Aerospace Science and Technology 41 (2015) 199–208

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Continuous second-order sliding mode based impact angle guidance law

Shaoming He *, Defu Lin, Jiang Wang

School of Aerospace Engineering, Beijing Institute of Technology, Beijing, 100081, People's Republic of China

ARTICLE INFO

Article history:
Received 14 August 2014
Received in revised form 17 October 2014
Accepted 3 November 2014
Available online 8 January 2015

Keywords:
Second-order sliding mode
Nonsingular terminal sliding mode
Disturbance observer
Missile guidance
Impact angle constraint
Maneuvering targets

ABSTRACT

In this paper, a new continuous robust impact angle constraint guidance law with finite-time convergence is proposed for intercepting maneuvering targets with unknown acceleration bounds. The presented guidance law is based on nonsingular terminal sliding mode (NTSM), smooth second-order sliding mode and finite-time convergence disturbance observer (FTDOB). In light of the introduced FTDOB, which is used to estimate and compensate the lumped uncertainty in missile guidance system, no prior knowledge of target maneuver is required. Thus, the proposed guidance law is capable of real implementation. Differently from the widely used boundary layer technique, chattering is eliminated effectively under the proposed guidance law without any performance sacrifice. Using finite-time bounded function approach and Lyapunov stability criteria, rigorous finite-time stability proof in both reaching and sliding phases is given. Theoretical analysis and numerical simulations show that the proposed guidance law can achieve more accurate interception with a wide range of intercept angles and superior overall performance than traditional NTSM algorithm.

1. Introduction

With the development of missile guidance in recent years, it is hoped that not only a minimum miss distance but also a desired terminal angle is required for many kinds of missiles in future precise interceptions. The motivation for achieving desired impact angles comes from the requirement of increasing the effect of the warhead the missile carries.

In the literature, a variety of guidance laws have been reported to satisfy the terminal angle constraint. As one of the initial efforts in this research field, Ref. [7] presented a suboptimal guidance law for ballistic reentry vehicles to intercept a non-maneuvering target with desired terminal angle constraint. Ref. [8] presented a biased proportional navigation guidance (PNG) law against a moving target, where a time-varying component was augmented to classical PNG to control intercept angles. In [19,24], an nth order time-to-go weighted performance index is used and new angle constrained guidance schemes are derived using linear quadratic optimal regulator method. The reason to use this kind of performance index is to obtain a guidance law that results in a relatively small acceleration command at the impact time to improve the overall performance of terminal guidance. The estimation of time-to-go, however, is a formidable challenge, and the practical applications of these optimal guidance laws are limited. Another linear quadratic optimal regulator based guidance law [23] also enables interception of a stationary target from various angles. Using the so-called high-performance sliding mode control methodology, a new guidance law was established in [12] to satisfy terminal angle constraint and enhance target observability for stationary or slowly moving targets. In [22], a linear sliding mode guidance law for intercepting non-maneuvering targets with desired terminal angles was proposed. With the aid of the newly developed model predictive static programming (MPSP) [20] and generalized MPSP (G-MPSP) [15] methods, novel suboptimal impact angle constraint guidance laws can also be found in [15,20]. Imposing an intercept angle can also be performed by a geometric circular navigation guidance (CNG) law [17], where the missile is guided to follow a pre-designated circular arc to a target.

Note that the guidance laws mentioned above are Lipschitz continuous and only concern the asymptotic or exponential stability. Besides faster convergent rate, the systems under finite-time convergent (FTC) control laws usually exhibit smaller steady-state tracking errors and better robustness against external disturbance as well as model uncertainty [3,11]. Moreover, the missile flight time during the terminal guidance phase is generally quite short. For instance, in a space interception, where an agile surface-to-air or air-to-air missile is required to intercept a fast-moving ballistic target, sometimes the lasting time is only several seconds. Conse-

* Corresponding author. Tel.: +86 01068914657.
E-mail address: shaoming.he.cn@gmail.com (S. He).

http://dx.doi.org/10.1016/j.ast.2014.11.020
1270-9638/

quently, designing guidance laws with finite-time convergence are more desirable [26,27,30]. To achieve finite-time stability, terminal sliding mode (TSM) and fast TSM (FTSM) proposed, respectively, in [16] and [28] are some notable works. However, TSM or FTSM controllers suffer from the inherent singularity problem, which means that the control effort requires to be infinite to guarantee the reachability of the pre-selected TSM or FTSM manifolds. To this end, NTSM [4,6,29] not only achieves finite-time convergence but also avoids singularity completely.

Besides the singularity, chattering is another main problem that limits the practical implementation of sliding mode controllers. One of the methods to address this problem is the widely used boundary layer technique [4,9,10,30], which replaces the discontinuous sign function with continuous saturation or sigmoid function. However, with this approach, only bounded motion around the sliding surface can be ensured and convergence to the origin is lost, which means that robustness decreases to some extent. In [29], the authors presented a novel continuous NTSM (CNTSM) controller for robotic manipulators by using a continuous fractional power term $|x|^\rho \operatorname{sgn}(x)$, but convergence to the origin is also lost as shown in this reference.

