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Robust constrained autopilot control for a generic missile in the presence of state and input constraints

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ABSTRACT

A robust constrained autopilot control is addressed for a generic missile subject to angle of attack constraint, actuator nonlinearities and matched and mismatched uncertainties by utilizing integral barrier Lyapunov functional (IBLF) technique and dynamic surface control (DSC). Comparing with the existing IBLF-based literatures, the exploited methodology not only ensures the state constraint satisfaction, but also tackles the actuator limitations which include magnitude, rate and width constraints by introducing an auxiliary compensation design. For the problem of matched and mismatched uncertainties, an extended state observer (ESO) is explicitly utilized. Rigorous proofs are derived to demonstrate that the constrained state remains in its compact set and the closed-loop system achieves uniform ultimately bounded stability. Finally, Simulation results are performed to verify the effectiveness of the proposed approach.

1. Introduction

Owing to the broad flight envelope, wide variation in parameters coupled with highly nonlinear dynamics, multi-constraints and external disturbances, the autopilot design for modern agile missile is still a challenging issue. In the past decades, numerous autopilot controls have been exploited in the existing literatures. For instance, classical gain-scheduling (GS) design [1–3], sliding mode control (SMC) method [4–6], backstepping-based control approach [7–9]. Although the desired missile control performance can be achieved by the aforementioned methods, constraints (i.e. magnitude, bandwidth and rate limitations on states and actuators) imposed on missile dynamics are rarely taken into account.

Actuator constrained issue has been widely researched since the inherent magnitude, rate and width limitations on actuators may lead to control performance degradation or even unstable of system in recent years. Anti-windup (AW) control is a feasible approach to handle actuator saturation and it has already been studied for hypersonic vehicle model control with input constraints [10–12]. However, the stability of closed-loop system is difficult to theoretically analyze. In addition, Wen and Zhou in [13] have introduced a Nussbaum-type function based robust adaptive control algorithm to compensate the nonlinear term arising from the input saturation. Command filter backstepping scheme (CFBS) [14] is another effective technique which derived for systems subject to magnitude, rate, and bandwidth constraints on actuators and intermediate states. Moreover, the CFBS scheme has been successfully developed to unmanned air vehicles constrained control [15], and hypersonic flight vehicle with actuator constraints [16,17].

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State constraint on flight vehicle is another intractable issue which caused by safety or performance restrictions (i.e. temperature, displacement of sensor locations et al.) needs to be urgently addressed. MPC is a promising approach that deals with the problem by an optimization paradigm inherently suitable for handling state constraints [18–20]. The predictive controller [20] combined with extended state observer is derived to maintain robustness and constraints satisfaction. However, these approaches depend heavily on computation for nonlinear control systems. Later, predictive functional control (PFC) design is proposed for fast processing [21–23]. For instance, Tang et al. [21] have proposed a PFC-based autopilot design to deal with various constraints. However, the control performance may be degraded in the presence of strong disturbances and uncertainties due to the lack of uncertainty rejection mechanism.

Integral Barrier Lyapunov function (IBLF) approach in [24] is proposed to simultaneously achieve tracking performance and satisfy state constraints imposed on system in recent years. It overcomes the conservatism of feasibility conditions comparing with the traditional BLF-based methodologies. In addition, IBLF-based methodologies have been widely applied in flexible mechanical systems [25], nonlinear systems with full state constraints [26], guidance control issue with filed-of-view constraint [27], flexible crane system with output constraint [28]. However, the state/output constraint is satisfied on condition that the control input is sufficient.

In this paper, a novel robust autopilot design is proposed which can simultaneously deals with angle of attack constraint, actuator nonlinearities, matched and mismatched uncertainties. Dynamic surface control method combining with integral barrier Lyapunov function (IBLF) technique is synthesized to achieve the required tracking performance and constraints satisfaction. In addition, ESO is proposed to compensate matched and mismatched uncertainties. Motivated by Farrell et al. [14], auxiliary error compensation is introduced to deal with the actuator nonlinearities in the control design. Ultimately bounded stability is guaranteed even when the actuator saturation is in effect.

The mainly contributions of this paper is summarized as follows:

1) Comparing with the existing IBLF based methodologies, both the state constraint and actuator limitations are taken into account in the proposed control scheme which achieves state constraint satisfaction and uniform ultimately bounded stability of the closed-loop signals. In addition, the problem of explosion of complexity is avoided by utilizing the DSC technique.
2) By employing the auxiliary compensation design, the effects of actuator constraints (i.e. magnitude, rate, et al.) imposed on missile control system is effectively eliminated. Moreover, the stability of closed-loop control system is rigorously analyzed and guaranteed even when actuator constraints occur.

The reminder of this work is following: In Section 2, the missile dynamic model and some preliminaries are formulated. Then constrained autopilot design and stability analysis are presented in Section 3. Subsequently, numerical simulations are carried out to demonstrate the effectiveness of the proposed method. Conclusions are drawn in the last section.

2. Problem formulations

The longitudinal model of a generic missile in [29] is described as follows:

$$\begin{cases} \dot{\alpha} = \cos(\alpha) K_\alpha M C_n(\alpha, \delta, M) + q \\ \dot{q} = K_q M^2 C_m(\alpha, \delta, M) \end{cases} \tag{1}$$

where α, q, M, δ are the angle of attack (rad), pitch rate (rad/s), mach number and fin deflection angle respectively. K_α, K_q are two known constants. The nominal force and pitch moment aerodynamic coefficients C_n, C_m are following:

$$\begin{cases} C_n(\alpha, \delta, M) = a_n\alpha^3 + b_n|\alpha|\alpha + c_n(2 - M/3)\alpha + d_n\delta \\ C_m(\alpha, \delta, M) = a_m\alpha^3 + b_m|\alpha|\alpha + c_m(-7 + 8M/3)\alpha + d_m\delta \end{cases} \tag{2}$$

where a_n, b_n, c_n, d_n, a_m, b_m, c_m, d_m are aerodynamic coefficients.

Remark 1. As is well known, the control surfaces are primarily moment-producing devices thus, their contribution in the force equation can be neglected [20,30], where $d_n = 0$. Since the aerodynamic coefficients in (2) are nonlinear functions with respect to α and the change of α may severely affect the control performance and flight safety. Therefore, α must be strictly constrained in the specified region. In this paper, we require that $|\alpha| < 8^\circ$.

Remark 2. The missile tailfin actuator model in [21] is described in Fig. 1. It is clear that the model is highly nonlinear with magnitude and rate limits, i.e. $-\delta_{\max} \le \delta(t) \le \delta_{\max}$, $-\dot{\delta}_{\max} \le \dot{\delta}(t) \le \dot{\delta}_{\max}$, where $\delta_{\max}$, $\dot{\delta}_{\max}$ are the known bounds of $\delta(t)$ and $\dot{\delta}(t)$ respectively.

When saturations do not occur, the missile tailfin actuator model can be described as follows:

$$\ddot{\delta}(t) = -\omega_n^2\delta(t) - 2\omega_n\zeta\dot{\delta}(t) + \omega_n^2\delta_c(t) \tag{3}$$

where ω_n is actuator natural frequency, and ζ is actuator damping ratio. δ_c denotes ideal fin deflection angle.