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Research Article

Guidance law against maneuvering targets with intercept angle constraint

Shaofeng Xiong [a,b,*], Weihong Wang [a,b], Xiaodong Liu [c,d], Sen Wang [a,b], Zengqiang Chen [e]

[a] School of Automation Science and Electrical Engineering, Beijing University of Aeronautics & Astronautics, Beijing 100191, China
[b] Science and Technology on Aircraft Control Laboratory, Beijing University of Aeronautics & Astronautics, Beijing 100191, China
[c] Beijing Aerospace Automatic Control Institute, Beijing 100854, China
[d] National Key Laboratory of Science and Technology on Aerospace Intelligence Control, Beijing 100854, China
[e] Department of Automation, Nankai University, Tianjin 300071, China

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ABSTRACT

This study explores the guidance law against maneuvering targets with the intercept angle constraint. The limitation of the traditional guidance law, which simply treats the unknown target acceleration as zero, has been analyzed. To reduce this limitation, a linear extended state observer is constructed to estimate the acceleration of the maneuvering target to enhance the tracking performance of the desired intercept angle. Furthermore, a nonsingular terminal sliding mode control scheme is adopted to design the sliding surface, which is able to avoid the singularity in the terminal phase of guidance. Simulation results have demonstrated that the proposed guidance law outperforms the traditional guidance law in the sense that more accurate intercept angle can be achieved.

1. Introduction

In order to increase the lethality of the missile's warhead against targets such as new large aircrafts, modern warships, submarines, tanks and large buildings, not only obtaining accurate interception with the target, but also striking the target at a desired intercept angle would be required. There is currently a vast literature on the design of intercept angle guidance law (IAGL), accumulated over more than four decades of investigations. In the early stage, traditional proportional navigation guidance law and its variants were employed to satisfy impact angle constraint [1–4]. Afterwards, optimal control theory was exploited to construct IAGL [5–7].

Thanks to the robustness to highly nonlinear dynamic systems with large modeling errors and external disturbance [8], the sliding mode control (SMC) technique had been employed for the design of guidance law [9–12]. In [13], the traditional linear SMC methodology was used to derive IAGL which enables intercepting a maneuvering target in three kinds of interception geometries, i.e., head-on, tail-chase and novel head pursuit. In [13], the information of the target acceleration was necessary for constructing the sliding variable, while no information was given about how to get the target acceleration in the simulation section. The guidance law in [13] can only guarantee asymptotic stability, and the investigations on the finite-time convergent IAGL had been proposed in [14–18]. With the help of the technique of line of sight (LOS) rate shaping, a finite-time convergent impact time and angle guidance law for stationary or constant velocity targets was proposed in [14] by the use of the second order SMC algorithm. In [15,17], the traditional terminal sliding mode (TSM) control algorithm was employed to construct a sliding variable to satisfy the intercept angle constraint. Furthermore in [16], considering a first-order-lag autopilot, an integral sliding mode controller combining nonlinear disturbance observer was developed to derive a novel composite IAGL. Both of the guidance laws in [15,16] defined the LOS angle as the intercept angle.

Different from the guidance laws in [15,16], the intercept angle in [17,18] was defined as the angle between the velocity vectors of the missile and the target when the interception occurs. For a given intercept angle, whether or not the target is maneuvering, the desired LOS angle is constant and its first time derivative is zero under the definition of intercept angle proposed in [15,16]. Comparatively, under the definition of intercept angle proposed in literatures [17,18], it holds only when the target executes no maneuver. The desired LOS angle is time-varying and its first time derivative is proportional to the target acceleration when the

* Corresponding author at: School of Automation Science and Electrical Engineering, Beijing University of Aeronautics & Astronautics, XueYuan Road No. 37, HaiDian District, Beijing 100191, China.
E-mail address: 15210985746@163.com (S. Xiong).

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target executes maneuvering. Both guidance laws in literatures [15,17] performed well for intercepting stationary and constant velocity targets. Especially, the guidance law proposed in [17] could steer the missile to intercept the stationary and constant velocity targets at all-aspect impact angle with different initial heading angles. However, in the case of intercepting maneuvering targets, the desired LOS angle is time-varying and its first time derivative is no longer zero but proportional to the target acceleration. So in [17], the target acceleration was included in the designed terminal sliding variable when target executes maneuvering. As pointed out in [17], it was usually difficult to measure the target acceleration directly in practice, and the target acceleration was treated as an unknown bounded variable. It is important to deal with the problem of unknown target acceleration when calculating the designed terminal sliding surface. Unfortunately, in the simulation of intercepting maneuvering targets, the literature [17] did not explain how to deal with the unknown target acceleration which was crucial for implementing the proposed IAGL. In addition, both of the guidance laws in [15,17] suffered from the problem of singularity. The literature [18] proposed a nonsingular terminal sliding mode (NTSM) control scheme based IAGL which was only suitable for non-maneuvering targets.

