Optimum Design and Simulation of Autonomous Attack Guidance Law for UCAV

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Abstract: Due to the influence of parameter perturbation and external disturbance, the traditional linear guidance control method with small disturbance can’t meet the needs of UCAV guided control. An adaptive sliding mode variable structure guidance law was optimized in order to improve the stability and nonlinearity of UCAV. The mathematical model of the target was established by the secondary calibration. The relative motion model of UCAV and target was established based on the six degree of freedom nonlinear model of UCAV. With using the variable structure control theory into the UCAV's guide, the adaptive sliding variable structure guidance law is derived. The simulation results show that the optimal control of UAV guidance law can improve the nonlinear performance of UCAV, and has a good anti disturbance ability. The control variables of UAV in the guidance law control process change smoothly and have good dynamic quality. The feasibility analysis proves the validity and rationality of the method. The design has the good dynamic quality.

1. Introduction

At present, autonomous attack guidance control of UCAV is a research hotspot in the field of control, which has attracted the attention of scholars at home and abroad. Because of the characteristics of UCAV, it’s necessary to guide the UAV to the attack area quickly and accurately. Due to the lack of pilot's control, UAV is different from the ordinary fighter, and its maneuverability is relatively poor in the process of autonomous attack [1, 2, 3]. In addition, when the UCAV attacks the target, it may be found or even shot down by the target. Therefore, the performance of guidance law is very high in the process of autonomous attack, and the design of guidance law is very important in the autonomous attack [4, 5, 6].

Considering the concealment of UCAV in the attack process, the design of UCAV guidance law should not only meet the stability of the attack process, but also meet the rapidity and accuracy of guidance. Firstly, the paper analyzes the autonomous attack guidance process of UCAV. The variable structure theory is applied to the optimal control of UCAV guidance law, and the adaptive sliding mode variable structure guidance law of UCAV is derived. Through simulation analysis, the change curve of UCAV control quantity in autonomous attack flight control is obtained, and the traditional proportional guidance method is compared, which proves the effectiveness and rationality of the method.

2. UCAV Autonomous Attack Model

2.1 Analysis of Autonomous Attack Guidance Process.

Owing to the limitation of UCAV itself, once it’s found by the target, the target is easy to evade attack, while the UCAV itself is easy to be attacked by the target [7, 8]. In order to reduce the probability of being searched and found by the target’s radar, give full play to the stealth performance of the UCAV, and improve the defense ability of the UCAV itself, it is assumed that the UCAV will approach the target from the bottom of the target plane when attacking autonomously. When the distance between the UCAV and the target is at a certain distance, the UCAV can move to the attack area quickly and launch the airborne missile to attack the target [9, 10, 11]. The guidance process is shown in Fig. 1.

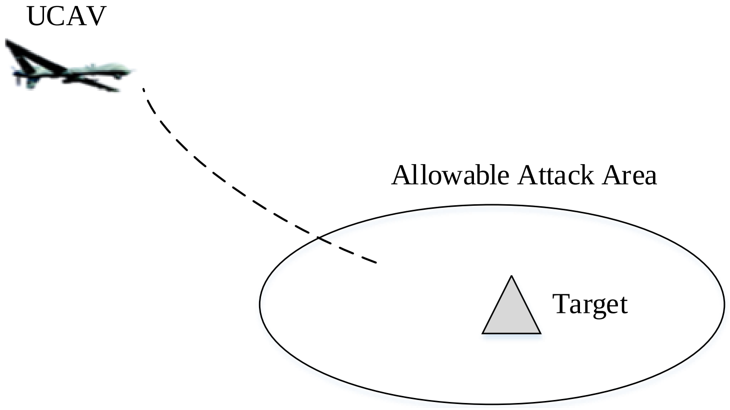

Figure 1. Autonomous attack guidance process

2.2 Mathematical Model of Objectives.

As shown in Fig. 2, at the first calibration, the location of the UCAV is A1, and the target location is M1. In the second calibration, the location of UCAV is A2, and the target location is M2. In the whole tracking and measurement process, the UCAV moves from point A1 to point A2, and the target moves from point M1 to point M2. We can get:

