Sliding mode guidance law for a receiver UAV in the rendezvous phase of autonomous aerial refueling

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ABSTRACT

The rendezvous guidance problem between a receiver unmanned aerial vehicle (UAV) and a virtual tanker was researched. In order to drive elevation angle and azimuth angle of the UAV to satisfy both constraints, two sliding mode guidance laws were designed to control them, respectively. The attitude angle commands were produced by the transformation relationships. The flight control system (FCS) was designed to control the UAV to track the virtual tanker. The FCS was divided into the attitude angles control system and the velocity control system. The attitude angles control system produced the desired fin deflections. The simulation results demonstrate that the designed sliding mode guidance laws and the FCS control the UAV to complete favourably the rendezvous process.

Keywords: Rendezvous guidance, receiver UAV, sliding mode guidance law

1. INTRODUCTION

For unmanned aerial vehicles (UAVs) have some advantages, such as agility, safety, economy, and good ability, they are widely used in both military field and civilian field. Autonomous aerial refueling (AAR) technique can satisfy the long-endurance and long-range requirements of the receiver UAVs, so it has attracted many researchers' interests[1]. The rendezvous phase is an important phase in the process of AAR, and some scholars have studied the rendezvous problem. In this paper the active rendezvous strategy[2] is adopted by the receiver UAV. It is depends on the guidance law and the flight control system that the UAV finishes the rendezvouses process, so the guidance law design is an important task in the rendezvous phase.

Recently some scholars have studied the rendezvous guidance problem of the receiver UAV. The rendezvous strategy was analyzed[3], a nonlinear lateral trajectory tracking guidance law was designed to solve the rendezvous guidance problem, and a trajectory was designed for the UAV to approach the tanker. An iterative computation guidance law was proposed for a receiver UAV[4], and it could get the solution of a control variable for the rendezvous problem. A guidance law based on fractional-order sliding mode control was presented for the receiver UAV[5], which was employed to modify the proportional navigation guidance law, and the resultant guidance law satisfied the terminal angle constraint and the terminal velocity constraint. A guidance algorithm satisfying the tracking of position and velocity was designed in[6], the control law was designed using dynamic inversion, and the simulation results expressed that the control system is capable of guiding the receiver rendezvous with the tanker. It was designed that the modified three-dimensional (3D) proportional navigation guidance law with angle constraint[7], the guidance commands were transformed into the attitude commands with the turn coordination, and the simulation results verified that the guidance law achieved the autonomous rendezvous in the AAR. The 3D path planning and a guidance law were performed for multiple receiver UAVs[8], the rendezvous path included two phases: approach phase and rendezvous phase, and the guidance commands of multiple UAVs were designed by the pure pursuit guidance law. The linear quadratic optimal guidance law was presented for the AAR problem[9], the receiver flied a straight and level trajectory, and the rendezvous task was completed by the tanker aircraft. The receiver UAV's guidance law was designed by dividing terminal angle constraint and speed constraint, and the fast terminal sliding mode control strategy was applied to design the guidance law[10], but there existed the singular problem in the guidance law. A nonlinear rendezvous guidance law was designed for the receiver UAV based on the Lyapunov stability theory[11], and it controlled the receiver UAV to complete favourably the rendezvous process.

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However, the former research achievements in the field of the receiver rendezvous guidance are not enough. It is obvious that the sliding mode guidance law has stronger robustness and faster convergence speed than other conventional guidance laws, besides, it has no the singular problem. Therefore the sliding mode guidance law is adopted for the UAV in the rendezvous phase, in order to meet with the track angle constraint. The remainder of this paper is arranged as follows. The rendezvous guidance problem is described in Section 2. Two sliding mode guidance laws are designed to yield the attitude angle commands in Section 3. In Section 4, the flight control system is designed to yield the desired fin deflections. In Section 5 the simulation results are given and analyzed. Finally, the conclusions are summarized in Section 6.

