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Fuzzy adaptive tracking control within the full envelope for an unmanned aerial vehicle

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Abstract Motivated by the autopilot of an unmanned aerial vehicle (UAV) with a wide flight envelope span experiencing large parametric variations in the presence of uncertainties, a fuzzy adaptive tracking controller (FATC) is proposed. The controller consists of a fuzzy baseline controller and an adaptive increment, and the main highlight is that the fuzzy baseline controller and adaptation laws are both based on the fuzzy multiple Lyapunov function approach, which helps to reduce the conservatism for the large envelope and guarantees satisfactory tracking performances with strong robustness simultaneously within the whole envelope. The constraint condition of the fuzzy baseline controller is provided in the form of linear matrix inequality (LMI), and it specifies the satisfactory tracking performances in the absence of uncertainties. The adaptive increment ensures the uniformly ultimately bounded (UUB) predication errors to recover satisfactory responses in the presence of uncertainties. Simulation results show that the proposed controller helps to achieve high-accuracy tracking of airspeed and altitude desirable commands with strong robustness to uncertainties throughout the entire flight envelope.

1. Introduction

As the development of modern UAVs, the flight envelope is expanded constantly. Flight control confronts the challenge of high-precision tracking of desirable instruments with strong robustness for the entire flight envelope. A UAV is a multi-input, multi-output nonlinear system with strong coupling, and the aerodynamic forces and moments for the kinetics depend not only on the dynamic pressure but also on the force and moment coefficients as a function of aerodynamic derivatives. The engine thrust, dynamic pressure, and aerodynamic derivatives vary significantly along with the changes of Mach number and altitude, especially during a transonic flight. Therefore, the operating and stability characteristics of a UAV at different operating points vary remarkably.[1] In addition, undesirable uncertainties intensify the difficulty due to modeling errors, parametric perturbations, and control efficiency failures within the full envelope.

Although local model based robust control,[2] adaptive dynamic inversion control,[3] and L1 adaptive control[4] enhance performances, they are not applicable for a flight over a large envelope. The interpolation of local linearization-based

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controllers in terms of flight condition is widely applied in engineering, but stability could not be guaranteed.[1] The gap metric[5] and guardian maps[6] approaches extend stability to the entire envelope iteratively, but the processes are time-consuming.

The linear parameter varying (LPV) control is a popular gain-scheduling approach for a large envelope. However, the conservatism of the common Lyapunov method based robust[7] or adaptive controllers[8,9] may lead to no feasible solution for desired performances. To relax the conservatism, Huang et al.[10] provided switching the LPV robust controller using multiple Lyapunov functions for air-breathing hypersonic vehicles, while Lu et al.[11] switched the LPV controller using hysteresis and average dwell time logics respectively. However, higher computational complexities emerge and they ensure robustness at the price of response performances. Hou et al.[12,13] enhanced the response performances with the adaptive increment, but dwell time restricts the arbitrary switching and switching dynamics may cause underlying damages.

The fuzzy control is also an attractive alternative for robust control within a full envelope.[14] The generalized fuzzy hybrid controllers blend the common Lyapunov function with $H\infty$,[15] the sliding mode,[16] or MRAC,[17] and they degrade control performances due to the conservatism. To reduce the conservatism, Feng[18] proposed a piecewise Lyapunov function based fuzzy $H\infty$ controller, but the switching dynamics could not be avoided. The fuzzy multiple Lyapunov functions can reduce the control conservatism with the advantage of a continuity feature,[19] and Bouarar et al.[20] reduced computational complexity by adopting the descriptor system approach, yet the local $H\infty$ controller guarantees robustness at the cost of response performances.[21] Although Wu and Juang[22] employed a fuzzy adaptive sliding-mode controller to relax the cost of response for robustness, chattering emerges owing to the discontinuous control signals across the sliding surfaces.

Based on the above analysis, a fuzzy multiple Lyapunov function based tracking controller augmenting a fuzzy baseline controller with an adaptive increment is proposed. The key breakthroughs can be concluded as follows:

(1) The conservatism of the fuzzy baseline controller and the adaptation law for the entire flight envelope is relaxed by employing the fuzzy multiple Lyapunov method.
(2) The computational complexity of LMI for the fuzzy baseline controller is reduced by using the descriptor system approach.
(3) The controller provides smooth control signals throughout the flight envelope.