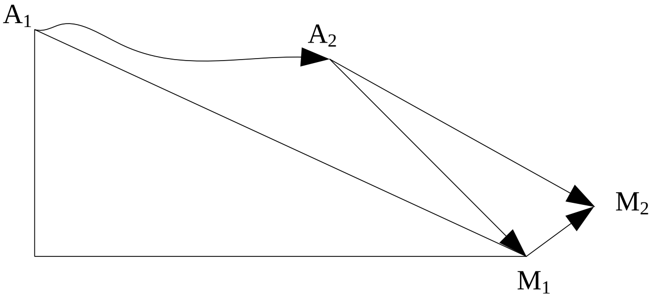

Figure 2. Secondary calibration of target

$$\begin{cases} \overrightarrow{M_1M_2} = \overrightarrow{A_2M_2} - \overrightarrow{A_2M_1} \\ \overrightarrow{A_2M_1} = \overrightarrow{A_1M_1} - \overrightarrow{A_2A_1} = \overrightarrow{A_1M_1} - \int_0^t V dt \\ \vec{v_t} = \dfrac{\overrightarrow{M_1M_2}}{t} \end{cases} \tag{1}$$

In the above formula (1), V is the flight speed of the UCAV; $\vec{v_t}$ is the moving speed of the target; t is the interval time of secondary calibration.

Suppose that the motion equation of the target in the ground coordinate system is:

$$\begin{cases} \dot{x}_t = v_t \cos\theta_t \cos\psi_t \\ \dot{z}_t = v_t \cos\theta_t \sin\psi_t \\ \dot{y}_t = v_t \sin\theta_t \\ \dot{v}_t = n_{tx} g \\ \dot{\theta}_t = \dfrac{n_{ty} g}{v_t} \\ \dot{\psi}_t = \dfrac{n_{tz} g}{v_t \cos v_t} \end{cases} \tag{2}$$

In the above formula (2), the coordinates of the target in the ground coordinate system are expressed as (x_t, y_t, z_t). ψ_t is the yaw angle of the target; θ_t is the pitch angle of the target; v_t is the speed of the target; n_{tz} is the turning overload of the target in the yaw direction; n_{ty} is the overload of the target in the pitch direction; n_{tx} is the longitudinal overload of the target.

2.3 UCAV Mathematical Model.

In order to accurately reflect the motion state of UCAV and facilitate simulation calculation, the paper assumes the earth as an inertial reference system, ignoring the influence of curvature of the earth and taking no account of UCAV elasticity. The six degree of freedom model of UCAV is established.

$$\begin{cases} \dot{p} = (c_1 r + c_2 p) q + c_3 \overline{L} + c_4 N \\ \dot{q} = c_5 pr - c_6 \left(p^2 - r^2\right) + c_7 M \\ \dot{r} = (c_8 p - c_2 r) q + c_4 \overline{L} - c_9 N \\ \dot{\alpha} = q - p\cos\alpha\tan\beta - r\sin\alpha\tan\beta - \dfrac{\dot{\gamma}\cos\mu + \dot{\chi}\sin\mu\cos\gamma}{\cos\beta} \\ \dot{\beta} = p\sin\alpha - r\cos\alpha - \gamma\tan\beta - \dfrac{\dot{\gamma}\cos\mu + \dot{\chi}\sin\mu\cos\gamma}{\cos\beta} \\ \dot{\mu} = \dfrac{p\cos\alpha + r\sin\alpha}{\cos\beta} + \dot{\gamma}\tan\beta\cos\mu + \dot{\chi}(\sin\gamma + \tan\beta\sin\mu\cos\gamma) \\ \dot{\chi} = \dfrac{1}{mV\cos\gamma}(L\sin\mu + Y\cos\mu) + \dfrac{T_x}{mV\cos\gamma}(\sin\mu\sin\alpha - \cos\mu\cos\alpha\sin\beta) + \dfrac{T_y}{mV\cos\gamma}\cos\mu\cos\beta - \dfrac{T_z}{mV\cos\gamma}(\sin\mu\cos\alpha + \cos\mu\sin\alpha\sin\beta) \\ \dot{\gamma} = \dfrac{1}{mV}\left(L\cos\mu - Y\sin\mu - mg\cos\gamma - T_y\sin\mu\cos\beta\right) + \dfrac{T_x}{mV}(\sin\mu\cos\alpha\sin\beta + \cos\mu\sin\alpha) + \dfrac{T_z}{mV}(\sin\mu\sin\alpha\sin\beta + \cos\mu\cos\alpha) \\ \dot{x} = V\cos\gamma\cos\chi \\ \dot{y} = V\cos\gamma\sin\chi \\ \dot{z} = -V\sin\gamma \\ \dot{V} = g\left(\tau P_m - Q_0 - {n_y}^2 Q_i - \sin\gamma\right) \end{cases} \tag{3}$$