2. DESCRIPTION OF RENDEZVOUS GUIDANCE PROBLEM

The receiver UAV docks with the drogue, which is dragged by the refueling hose of the tanker[12]. In the rendezvous phase the drogue is treated as a virtual tanker, and its kinematic model is expressed as,

$$\dot{x}_T = V_T \cos\chi_T,\ \dot{y}_T = V_T \sin\chi_T,\ \dot{z}_T = 0 \tag{1}$$

where (x_T, y_T, z_T) is the coordinate of the virtual tanker in the inertial frames, V_T is its velocity, χ_T is its azimuth angle, and its elevation angle is $\gamma_T = 0$. The flight height of the virtual tanker is $h_T = -z_T$.

The UAV's kinematic model is expressed as follows,

$$\dot{x}_U = V_U \cos\gamma_U \cos\chi_U,\ \dot{y}_U = V_U \cos\gamma_U \sin\chi_T,\ \dot{z}_T = -V_U \sin\gamma_U \tag{2}$$

where (x_U, y_U, z_U) is the UAV's coordinate in the inertial frames, V_U is its velocity, γ_U is its elevation angle, and χ_U is its azimuth angle. The UAV's flight height is $h_U = -z_U$.

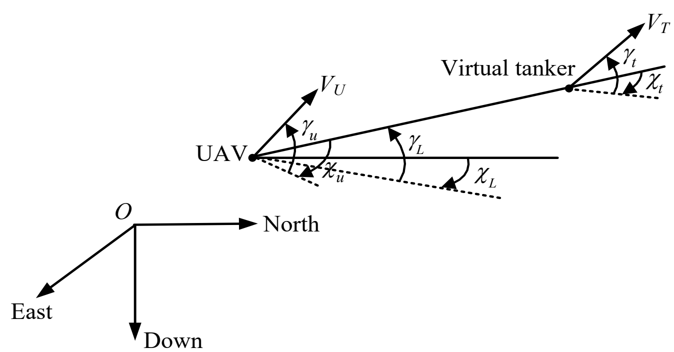

Figure 1. Geometric relationship of the UAV tracking the virtual tanker.

Figure 1 depicts the geometric relationship of the UAV tracking the virtual tanker. The physical meanings of all variables in Figure 1 are explained in[11]. According to Figure 1 and the previous achievements[11, 13], the 3D rendezvous guidance model is described as follows,

$$\dot{R} = V_T \cos\gamma_t \cos\chi_t - V_U \cos\gamma_u \cos\chi_u \tag{3}$$

$$\dot{\chi}_L = (V_T \cos\gamma_t \sin\chi_t - V_U \cos\gamma_u \sin\chi_u)/(R\cos\gamma_L) \tag{4}$$

$$\dot{\gamma}_L = (V_T \sin\gamma_t - V_U \sin\gamma_u)/R \tag{5}$$

$$\dot{\gamma}_t = -\dot{\gamma}_L \cos\chi_t - \dot{\chi}_L \sin\gamma_L \sin\chi_t \tag{6}$$

$$\dot{\chi}_t = \dot{\chi}_L \sin\gamma_L \cos\chi_t \tan\gamma_t - \dot{\chi}_L \cos\gamma_L - \dot{\gamma}_L \sin\chi_t \tan\gamma_t \tag{7}$$

$$\dot{\gamma}_u = \frac{a_{U,n}}{V_U} - \dot{\gamma}_L \cos\chi_u - \dot{\chi}_L \sin\gamma_L \sin\chi_u \tag{8}$$

$$\dot{\chi}_u = \frac{a_{U,l}}{V_U \cos\gamma_u} + \dot{\chi}_L \sin\gamma_L \cos\chi_u \tan\gamma_u - \dot{\chi}_L \cos\gamma_L - \dot{\gamma}_L \sin\chi_u \tan\gamma_u \tag{9}$$

where the physical meanings of all variables are explained in[11]. The following equations are also given in[11],

$$\ddot{\chi}_L = 2\dot{\chi}_L\dot{\gamma}_L \tan\gamma_L - \frac{2\dot{R}}{R}\dot{\chi}_L + \frac{1}{R\cos\gamma_L}\left(a_{U,n}\sin\gamma_u \sin\chi_u - \dot{V}_U \cos\gamma_u \sin\chi_u - a_{U,l}\cos\chi_u\right) \tag{10}$$

$$\ddot{\gamma}_L = -\dot{\chi}_L^2 \sin\gamma_L \cos\gamma_L - \left(2\dot{R}\dot{\gamma}_L + \dot{V}_U \sin\gamma_u + a_{U,n}\cos\gamma_u\right)/R \tag{11}$$

