, the optimal design of UAV flight disturbance control algorithm is carried out, and a UAV flight disturbance control algorithm based on dynamic trajectory learning is proposed in this paper [11]. Adaptive weighted learning algorithm is used to deal with the dynamic trajectory of UAV by using adaptive weighted learning algorithm under external variable disturbance. The fusion model of dynamic trajectory tracking of UAV is described as follows:

$$2\xi^T(t)W\left[x(t-d_1(t))-x(t-h_1)-\int_{t-h_1}^{t-d_1(t)}\dot{x}(s)ds\right]=0 \tag{13}$$

$$2\xi^T(t)K\left[x(t)-x(t-d_1(t))-\int_{t-d_1(t)}^{t}\dot{x}(s)ds\right]=0 \tag{14}$$

$$2\xi^T(t)M\left[x(t-d_1(t))-x(t-d(t))-\int_{t-d(t)}^{t-d_1(t)}\dot{x}(s)ds\right]=0 \tag{15}$$

$$2\xi^T(t)L\left[x(t-d(t))-x(t-h)-\int_{t-h}^{t-d(t)}\dot{x}(s)ds\right]=0 \tag{16}$$

Under the small linear disturbance, the adaptive weighted learning algorithm is used to predict the dynamic trajectory of UAV. The prediction output is obtained as follows:

$$\| u \|_{S_s(I)} := \sup_{(q,r)\subset \dot{H}_x^s} \|u\|_{L_t^q L_x^r(I\times IR^d)} \tag{17}$$

In finite dimension, the lift coefficient is taken as the conduction coefficient. By k iteration, the state space description of flight stability control is obtained as follows:

$$\| u \|_{N_s(I)} := \inf_{(q,r)\subset \dot{H}_x^s} \|u\|_{L_t^{q'} L_x^{r'}(I\times IR^d)} \tag{18}$$

Where, $\frac{1}{r}+\frac{1}{r'}=1, \frac{1}{q}+\frac{1}{q'}=1$, in order to improve the flight stability of UAV, the disturbance error is compensated by adding a post integral term at the end point of the learning trajectory, and the attitude angle of UAV is modulated by using fuzzy control method [12].

3.2. Adaptive optimal control of UAV flight disturbance

At the end point of the learning trajectory, the disturbance error is compensated by adding the post integral term, and the stability analysis is carried out with the Lyapunov function [13]. The steady-state integral term of UAV flight control is obtained as follows:

$$\Psi(h_1,h_2)=\Psi+h_1K\left(Z_1+Z_2+Z_3\right)^{-1}K^T+h_2M\left(Z_2+Z_3\right)^{-1}M^T<0 \tag{19}$$

By using Lyapunov stability functional theory, the convergence conditions of linear ADRC are obtained.

$$\begin{aligned} &\| |\nabla|^{\frac{5}{4}}\Phi(u)\|_{S_{\frac{1}{4}}}+\||\nabla|^{\frac{1}{4}}\partial_t\Phi(u)\|_{S_{\frac{1}{4}}}\le \||\nabla|^{\frac{5}{4}}w(t)(u_0,u_1)\|_{S_{\frac{1}{4}}}+\||\nabla|^{\frac{5}{4}}\int_0^t\frac{\sin((t-s)|\nabla|)}{|\nabla|}(|u(s)|^4u(s))ds\|_{S_{\frac{1}{4}}} \\ &+\||\nabla|^{\frac{1}{4}}w(t)(u_0,u_1)\|_{S_{\frac{1}{4}}}+\||\nabla|^{\frac{1}{4}}\int_0^t\cos((t-s)|\nabla|)(|u(s)|^4u(s))ds\|_{S_{\frac{1}{4}}}\le C[\|(u_0,u_1)\|_{\dot{H}_x^{s_c}\times\dot{H}_x^{s_c-1}}+\||\nabla|^{\frac{5}{4}}(|u|^4u)\|_{N_{\frac{3}{4}}} \\ &\le CA+C\||\nabla|^{\frac{5}{4}}u\|_{S_{\frac{1}{4}}}\|u\|^4_{L^{10}_{t,x}}\le CA+Ca^4b \end{aligned} \tag{20}$$