2. Problem formation

2.1. Nonlinear kinetic model

The flight envelope[23] of a UAV refers to the capabilities of operating ranges in terms of Mach number and altitude. For a fix-wing UAV, the flight envelope is restricted by the stalling angle, service ceiling, maximum march, maximum dynamic pressure, performances of the engine, etc.

The original nonlinear model[23,24] in the path coordinate frame can be constructed as

$$\begin{cases} \dot{V}_{\mathrm{T}} = (T\cos(\alpha+\varphi) - D - mg\sin\gamma)/m \\ \dot{\gamma} = (T\sin(\alpha+\varphi) + L - mg\cos\gamma)/(mV_{\mathrm{T}}) \\ \dot{q} = M/J_z \\ \dot{\theta} = q \\ \alpha = \theta - \gamma \\ \dot{H} = V_{\mathrm{T}}\sin\gamma \end{cases} \tag{1}$$

where V_{T}, α, q, θ, γ and H are the airspeed, angle of attack, pitch rate, pitch angle, path angle, and altitude, respectively; φ is the angle of the thrust line; m is the mass; g is the gravitational constant; J_z is the pitch moment of inertia; T, L, D and M are the engine thrust, lift, drag, and pitch moment[24] expressed as

$$\begin{cases} T = P(\delta_{\mathrm{th}}, Ma, H) \\ L = \bar{q}SC_L \\ D = \bar{q}SC_D \\ M = \bar{q}S\bar{c}C_M - e_{\mathrm{p}}T \end{cases} \tag{2}$$

with $P(\cdot)$ the thrust curve; δ_{th} the throttle setting; Ma the Mach number; S, $\bar{c}$ and e_{p} the wing area, wing mean geometric chord, and thrust eccentricity; $\bar{q} = 0.5\rho(H)V_{\mathrm{T}}^2$ the dynamic pressure, and $\rho(H) = 1.225\ (1 - H/44331)^{4.25588}$ the air density; and C_L,C_D, C_M the lift, drag, and pitching moment coefficients defined by

$$\begin{cases} C_L = C_{L\alpha}Ma(\alpha - \underline{\alpha}) + C_{L\delta_{\mathrm{e}}}Ma\delta_{\mathrm{e}} \\ C_D = AMaC_L^2 + C_{D0}Ma \\ C_M = C_{M0}Ma + \left(x_{\mathrm{cgR}} - x_{\mathrm{caR}}Ma\right)C_L \\ \qquad + C_{M\delta_{\mathrm{e}}}Ma\delta_{\mathrm{e}} + \dfrac{C_{Mq}Maq\bar{c}}{V_{\mathrm{T}}} + \dfrac{C_{M\dot{\alpha}}Ma\dot{\alpha}\bar{c}}{V_{\mathrm{T}}} \end{cases} \tag{3}$$

where $\underline{\alpha}$ is the zero lift angle; δ_{e} is the elevator deflections; $\dot{\alpha}$ is the derivative of the angle of attack; $C_{L\alpha}, C_{L\delta_{\mathrm{e}}}, A, C_{D0}, C_{M0}, C_{M\delta_{\mathrm{e}}}, C_{Mq}$, and $C_{M\dot{\alpha}}$ are the aerodynamic derivatives; and x_{cgR} x_{caR} are the reference locations of the gravity and aerodynamic centers.

The relationship between the flight of a UAV over a large envelope and the nonlinear kinetics can be illustrated in Fig. 1. As shown in Fig. 1, the thrust and aerodynamic derivatives connect the operating points in the flight envelope with the forces and moments in the nonlinear model. The natural frequency and damp of short-period and phugoid-period vary remarkably along with airspeed, altitude, dynamic pressure, and aerodynamic derivatives.[24] Hence, we can use the Mach number and the altitude as the premise variables to distinguish the natural characteristics of the UAV over a large flight envelope.[1]

2.2. Fuzzy T–S model

As the fuzzy system with the Gaussian membership function has been shown to realize the universal approximation of any nonlinear functions on the considered compact set,[25] the nonlinear model of Eq. (1) can be transformed to an uncertain fuzzy T–S system as