In the above formula (3), (x, y, z) is the position of the UCAV; V is the flight speed of the UCAV; α is the angle of attack; μ is the roll angle; y is the track inclination; β is the sideslip angle; χ is the track deflection angle; m is the mass of the UAV; g is the acceleration of gravity. p is the roll angular velocity; q is the pithing angular velocity; r is the yaw rate. τ is the thrust coefficient; P_m is the maximum thrust; Q_0 is the zero lift resistance; Q_i is the induced resistance; N_y is the normal phase overload.

2.4 Relative Motion Model of UCAV and Target.

The motion model of UCAV with six degrees of freedom mainly includes the kinematics and dynamics equations of rotating around the center of mass, the kinematics and dynamics equations of translational motion of the center of mass and the equations of mass change. Considering that there are many factors involved and the coupling between them, the motion of UCAV is regarded as the motion of longitudinal plane and lateral plane, and the longitudinal plane is taken as an example to study.

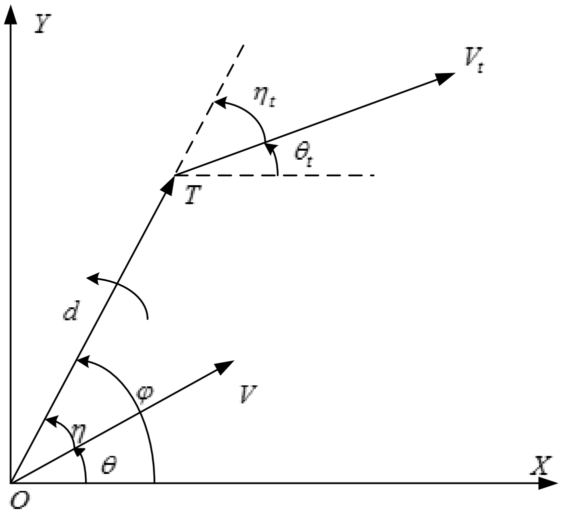

Figure 3. Schematic diagram of relative motion

As shown in Figure 3, point *O* represents the position of the UCAV, point *T* represents the position of the target, θ and θ_t represent the pitch angle of the UCAV and the target, η and η_t represent the velocity lead angle of both, and φ represents the line of sight angle.

$$\begin{cases} \dot{d} = V_t \cos\left(\varphi - \theta_t\right) - V\cos\left(\varphi - \theta\right) \\ d\dot{\varphi} = V\sin\left(\varphi - \theta\right) - V\sin\left(\varphi - \theta_t\right) \end{cases} \tag{4}$$

3. Optimal Design of Guidance Law for Autonomous Attack

As a result of the increasing difficulty of UCAV combat mission, the flight envelope is also growing, and the performance requirements of UCAV are becoming higher and higher. The nonlinear characteristics of guidance law control are becoming more and more prominent. In order to improve the stability and nonlinearity of the guidance law, the variable structure theory is applied to the design of the guidance law.

