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Safe control of trailing UAV in close formation flight against actuator fault and wake vortex effect ☆

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A B S T R A C T

In the close formation flight, the wake vortex induced by the leading aircraft will have adverse effects on the safe flight of the trailing unmanned aerial vehicle (UAV). Hence, this paper investigates a difficult problem of safe control for the trailing UAV against actuator faults, input saturation, and wake vortex effect. By using disturbance observers, external wake vortex, disturbances, and internal actuator faults are estimated. Then, with the help of estimated knowledge of disturbance, backstepping control laws are developed for the longitudinal dynamics and the lateral-directional dynamics, respectively. One of the key features of the proposed strategy is that, the inherent problem, i.e., "explosion of complexity" in conventional backstepping control, is solved by the presented dynamic surface control scheme. Another key feature is that external wake vortex, disturbances, and internal actuator faults, input saturation are simultaneously considered. It is shown by Lyapunov stability analysis that the closed-loop system is uniformly ultimately bounded with safety requirements guaranteed even in the presence of wake vortex and actuator faults. The effectiveness of the proposed approach is further validated by simulation results.

1. Introduction

In recent years, close formation flight has attracted more and more consideration in the aerospace community [1–3]. Its potential benefits include energy saving [4], improved aircraft coordination in increasingly crowed airspace [5], and mixed operations of unmanned aerial vehicle (UAV) and manned aircraft [6]. Due to these advantages, close formation flight has been widely used in many fields, such as swarm operations [7], autonomous aerial refueling (AAR) [8], fire monitoring and detection [9]. When the close formation of UAVs is utilized, the fire spot has a higher probability to be detected in the forest fire monitoring by sharing the information [9]. Moreover, AAR is a typical application of close formation flight of UAVs [8,10]. In AAR, the trailing UAV first flies to the region behind the leading aircraft (tanker), then keeps the close formation flight with the leading aircraft, and waits for the leading aircraft to transfer the fuel to the trailing UAV. In such safety-critical applications involving close formation flight, safe requirement is essential for both task execution and UAV itself since the performance degradations induced by the external wake vortex, disturbances, and internal actuator saturation, faults, may cause catastrophic consequences (collisions).

Although there are many control approaches available for the close formation flight of UAVs, this problem is still open. One of the challenges is the accurate control of relative position between the leading vehicle and the trailing vehicle in the presence of wake vortex [11]. Actually, wake vortex may have adverse influence on the safe flight of the trailing UAV. On September 28, 2004, an F/A-22 suffered a Class-A mishap near Edwards Air Force Base during an air-to-air tracking flight for a F-16. The accident was due to the wake vortex generated by the leading F-16. It led the F/A-22 to exceed both angle of attack and structural limits [12]. Without loss of generality, the wake vortex can be viewed as an external disturbance. At present, many control strategies have been proposed for the close formation flight of UAVs with such disturbance accommodation [13,14]. It should be noted that although above referred efforts, only few literatures investigate the wake vortex acting on the trailing UAV in the controller design. In [15], a $\mathcal{L}_1$ neural network-based adaptive control approach was developed for AAR. The uncertainties caused by the wake vortex were compensated by an adaptive control scheme. [16] proposed a formation controller by using backstepping technique and an uncertainty/disturbance estimator was then incorporated to enhance the robustness of the formation controller. As an active and effective method