When the attitude transfer control coefficient $b = 2AC$, a satisfies the $Ca^4 \leq \frac{1}{2}$, and Lyapunov stability principle [14], the adaptive optimal control law for the flight disturbance of $\||| \nabla |^{\frac{5}{4}} \Phi(u) \|_{S_{\frac{1}{4}}} + \||| \nabla |^{\frac{1}{4}} \partial_t \Phi(u) \|_{S_{\frac{1}{4}}} \leq b$, UAV is obtained as follows:

$$\| \Phi(u) \|_{L_{t,x}^{10}} \leq \| w(t)(u_0, u_1) \|_{L_{t,x}^{10}} + \| \int_0^t \frac{\sin((t-s)|\nabla|)}{|\nabla|} (|u(s)|^4 u(s)) ds \|_{L_{t,x}^{10}} \leq \eta + \||| \nabla |^{\frac{5}{4}} (|u|^4 u) \|_{N_{\frac{3}{4}}} \leq \eta + C \||| \nabla |^{\frac{5}{4}} u \|_{S_{\frac{1}{4}}} \| u \|_{L_{t,x}^{10}}^4 \leq \eta + Ca^4 b \quad (21)$$

If $\eta = \frac{a}{2}$, a satisfies the homogeneous convergence condition such that the upper bound of flight control law of $Ca^4 b \leq \frac{a}{2}$, when $\Phi(B) \subset B$, the Lyapunov function of flight disturbance control of UAV satisfies:

$$\begin{aligned}
\| \Phi(u) - \Phi(v) \|_B = {} & \||| \nabla |^{\frac{5}{4}} [\Phi(u) - \Phi(v)] \|_{S_{\frac{1}{4}}} + \| \nabla |^{\frac{1}{4}} \partial_t [\Phi(u) - \Phi(v)] \|_{S_{\frac{1}{4}}} + \| \Phi(u) - \Phi(v) \|_{L_{t,x}^{10}} \leq C \||| \nabla |^{\frac{5}{4}} [|u|^4 u - |v|^4 v] \|_{N_{\frac{3}{4}}} \\
& \leq C \||| \nabla |^{\frac{5}{4}} (u-v)[|u|^4 + |v|^4] \|_{N_{\frac{3}{4}}} \leq C \||| \nabla |^{\frac{5}{4}} (u-v)[|u|^4 + |v|^4] \|_{L_t^{\frac{20}{13}} L_x^{\frac{40}{31}}} \leq C\{\||| \nabla |^{\frac{5}{4}} (u-v) \|_{L_t^4 L_x^{\frac{8}{3}}} \||u|^4 + |v|^4\|_{L_{t,x}^{\frac{5}{2}}} + \| u-v \|_{L_{t,x}^{10}} \||| \nabla |^{\frac{5}{4}} [|u|^4 + |v|^4] \|_{L_t^{\frac{20}{11}} L_x^{\frac{40}{27}}}\} \quad (22) \\
& \leq C \||| \nabla |^{\frac{5}{4}} (u-v) \|_{L_t^4 L_x^{\frac{8}{3}}} (\| u \|_{L_{t,x}^{10}}^4 + \| v \|_{L_{t,x}^{10}}^4) + C \| u-v \|_{L_{t,x}^{10}} (\| u^3 \|_{L_{t,x}^{\frac{10}{3}}} \||| \nabla |^{\frac{5}{4}} u \|_{L_t^4 L_x^{\frac{8}{3}}} + \| v^3 \|_{L_{t,x}^{\frac{10}{3}}} \||| \nabla |^{\frac{5}{4}} v \|_{L_t^4 L_x^{\frac{8}{3}}}) \leq C \| u-v \|_B (\| u \|_{L_{t,x}^{10}}^4 + \| v \|_{L_{t,x}^{10}}^4 \\
& + \|\|| u \|_{L_{t,x}^{10}}^3 \||| \nabla |^{\frac{5}{4}} u \|_{S_{\frac{1}{4}}} + \| v \|_{L_{t,x}^{10}}^3 \||| \nabla |^{\frac{5}{4}} v \|_{S_{\frac{1}{4}}}) \leq C \| u-v \|_B (a^4 + 2a^3 b)
\end{aligned}$$

Combined with the Lyapunov stability condition, the proposed flight disturbance control algorithm based on dynamic trajectory learning is steady convergence [15].

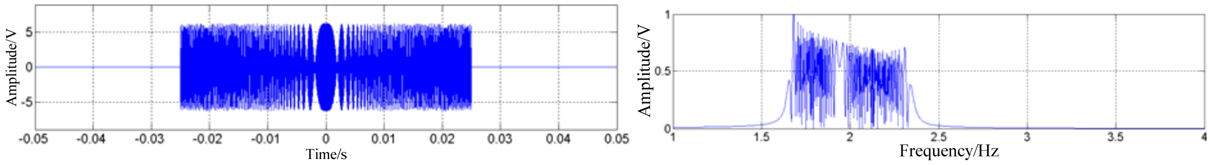
4. Simulation experiment and result analysis

In order to test the application performance of this method in UAV flight disturbance control, the simulation experiment is carried out. Matlab 7 is used to design the experiment, and LESO magnetic force sensor and L3G4200D acceleration sensor are used to collect the original parameters of UAV flight control. Combined with LMI toolbox, the static and model parameters of UAV flight control are obtained. The initial value of the control parameters is set to the $\varpi = 25, k_p = 1.25, k_d = 16$, yaw angle is 0.26 N.m. The physical model of the time-delay $\tau(t) = 8.183$, inertial weight $\sigma(t) = 7.662$, UAV with flight tracking is shown in figure 2.