3. DESIGN OF SLIDING MODE GUIDANCE LAW

The active rendezvous scheme requires that the UAV's track angles and velocity are the same as those of the virtual tanker at the rendezvous point. Because the track angles divide into the elevation angle and the azimuth angle, two sliding mode guidance laws are designed to control them, respectively, so as to reach the track angle constraints.

In the longitudinal plane the sliding surface is design as follows,

$$s_{lon} = \dot{\gamma}_L + k_1(\gamma_L - \gamma_{Lf}) \tag{12}$$

where $k_1 > 0$, γ_{Lf} denotes the desired terminal elevation angle of the LOS. When $s_{lon} = 0$, $\dot{\gamma}_L \to 0$, $\gamma_L \to \gamma_{Lf}$, which means that the elevation angle satisfies its constraint in the longitudinal plane.

The derivative of equation (12) is expressed as the following formula, by importing equation (11)

$$\dot{s}_{lon} = \left(k_1 - 2\dot{R}/R\right)\dot{\gamma}_L - \dot{\chi}_L^2 \sin\gamma_L \cos\gamma_L - \left(\dot{V}_U \sin\gamma_u + a_{U,n}\cos\gamma_u\right)/R \tag{13}$$

In order to drive s_{lon} to reach zero in finite time, the following power reaching law is adopted,

$$\dot{s}_{lon} = -k_{s1}\left|s_{lon}\right|^{a_1}\operatorname{sign}(s_{lon}) \tag{14}$$

where $k_{s1} > 0$, $a_1 > 0$, $\operatorname{sign}(s_{lon})$ is the signum function. Combining (13) and (14), the guidance command of the normal acceleration is designed as

$$a_{U,n} = \left[(k_1 R - 2\dot{R})\dot{\gamma}_L - R\dot{\chi}_L^2 \sin\gamma_L \cos\gamma_L - \dot{V}_U \sin\gamma_u + Rk_{s1}\left|s_{lon}\right|^{a_1}\operatorname{sign}(s_{lon})\right]/\cos\gamma_u \tag{15}$$

In the lateral plane the sliding surface is designed as follows,

$$s_{lat} = \dot{\chi}_L + k_2(\chi_L - \chi_{Lf}) \tag{16}$$

where $k_2 > 0$, χ_{Lf} is the desired terminal azimuth angle of the LOS. When $s_{lat} = 0$, $\dot{\chi}_L \to 0$, $\chi_L \to \chi_{Lf}$, which means that the azimuth angle satisfies its restriction in the lateral plane.

The guidance command of the lateral acceleration is designed as, applying the similar design process,

$$\begin{aligned} a_{U,l} = \big[&(k_2 R - 2\dot{R})\dot{\chi}_L \cos\gamma_L + 2R\dot{\gamma}_L\dot{\chi}_L \sin\gamma_L + a_{U,n}\sin\gamma_L \sin\chi_u - \\ &\dot{V}_U \cos\gamma_u \sin\chi_u + k_{s2}R\cos\gamma_L\left|s_{lat}\right|^{a_2}\operatorname{sign}(s_{lat})\big]/\cos\chi_u \end{aligned} \tag{17}$$

where $k_{s2} > 0$, $a_2 > 0$. Since the UAV's attitude angle commands are the actual input commands of the flight control system, we take the following transformation,

$$\alpha_d = \frac{m a_{U,n} - T\sin\alpha + mg\cos\gamma_U}{QSC_{L\alpha}} - \frac{1}{C_{L\alpha}}\left[C_{L0} + C_{Lq} q\frac{c}{2V_U} + C_{L\delta}\delta_e\right] - \alpha_0 \tag{18}$$

$$\beta_d = 0 \tag{19}$$

$$\phi_d = \arctan\left[a_{U,l}/(a_{U,n} + g\cos\gamma_U)\right] \tag{20}$$

4. FLIGHT CONTROL SYSTEM DESIGN

The above commands α_d, β_d and ϕ_d are the input signals of the flight control system. The flight control system produces the desired fin deflections, so as to control the UAV's trajectory in the rendezvous process. The flight control system is divided into the attitude angles control system and the velocity control system. The attitude angles include three angles: the pitch angle, the yaw angle, and the roll angle, accordingly, the attitude angles control system divides into three control subsystems. We apply the sliding mode control method to design three control subsystems, respectively.