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Nomenclature

ρ	air density
$\bar{q}$	dynamic pressure
m, g	mass of the trailing UAV and acceleration due to gravity
I_x, I_y, I_z, I_{xz}	moments of inertia about x, y, z axes and cross-product of inertia
s_t, b_t, c_t	reference wing area, wing span, mean aerodynamic chord of the trailing UAV
ζ_{t1}, ζ_{t2}	dihedral angle, sweepback angle at quarter-chord of the trailing UAV
L_F, D_F	length and height of the trailing UAV fuselage
$X_L Y_L Z_L$	leading aircraft's body-fixed frame
XYZ	trailing UAV's body-fixed frame
x, y, z	coordinates of the trailing UAV in the leading aircraft's body-fixed frame
V, β, α	velocity, sideslip angle, and angle of attack of the trailing UAV
ϕ, θ, ψ	roll, pitch, and yaw angles of the trailing UAV
p, q, r	roll, pitch, and yaw rates of the trailing UAV
T, D, S_y	thrust, drag, and side forces of the trailing UAV
$\mathcal{L}$, $\mathcal{M}$, $\mathcal{N}$	roll, pitch, and yaw moments of the trailing UAV
w_x, w_y, w_z	vortex-induced velocities expressed in the trailing UAV's body-fixed frame
p_w, q_w, r_w	vortex-induced angular velocities expressed in the trailing UAV's body-fixed frame
δ_a, δ_e, δ_r	aileron, elevator, and rudder deflections
$\delta_{a_{max}}$, $\delta_{a_{min}}$	maximum, minimum aileron deflections
$\delta_{e_{max}}$, $\delta_{e_{min}}$	maximum, minimum elevator deflections
$\delta_{r_{max}}$, $\delta_{r_{min}}$	maximum, minimum rudder deflections
δ_T	instantaneous thrust throttle setting
$\delta_{T_{max}}$, $\delta_{T_{min}}$	maximum, minimum thrust throttle settings
C_{D0}, $C_{D\alpha^2}$	coefficient to drag, coefficient of α^2 to drag
C_{Y0}, $C_{Y\beta}$	coefficient to side force, coefficient of β to side force
C_{L0}, $C_{L\alpha}$	coefficient to lift force, coefficient of α to lift force
C_{l0}, $C_{l\beta}$	coefficient to roll moment, coefficient of β to roll moment
C_{lp}, C_{lr}	coefficients of p, r to roll moment
$C_{l\delta_a}$, $C_{l\delta_r}$, C_{M0}	coefficients of δ_a, δ_r to roll moment, coefficient to pitch moment
$C_{M\alpha}$, C_{Mq}, C_{Mq}^0	coefficients of α, q to pitch moment, coefficient to C_{Mq}
C_{Mq}^{α}, $C_{Mq}^{\alpha^2}$, $C_{Mq}^{\alpha^3}$	coefficients of α, α^2 to C_{Mq}, coefficient of α^3 to C_{Mq}
$C_{M\delta_e}$, C_{n0}, $C_{n\beta}$	coefficient of δ_e to pitch moment, coefficient to C_n, coefficient of β to C_n
C_{np}, C_{nr}, $C_{n\delta_a}$	coefficients of p, r, δ_a to C_n
$C_{n\delta_r}$, C_{LL}, V_{L0}	coefficient of δ_r to C_n, lift coefficient and velocity of the leading aircraft
b_L, c_L	wing span and mean aerodynamic chord of the leading aircraft
d_1, d_2, d_3, d_4	external disturbances

to reject external disturbances, disturbance observer technique has received significant attention and has been successfully applied to numerous flight control problems, such as hypersonic vehicle [17], small-scale helicopter [18], and transport aircraft [19].

In engineering systems, the internal input saturation is often encountered due to structural limits, which can cause system instability and performance degradation if the saturation is not taken into account in the early design of the controller [20–23]. To handle the input saturation and stabilize the system in the presence of input saturation, auxiliary dynamic signals are constructed to compensate the input saturation [24,25]. Recently, the input saturation was addressed in [26] by the combination of dynamic surface control (DSC) strategy and auxiliary dynamic system. Moreover, it is also significant to guarantee an acceptable system performance when the system is encountered by internal actuator faults since the faults may cause system performance deterioration and instability if the internal faults are not timely handled [27–30]. Despite the fact that numerous results have been obtained for the fault-tolerant control (FTC) design of single UAV [31–33], and fault-tolerant cooperative control (FTCC) of multiple UAVs [34,35], only a few literatures are concentrated on the FTC design for UAVs in the close formation flight. Recently, a fault-tolerant structured adaptive model inversion tracking controller was proposed in [36] for AAR by integrating visual navigation vision-based sensor system. Therefore, to further enhance the flight safety in the close formation flight, more investigations should be conducted to propose new and effective control schemes for UAVs.

It should be noted that the safe requirement will becomes increasingly essential when the trailing UAV simultaneously encounters wake vortex and actuator fault. Unfortunately, to the best of authors' knowledge, few results are reported on the fault-tolerant control for the close formation flight of UAVs under external wake vortex, disturbances, internal actuator fault, and input saturation. Motivated by solving this challenging problem, this paper has designed a new fault-tolerant close formation control approach for the trailing UAV. The proposed scheme is designed by the combination of backstepping control method and disturbance observer technique. To be more specific, in the proposed control scheme, the nonlinear disturbance observer is first employed to estimate the lumped uncertainties, which consists of external wake vortex, disturbances, and internal actuator faults. Then, auxiliary dynamic signals are constructed to compensate the adverse effects caused by the internal input saturation. Finally, backstepping method is used to obtain the control signals with the estimated lumped disturbance including wake vortex, disturbances, and actuator faults. To eliminate the inherent problem of "explosion of complexity" in backstepping control [37], dynamic surface control is incorporated into the backstepping architecture. The main contributions of this paper are listed as follows:

1. To the best of authors' knowledge, the proposed approach might be the first result to achieve fault-tolerant close formation flight with external wake vortex, disturbance, internal actuator fault, and input saturation addressed simultaneously. Moreover, the proposed control scheme can be applied to AAR directly.
2. Different from [14], in which the controller does not utilize the information of wake vortex caused by the leading aircraft, the effects of external wake vortex, disturbance, and internal actuator fault on the trailing UAV are explicitly considered through the disturbance observer in this paper. Compared with [8], which investigates the anti-disturbance flight controller for AAR, this paper further solves the safe control problem for the trailing UAV in the presence of actuator faults.
3. In contrast to the fault-tolerant control design in [36], to ensure the flight safety, the input saturation of the faulty UAV is further considered by constructing the auxiliary system in the controller design.
4. With comparative simulations, it can find out that the lumped uncertainties including external disturbances, wake vortex, and

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