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Robust partial integrated guidance and control for missiles via extended state observer

Qing Wang [a], Maopeng Ran [a,*], Chaoyang Dong [b]

[a] School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China
[b] School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China

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ABSTRACT

A novel extended state observer (ESO) based control is proposed for a class of nonlinear systems subject to multiple uncertainties, and then applied to partial integrated guidance and control (PIGC) design for a missile. The proposed control strategy incorporates both an ESO and an adaptive sliding mode control law. The multiple uncertainties are treated as an extended state of the plant, and then estimate them using the ESO and compensate for them in the control action, in real time. Based on the output of the ESO, the resulting adaptive sliding mode control law is inherently continuous and differentiable. Strict proof is given to show that the estimation error of the ESO can be arbitrarily small in a finite time. In addition, the adaptive sliding mode control law can achieve finite time convergence to a neighborhood of the origin, and the accurate expression of the convergent region is given. Finally, simulations are conducted on the planar missile–target engagement geometry. The effectiveness of the proposed control strategy in enhanced interception performance and improved robustness against multiple uncertainties are demonstrated.

1. Introduction

Classical missile guidance and control loops are designed separately due to the assumption that there is a spectral separation between the two loops. For its simplicity in theoretical analysis and engineering implementation, this paradigm has received much attention in academia and industry, and many effective methods can be applied [1–4]. However, in the end-game phase of the interception the spectral separation may not be valid, especially in the case that the target performs a large maneuver. The integrated guidance and control (IGC) design is a potential solution candidate to solve this problem. The basic idea of the IGC design is to view the guidance dynamics and the control dynamics as an integrated system and account for the coupling between the two loops directly during the design process. The IGC design has the potential of improving the interception performance, and many control techniques have been successfully adopted, such as θ-D method [5], numerical state-dependent Riccati equation approach [6], sliding mode control (SMC) [7], small-gain theorem [8], model predictive control [9], and fuzzy control [10]. However, it has now realized that the IGC design cannot fully exploit the inherent time scale separation that exists in aerospace vehicles between rotational and translational motions [11]. Specifically, since in general the rotational dynamics are much faster than the translational dynamics, and the IGC design generates the control surface deflections directly from the translational error correction demands, the rotational dynamics are likely to be unstable.

Considering the deficiencies of the classical design and the IGC design, a novel so-called partial integrated guidance and control (PIGC) design concept was proposed [11–14]. The PIGC design framework falls into a two-loop control structure: the outer loop guarantees the interception with the body rates as virtual control inputs and yields the body rate commands, while the inner loop tracks the body rate commands with the fin deflections as the real control inputs and yields the fin deflection commands. The PIGC design combines the benefits of both the classical design and the IGC design, and has received much attention in recent years. In [11], two computationally efficient approaches, the model predictive static programming (MPSP) and the model predictive spread control (MPSC), were applied to the PIGC outer loop design, and the inner loop design was based on the nonlinear dynamic inversion (NDI) approach. In [12], a direct adaptive tracking control architecture with Gaussian radial basis function (RBF) network was used to compensate for the plant nonlinearities in the PIGC design. In [15], a nonsingular terminal SMC was proposed for a class of second-order nonlinear systems and applied to the PIGC design. The main feature of the proposed SMC law was that the finite time convergence in both reaching and sliding phase can be

* Corresponding author.
E-mail address: ranmp@buaa.edu.cn (M. Ran).

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achieved. PIGC design with impact angle constraints by using SMC was also considered, both in two-dimensional (2-D) space [16] and three-dimensional (3-D) space [17]. In [18], two novel SMC methods were proposed for PIGC design, both of which can achieve finite-time convergence. We note that, in practice, the missile guidance and control systems are inevitably subject to multiple uncertainties and system states maybe not fully available for measurement, due to the unknown target maneuver. However, the majority of the aforementioned approaches that applied to PIGC design were based on the assumption that the system dynamics apart from the bounded disturbance term are completely known and system states can be accurately measured.

On the other hand, active disturbance rejection control (ADRC) is an effective method to deal with uncertain nonlinear systems. This methodology was originally proposed by Han in 1980–1990s [19–21], and has become quite attractive in recent years. ADRC can be found wide industrial applications, such as motor control [22], noncircular turning process [23], micro-electro-mechanical systems gyroscope [24], and antenna pointing control of flexible satellite systems [25]. Compared with its broad applications, the theoretical analysis for ADRC was lagging behind for quite some time [26]. In [27], a parameterized linear ADRC (LADRC) was proposed, which is easy to implement and to tune. The stability analysis of the LADRC in the time-domain and frequency-domain were considered in [28,29], respectively. In [30], the rigorous proof of the convergence of the nonlinear ADRC was first given with some additional assumptions. In [31], a linear matrix inequality (LMI) based approach is proposed for a class of uncertain saturated nonlinear systems with LADRC. For more details of ADRC and the progress of its theoretical analysis, one can refer to [26]. We should point out that, to our best knowledge, the philosophy of ADRC has never been applied to the PIGC design for missiles before, and few efforts have contributed to the finite-time convergence and accurate description of the convergent region of ADRC.

Inspired by the above discussion, a novel control based on extended state observer (ESO), which is essential for ADRC, is proposed for a class of second-order uncertain nonlinear systems. The developed approach, when compared with the existing PIGC design methods, is novel in that it requires less information about the plant dynamics and has a good robust performance against system multiple uncertainties. The main contributions in this paper are summarized as follows.