Adaptive sliding mode variable structure method has good nonlinear characteristics, which can effectively improve the stability and nonlinearity of UCAV guidance rate control [12]. According to Lyapunoy's stability principle, the sliding mode arrival condition is satisfied. Because it is expected that the UCAV will ensure a small overload when flying at the preset trajectory point, and can fly straight, the UCAV's line of sight angular velocity tends to zero, the following sliding surface is designed:

$$S = w = -V\sin\left(\theta - \varphi\right)/d = -V\sin\eta/d \tag{5}$$

Considering the influence of buffeting on UCAV in autonomous flight, adaptive variable index approach law is adopted:

$$\dot{S} = -k\frac{|\dot{d}|}{d}S - \frac{\xi}{d}\operatorname{sgn}(S), k > 0, \xi > 0$$
$$\operatorname{sgn}(S) = \frac{S}{|S| + \lambda}, \lambda > 0 \tag{6}$$

Where k, λ, ξ is constant, $k > 0$, $\lambda > 0$, $\xi > 0$.

$$S\dot{S} = -\frac{k|\dot{d}|}{d}S^2 - \frac{\xi}{d}S\operatorname{sgn}(S) = -\frac{k|\dot{d}|}{d}S^2 - \frac{\xi}{d}\frac{S^2}{|S| + \lambda} < 0 \tag{7}$$

$SS < 0$ can be obtained, which satisfies the condition. After the derivation of formula (5) and formula (6), we can get:

$$\dot{\theta} = \frac{1}{V\cos\eta}\left(k|\dot{d}|S + \xi\operatorname{sgn}(S)\right) - \dot{V}\sin\eta - 2\dot{d}w \tag{8}$$

4. Simulation Analysis

4.1 Simulation Condition.

The initial conditions of simulation are as follows: the track inclination is 25°, the track deflection is 10°, the roll angle is -10°, the normal phase overload is 3*g*, the flight speed of UAV is 280 *m/s*, and the target speed is 260 *m/s*. The acceleration limit of UAV is [-250, 250] (m/s^2). Control parameters in variable structure guidance rate: $k = 4$, $\xi = 5$, $k_\chi = 5$, $\xi_\chi = 5$, and the simulation step is 0.01s. Suppose the UCAV is at (20, 3, 20) *km*, and the target is at (23, 5, 23) *km*.

4.2 Simulation Results.

The proportional navigation method (PNM) and the sliding mode variable structure guidance control method (SMC) are used to simulate the guidance process of UCAV in longitudinal plane.

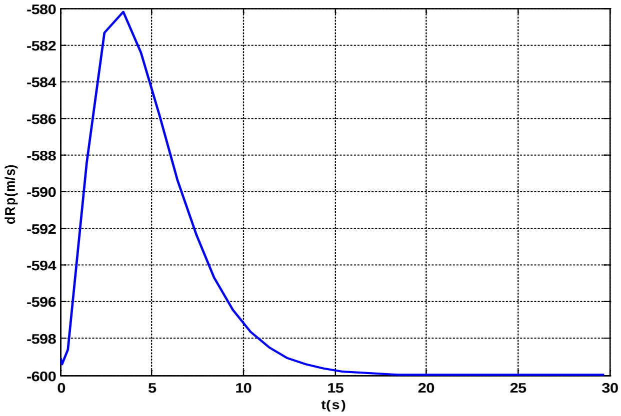

Figure 4. Change rate of relative distance

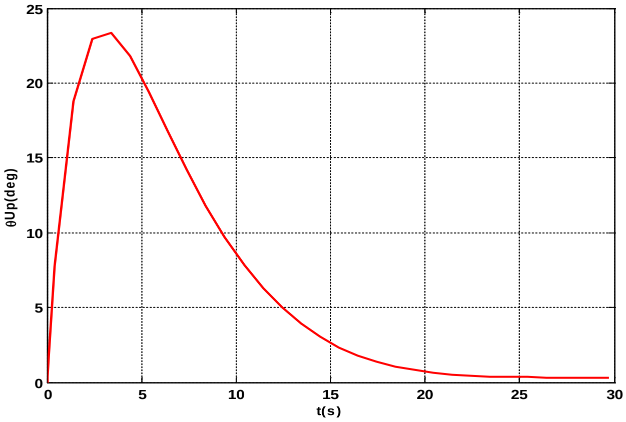

Figure 5. UCAV velocity angle curve

It can be seen from Fig. 4 and Fig. 5 that after flying for 25 seconds, the UCAV can be at the same level with the target and track stably.