The pitch angle control subsystem is designed firstly. Its control objective is to control the pitch angle to converge to its command, i.e., $\theta \to \theta_d$. According to the angle geometric relationship, the pitch angle is expressed as follows,

$$\theta = \alpha + \gamma_U \tag{21}$$

From $a_{U,n} = V_U\,\dot{\gamma}_U$, we get

$$\gamma_U = \int_0^t \dot{\gamma}_U d\tau = \int_0^t a_{U,n}/V_U\, d\tau \tag{22}$$

Therefore, the desired command of the UAV's pitch angle is expressed as follows,

$$\theta_d = \alpha_d + \int_0^t a_{U,n}/V_U\, d\tau \tag{23}$$

The pitch dynamics is depicted as follows, from the reference[11],

$$\begin{cases} \dot{\theta} = q\cos\phi - r\sin\phi \\ \dot{q} = c_5 pr - c_6(p^2 - r^2) + c_7 QSc\left[C_{M0} + C_{M\alpha}\alpha + C_{Mq}\, cq/(2V_U) + C_{M\delta_e}\delta_e\right] \end{cases} \tag{24}$$

For the pitch angle control subsystem, the sliding surface is designed as follows,

$$s_p = q + k_p(\theta - \theta_d) \tag{25}$$

where $k_p > 0$. The control objective can be achieved by applying the following power reaching law,

$$\dot{s}_p = -k_{sp}\left|s_p\right|^{a_3}\operatorname{sign}(s_p) \tag{26}$$

where $k_{sp} > 0$, $a_3 > 0$, and thus the desired elevator deflection is designed as,

$$\delta_e = \frac{-1}{c_7 QScC_{M\delta_e}}\left[c_5 pr - c_6(p^2 - r^2) + k_p(\dot{\theta} - \dot{\theta}_d) + k_{sp}\left|s_p\right|^{a_3}\operatorname{sign}(s_p)\right] - \frac{1}{C_{M\delta_e}}\left(C_{M0} + C_{M\alpha}\alpha + C_{Mq} q\frac{c}{2V_U}\right) \tag{27}$$

The control objective of the yaw angle control subsystem is to control the sideslip angle to converge to its command, i.e., $\beta \to \beta_d$, but the yaw angle doesn't be controlled. The desired rudder deflection is also designed by applying the similar design process.

The control objective of the roll angle control subsystem is to control the roll angle to converge to its command, i.e., $\phi \to \phi_d$, and the desired aileron deflection is also designed by applying the similar design process.

The control objective of the velocity control system is to drive the UAV's velocity to converge to the virtual tanker's velocity, and its design process is the same as that of the reference[11].

5. NUMERICAL SIMULATION

In this section, the numerical simulation is carried out to realize the receiver UAV's rendezvous phase. The simulation model is built by the MATLAB R2010b software. In the simulation the initial position, velocity, and angles of the virtual tanker are set as, respectively, $x_T = 8000\text{m}$, $y_T = 2000\text{m}$, $h_T = 4800\text{m}$, $V_T = 180\text{m/s}$, $\gamma_T = 0$, $\chi_T = 0$, and those of the UAV are set as, respectively, $x_U = 0$, $y_U = 0$ $h_U = 3800\text{m}$, $V_U = 220\text{m/s}$, $\gamma_U = 0$, $\chi_U = 0$. Through several adjustments, we chose the guidance parameters and control parameters as follows, respectively, $k_1 = 0.2$, $k_{s1} = 0.015$, $a_1 = 0.5$, $k_2 = 0.2$, $k_{s2} = 0.02$, $a_2 = 0.5$, $k_p = 0.6$, $k_{sp} = 2.5$, $a_3 = 0.5$, $k_y = 0.8$, $k_{sy} = 1.7$, $a_4 = 0.5$, $k_r = 1.5$, $k_{sr} = 3.5$, $a_5 = 0.5$. The simulation results are shown in Figures 2-5.