- A novel control is proposed for a class of second-order uncertain nonlinear systems, which incorporates both an ESO and an adaptive sliding mode controller. Using the output of the ESO, the proposed control law is inherently continuous and differentiable.
- Finite time convergence of the estimation error of the ESO and the system states are proved. Moreover, the accurate expressions of the convergent regions are given, in the form of several known design parameters.
- The obtained results are applied to the PIGC design of missile interception. The ESO-based control law achieves enhanced interception performance and is robust against target maneuver and system dynamics variations.

The rest of this paper is organized as follows. In the following section, the ESO-based control law and its stability analysis are presented. In Section 3, the partial integrated guidance and control scheme and design goal are introduced. In Section 4, the proposed ESO-based control law is applied to the PIGC design. Section 5 presents the simulation results, and a brief conclusion in Section 6 ends the paper.

2. A novel extended state observer based control

Consider the following second-order uncertain nonlinear system

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = f(x,t) + (b_0 + \Delta b(x,t))u + d(x,t), \\ y = x_1 \end{cases} \tag{1}$$

where $x = [x_1\ x_2]^T$ is the state of the system, u is the control input, y is the measured output, $f(x,t)$ is the possibly unknown nonlinear dynamics, b_0 is a given constant, $\Delta b(x,t)$ is the uncertainty of b_0, and $d(x,t)$ denotes the bounded external disturbance. $f(x,t)$, $\Delta b(x,t)$ and $d(x,t)$ are smooth functions, and the sign of $b_0 + \Delta b(x,t)$ is fixed and known. Without loss of generality, we assume $b_0 > 0$ and $b_0 + \Delta b(x,t) > 0$.

For the system above, the possibly unknown nonlinear dynamics f, the external disturbance d, and the parameter mismatch of control Δbu are viewed as an extended state of the plant. Let $x_3 = f + d + \Delta bu$ and $h = \dot{x}_3$, and then system (1) can be written as the following equivalent form:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = x_3 + b_0 u, \\ \dot{x}_3 = h, \\ y = x_1. \end{cases} \tag{2}$$

An ESO is correspondingly designed for system (2),

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 + \varepsilon g_1\left(\dfrac{x_1 - \hat{x}_1}{\varepsilon^2}\right), \\ \dot{\hat{x}}_2 = \hat{x}_3 + g_2\left(\dfrac{x_1 - \hat{x}_1}{\varepsilon^2}\right) + b_0 u, . \\ \dot{\hat{x}}_3 = \varepsilon^{-1} g_3\left(\dfrac{x_1 - \hat{x}_1}{\varepsilon^2}\right) \end{cases} \tag{3}$$

where $\hat{x} = [\hat{x}_1\ \hat{x}_2\ \hat{x}_3]^T$ is the observer state, ε is a small positive constant, g_i, $i = 1,2,3$, are some smooth functions. The above is a special form of the general ESO proposed in [19], and was also considered in [30–32]. When ε and g_i, $i = 1,2,3$, are properly designed, the states of the ESO (3), $\hat{x}_1$, $\hat{x}_2$, and $\hat{x}_3$, will approach x_1, x_2, and x_3, respectively.

Similar to [33], the sliding surface is given as

$$s = x_1 + a|x_2|^\tau \operatorname{sgn}(x_2) = 0 \tag{4}$$

where $a > 0$, $1 < \tau < 2$, and $\operatorname{sgn}(\cdot)$ is the sign function. Then, based on the output of the ESO (3), we propose the following control law for system (1):

$$u = -\frac{1}{b_0}\left(\hat{x}_3 + a^{-1}\tau^{-1}\varphi(\hat{x}_2) + k_1\hat{s} + k_2\psi(\hat{s}) + \frac{\hat{\kappa}_{\max}\hat{s}}{2\beta^2}\right) \tag{5}$$

where $k_1, k_2, \beta > 0$, $\hat{s} = \hat{x}_1 + a|\hat{x}_2|^\tau \operatorname{sgn}(\hat{x}_2)$, $\hat{\kappa}_{\max}$ is the estimation of the upper bound of $\kappa_1^2 + \kappa_2^2$, with κ_1 and κ_2 will be defined, and $\varphi(\hat{x}_2)$ and $\psi(\hat{s})$ are defined as

$$\varphi(\hat{x}_2) = \begin{cases} (1-\tau)\delta_1^{-\tau}\hat{x}_2^2\operatorname{sgn}(\hat{x}_2) + \tau\delta_1^{1-\tau}\hat{x}_2, & |\hat{x}_2| \le \delta_1 \\ |\hat{x}_2|^{2-\tau}\operatorname{sgn}(\hat{x}_2), & |\hat{x}_2| > \delta_1 \end{cases}$$

$$\psi(\hat{s}) = \begin{cases} (\mu-1)\delta_2^{\mu-2}\hat{s}^2\operatorname{sgn}(\hat{s}) + (2-\mu)\delta_2^{\mu-1}\hat{s}, & |\hat{s}| \le \delta_2 \\ |\hat{s}|^\mu \operatorname{sgn}(\hat{s}), & |\hat{s}| > \delta_2 \end{cases} \tag{6}$$

here $0 < \mu < 1$, δ_1 and δ_2 are small positive constants. The updating law of $\hat{\kappa}_{\max}$ is as follows:

$$\dot{\hat{\kappa}}_{\max} = a\tau|\hat{x}_2|^{\tau-1}k_3\left(\frac{\hat{s}^2}{2\beta^2} - k_4\hat{\kappa}_{\max}\right) - k_3\hat{\kappa}_{\max} \tag{7}$$

where $k_3, k_4 > 0$.

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