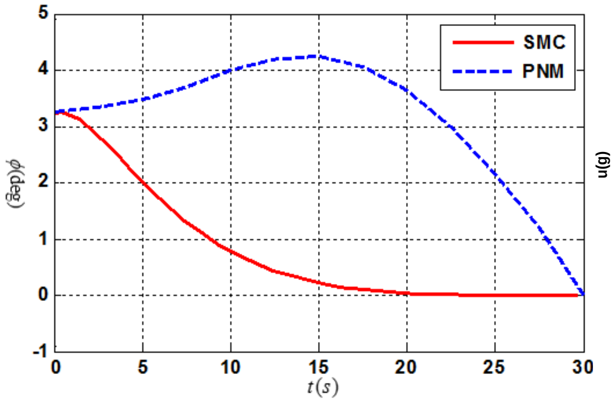

Figure 6. Line of sight angle change curve

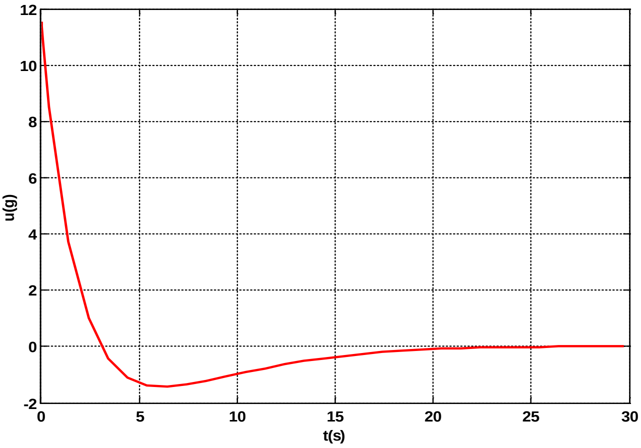

Figure 7. Change process of system control

It can be seen from Fig. 6 that with the sliding mode variable structure guidance control method, the line of sight angle and line of sight angle rate is relatively smooth, which can make the UCAV adjust the attack attitude accurately and improve the task completion rate.

In the guidance process of the adaptive sliding mode variable structure guidance law, the control quantity of the system is the normal acceleration. It can be seen from Fig. 7 that the UCAV control quantity is large at the beginning of guidance, making full use of the characteristics of large available overload of UAV, so as to make the system state smoothly enter the sliding surface. Then the normal overload converges to 0, which makes the UCAV stable at the end of guidance.

4.3 Feasibility Analysis.

The energy consumption of UCAV is defined as:

$$Y = \int_{t_0}^{t_f} |a| dt \tag{9}$$

In the above formula (9), a is the acceleration of UCAV, t_0 is the starting time of autonomous attack, and t_f is the time when UCAV captures the target. The acquisition time and energy consumption of PNM and SMC can be obtained respectively, as shown in Table 1

Table 1. Capture Target Time and Energy Consumption

Performance	PNM	SMC
Y	4145	4145
t_f / s	4145	4145

The simulation results show that the SMC method has less acquisition time and less energy consumption, which proves the effectiveness of the control method.

5. Conclusion

By introducing the theory of sliding mode variable structure into the design of guidance law, the guidance problem caused by external interference and parameter perturbation is solved. It improves the stability of the guidance process, enhances the ability of system identification, and weakens the dependence of the guidance law on the model. Finally, the curve of control variable in the process of autonomous attack is obtained by simulation, which verifies the effectiveness of the optimal design of guidance law. Therefore, this design method can solve the problem of UAV guidance and control in complex situation.

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