To handle the problem of the unknown target acceleration when intercepting maneuvering targets, an ingenious missile guidance law was proposed in [19]. In literature [19], the guidance design consisted of the estimation of the target acceleration by extended state observer (ESO) and achieved the decrease of undesired chattering effectively. However, only the problem of missile interception was investigated and the intercept angle constraint was not considered in [19]. In another method, the unknown target acceleration was directly set to zero. Setting the unknown target acceleration to zero is equivalent to letting the first time derivative of the desired LOS angle be zero. On the one hand, setting the first time derivative of the desired LOS angle to zero means that the first time derivative of the LOS angle should track zero, which is equivalent to rendering the LOS angle changeless in guidance. On the other hand, the LOS angle is required to track the time-varying desired LOS angle when the target executes maneuvering. The discrepancy of these two requirements poses a serious challenge for the LOS angle to precisely track the time-varying desired LOS angle when the target executes maneuvering, and furthermore gives rise to poor performance in obtaining the desired intercept angle.

As discussed above, under the definition of the intercept angle proposed in [17], how to deal with the unknown target acceleration has become the key problem in achieving higher tracking precision of the desired intercept angle for intercepting maneuvering targets. Other than simply setting the unknown target acceleration to zero, in this paper we treat it as an augmented state and estimate it by using a linear extended state observer (LESO) which is easier to implement. Due to the robustness and simplicity of LESO, an accurate estimation of the unknown target acceleration can be obtained. Different from the guidance law in [19], where the estimation of the unknown target acceleration was used to make the disturbance compensation in the control input and then reduce the chattering and control power, while in this paper it is used to calculate the designed nonsingular terminal sliding variable which satisfies the intercept angle constraint. With the accurate estimation of the unknown target acceleration, thus the time-varying desired LOS angle can be tracked accurately when the target executes maneuvering, which guarantees higher tracking precision of the desired intercept angle. To the authors' knowledge, under the definition of the intercept angle proposed in [17], no NTSM algorithm based IAGL for intercepting maneuvering targets has ever appeared in previously published literatures. So no need to set the unknown target acceleration to zero and singularity-free when attacking maneuvering targets with intercept angle constraint are the main contributions that set this work apart from other literatures.

The rest of this paper is organized as follows. The equations of engagement geometry and the definition of intercept angle are given in Section 2. The SMC and ESO algorithms are introduced in Section 3. In Section 4, the IAGL for intercepting maneuvering targets is proposed based on NTSM and LESO methods. In Section 5, numerical simulations are implemented for both setting the unknown target acceleration to zero and our proposed guidance law to justify the superiority of our proposed IAGL. Conclusions are given in Section 6.

2. Geometry of engagement

In this section, a two-dimensional engagement geometry involving missile and target is considered. To simplify the design, some assumptions are adopted that both of the missile and the target are viewed as point mass and the dynamics of autopilot and actuator are fast enough to be neglected. The interception geometry is shown in Fig. 1. The corresponding relative kinematic equations between the missile and the target in polar coordinate form are as follows:

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

$$\dot{\lambda} = \frac{V_T \sin(\phi_T - \lambda) - V_M \sin(\phi_M - \lambda)}{r} \tag{2}$$

$$\dot{\phi}_M = \frac{A_M}{V_M} \tag{3}$$

$$\dot{\phi}_T = \frac{A_T}{V_T} \tag{4}$$

where λ denotes the LOS angle, r denotes the distance between the missile and the target, A_M, ϕ_M, V_M, A_T, ϕ_T and V_T denote the normal accelerations, the heading angles and the tangential velocities of the missile and the target, respectively. Both V_M and V_T are assumed to be constant during the entire process of guidance. Here, two variables are defined as

$$V_r = \dot{r} \tag{5}$$

$$V_\lambda = r\dot{\lambda} \tag{6}$$

where V_r and V_λ represent relative velocities along and perpendicular to the LOS between the missile and the target respectively.

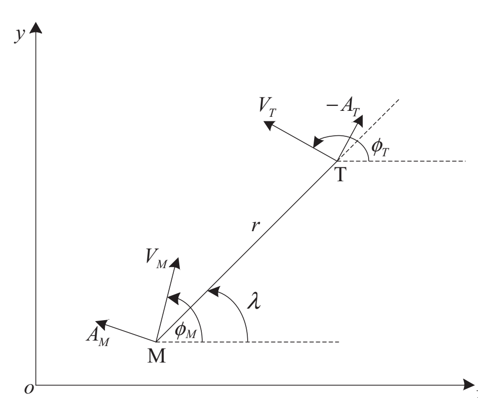

Fig. 1. Missile target engagement geometry.

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