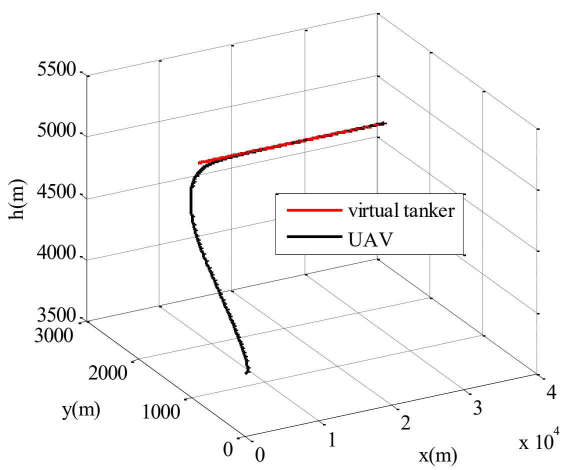

Figure 2. Trajectories of the UAV and the virtual tanker.

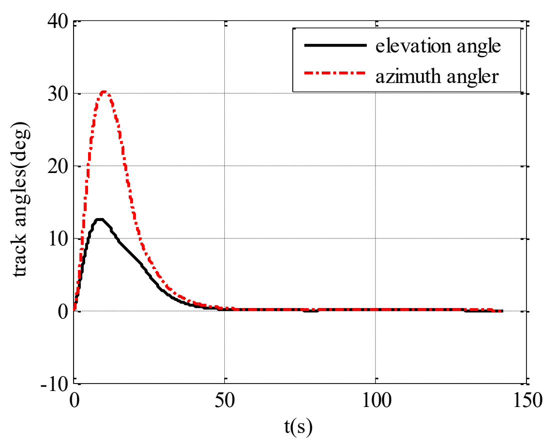

Figure 3. Curves of two track angles.

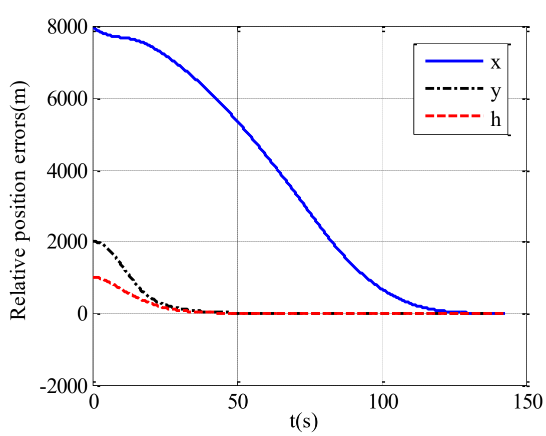

Figure 4. The relative position errors in three directions.

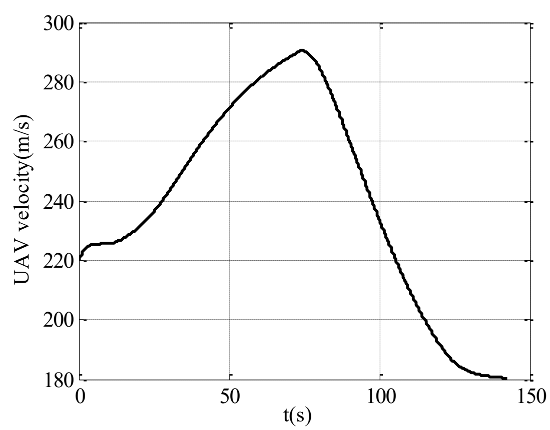

Figure 5. The UAV's velocity curve.