As to impact angle constraint guidance law with finite-time convergence, the authors in [5] presented a TSM based robust guidance law to satisfy both terminal angle constraint and seeker's field-of-view limit to intercept stationary or slowly moving targets. For maneuvering targets, TSM and NTSM based guidance laws are presented in [9] and [10], respectively, to impose a pre-selected intercept angle. These two references, however, have two main limitations: (1) the chattering problem; (2) requiring information on the upper bound of target maneuver. In reality, the target acceleration bound cannot or only very conservative bound can be obtained in advance for practical applications due to the complexity of the unpredictable target maneuver profiles. Therefore, to guarantee stability of the sliding variable dynamics, a quite large value of the switching gain should be selected, which in turn will increase energy consumption and worsen the undesired chattering phenomenon. Generally, guidance laws that require the upper bound of target maneuver are not practical.

To solve the two aforementioned problems encountered with standard NTSM guidance law, this paper has presented a new continuous second-order NTSM (SO-NTSM) impact angle constraint guidance law to intercept maneuvering targets with unknown target acceleration bounds. The contributions of this paper are: (1) the proposed SO-NTSM guidance law can achieve accurate interception without any information on the target maneuver; (2) the SO-NTSM guidance law is essentially a composite control approach, which enjoys the merits of NTSM, smooth second-order sliding mode and FTDOB, that is, finite-time convergence, chattering-free and exact uncertainty rejection; (3) the finite-time convergence of the closed-loop guidance system in both reaching and sliding phases is proved in theory via finite-time bounded (FTB) function and Lyapunov function methods; (4) the undesired chattering phenomenon of standard NTSM is eliminated effectively without any performance sacrifice; (5) the presented algorithm requires no estimations of the remaining flight time or the so-called time-to-go, which plays an important role in some existing impact angle guidance laws, such as [19,23,24] and references therein.

The remainder of this paper is organized as follows. In Section 2, some preliminary concepts are stated. The proposed SO-NTSM guidance law is provided in Section 3. In Section 4, the finite-time stability analysis of the closed-loop guidance system is presented. Nonlinear simulation results with some comparisons are shown in Section 5 while some conclusions are offered in Section 6.

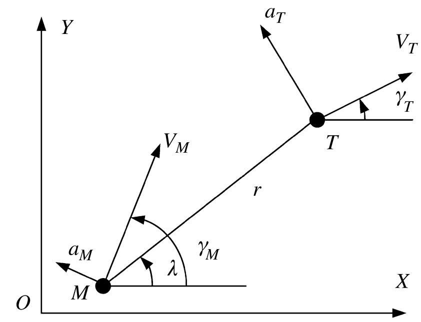

Fig. 1. Homing engagement geometry.

2. Preliminary concepts

In this section, a 2D nonlinear missile interception engagement and a singularity-free LOS angle error dynamics are derived. Some required basic fundamental facts are also presented.

2.1. Problem formulation

Assuming that the missile and the target are point masses with constant moving speeds, one possible planar homing engagement geometry between the missile and the target is depicted in Fig. 1, where the subscripts M and T denote the missile and the target, γ_M and γ_T the missile and the target flight path angle, λ and r the line-of-sight (LOS) angle and the missile–target relative range, V_M and V_T the missile and the target velocity, a_M and a_T the missile and the target acceleration, which are assumed normal to their corresponding velocities, respectively.

The corresponding differential equations describing the missile–target relative motion dynamics, in polar coordinate system, are formulated as

$$\dot{r} = V_T \cos(\gamma_T - \lambda) - V_M \cos(\gamma_M - \lambda) \tag{1}$$

$$\dot{\lambda} = \frac{1}{r}\left[V_T \sin(\gamma_T - \lambda) - V_M \sin(\gamma_M - \lambda)\right] \tag{2}$$

$$\dot{\gamma}_M = \frac{a_M}{V_M} \tag{3}$$

$$\dot{\gamma}_T = \frac{a_T}{V_T} \tag{4}$$

By accepting the intuition that zeroing the LOS angular rate will lead to a perfect interception [25], one can imply that

$$V_T \sin(\gamma_{Tf} - \lambda_f) = V_M \sin(\gamma_{Mf} - \lambda_f) \tag{5}$$

where the parameters with a subscript f denote their corresponding values at the time of impact.

The impact angle, denoted as θ_{imp}, is between the target velocity vector and the missile velocity vector at the time of interception. With this definition and Eq. (5), it is easy to obtain the following lemma.

Lemma 1. *(See [31].) For a pre-designated target with an expected impact angle, there always exists a unique desired terminal LOS angle. Hence, the control of intercept angle can be transformed into the control of the final LOS angle.*

Let λ^* be the desired terminal LOS angle. Then, the control objective here is to design a continuous guidance law such that $\lambda \to \lambda^*$, $\dot{\lambda} \to 0$ can be realized in finite time.