According to the above simulation environment and parameter setting, the UAV flight control simulation experiment is carried out. Firstly, the sensing parameters of UAV flight control are collected, and the magnetic force sensing data and acceleration sensing data are obtained as shown in figure 3.

Figure 2. UAV prototype model

IOP Conf. Series: Materials Science and Engineering **452** (2018) 042089 doi:10.1088/1757-899X/452/4/042089



(a) Magnetic sensing data (b) Acceleration sensing data

Figure 3. Sensing information acquisition results of flight control

Taking the data collected in figure 3 as the object of study, the flight disturbance control is carried out, and the adaptive weighted learning algorithm is used to deal with the dynamic trajectory of UAV by using adaptive weighted learning algorithm under external variable disturbance, and the dynamic trajectory learning tracking is realized. The convergence process of flight control is shown in figure 4.

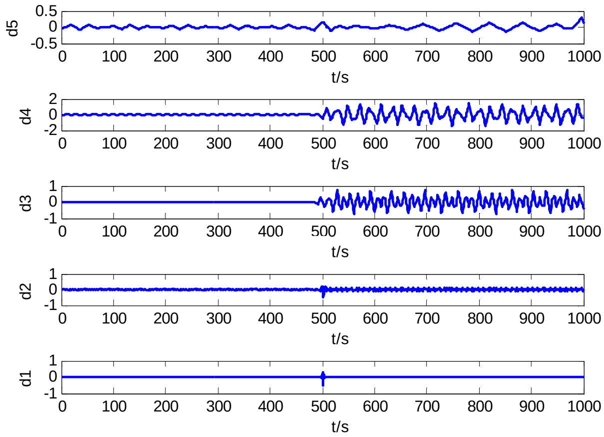


Figure 4. Output of UAV disturbance control

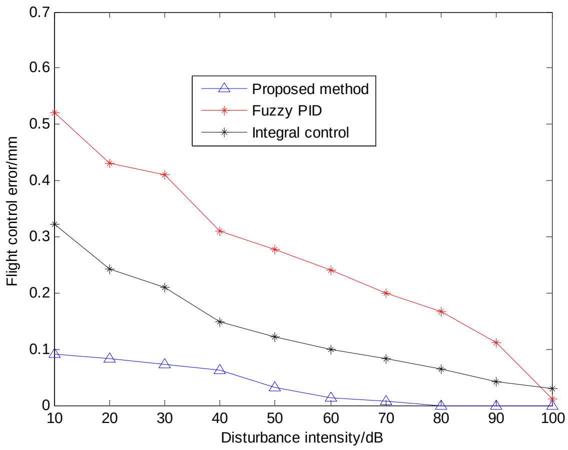


Figure 5. Control performance comparison

The control process in figure 4 shows that with the increase of iteration times the disturbance of UAV parametric output is effectively suppressed and finally converges to 0 which improves the flight anti-disturbance control ability and adaptive learning ability of UAV. In order to compare the performance of UAV flight control, different methods are used to control UAV. The comparison of control performance curve is shown in figure 5. The analysis figure 5 shows that the control accuracy of this method is higher and the global robustness is better, stable flight control can still be realized under higher disturbance intensity.

5. Conclusion

In the design of UAV, the robustness and stability of flight control is the key to determine the maneuverability of UAV. In this paper, a flight disturbance control algorithm based on dynamic trajectory learning is proposed. The constraint parameter model of UAV flight control is constructed by time-delay tracking compensation model, and the time-frequency decomposition of inertial constraint parameters of UAV flight auto-disturbance rejection control is carried out. The adaptive weighted learning algorithm is used to deal with the dynamic trajectory of UAV by means of primitive coupling under external variable disturbance, and the disturbance error is compensated by adding a post integral term. Combined with dynamic trajectory learning and dynamic motion primitive real-time feedback method, the real-time deviation correction of UAV flight trajectory is realized, and the adaptive optimal control of UAV flight disturbance is realized. The research shows that the anti-disturbance and the global stability of the flight control are strong, and the control quality of UAV is improved.

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