Figure 2 shows the UAV's trajectory and the virtual tanker's trajectory, and the two trajectories come together finally. Figure 3 describes the varying processes of two track angles of the UAV, in which the two angles of the UAV converge to those of the virtual tanker after 72.5s. Figure 4 draws the attenuation curves of the UAV's relative position errors in three directions, respectively. In Figure 4, both the y-direction position error and the h-direction (height) error converge to zero at 72.5s, and the x-direction position error converges to zero at 142.6s. Figure 5 describes the UAV's velocity varying curve in the rendezvous process, in which the UAV accelerates in the first 74.5s, and then it slows down, finally it reaches the similar velocity to the virtual tanker at 142.6s. The UAV completes the rendezvous task at 142.6s, so the simulation process ends at 142.6s.

6. CONCLUSIONS

In this paper the rendezvous phase in the AAR is researched. The 3D rendezvous guidance model is described as the mathematical equations. Two sliding mode guidance laws are designed to control the UAV's elevation angle and azimuth angle, respectively, which can satisfy the track angle constraints at the rendezvous point. Besides, the sliding mode control method is applied to design the UAV's three control subsystems, respectively, which produces three desired fin deflections to control the UAV's trajectory in the rendezvous process. The simulation results demonstrate that the designed rendezvous guidance law and the flight control system can control the UAV to complete favorably the rendezvous process. In the following work we will research the UAV's docking control system in AAR.

REFERENCES

[1] Liu, Y., Wang, H. and Fan, J., "Novel docking controller for autonomous aerial refueling with probe direct control and learning-based preview method," Aerospace Science and Technology, 94, 105403(2019).

[2] Mao, W., and Eke, F. O., "A survey of the dynamics and control of aircraft during aerial refueling," Nonlinear Dynamics and Systems Theory, 8, 375-388(2018).

[3] Xu, W., Luo, D., Yang, L. and Wu, S., "Guidance law research for autonomous aerial refueling of UAV," Proc. Int. Conf. on Cyber Technology in Automation, Control and Intelligent Systems, 440-445(2013).

[4] Luo, D., Xie, R. and Duan, H., "A guidance law for UAV autonomous aerial refueling based on the iterative computation method," Chinese Journal of Aeronautics, 27(4), 875-883(2014).

[5] Qu, Y., Yu, Z. and Zhang, Y., "Fractional-order sliding mode guidance control for rendezvous of unmanned aerial vehicles during air refueling," Control Theory & Applications, 32(11), 1464-1469(2015).

[6] Yuan, S., Gong, Q. and Zhang, J., "Guidance and control of autonomous aerial refueling rendezvous and docking," Science Technology and Engineering, 15(8), 238-243(2015).

[7] Wang, J., Zhang, T. and Li, L., "Guidance and control of UAV autonomous rendezvous in aerial refueling," Flight Dynamics, 35(2), 39-43(2017).

[8] Yoon, Y., Kim, M. and Kim, Y., "Three-dimensional path planning for aerial refueling between one tanker and multiple UAVs," International Journal of Aeronautical and Space Sciences, 19, 1027-1040(2018).

[9] Tsukerman, A., Weiss, M., Shima, T., Löbl, D. and Holzapfel, F., "Optimal rendezvous guidance laws with application to civil autonomous aerial refueling," Journal of Guidance Control and Dynamics, 41, 1164-1174(2018).

[10] Zhao, W., Duan, Y., Yu Z, Qu, Y., Zhang, Y., "Integrated guidance and control for autonomous rendezvous of unmanned aerial vehicle during aerial refueling," Proc. Int. Conf. on Unmanned Aircraft Systems, 814-820(2021).

[11] Zhao, H., Zhao, J. and Xu, H., "Nonlinear rendezvous guidance law design for a receiver UAV based on the Lyapunov stability theory," Journal of Physics: Conference Series, 2296, 012029(2021).

[12] Su, Z., Wang, H., Li, N., Yu, Y. and Wu, J., "Exact docking flight controller for AAR with back-stepping based high order sliding mode," Mechanical Systems and Signal Processing, 101, 338-360(2018).

[13] Zhao, H., Qi, Q. and Zhang, W., "Three-dimensional extended propotional navigation guidance law of anti-warship missile's large-airspace varying trajectory," Command, Control & Simulation, 35(1), 102-105(2013).