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Strictly convergent nonsingular terminal sliding mode guidance law with impact angle constraints

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ABSTRACT

In this paper, we develop a strictly convergent nonsingular terminal sliding mode guidance law for missiles with impact angle constraints. A novel nonsingular terminal sliding mode (NNTSM) control scheme is first proposed to improve the effectiveness of conventional terminal sliding mode in the whole phase plane, where the time taken to reach both the sliding surface and equilibrium point is guaranteed to be finite time. The proposed NNTSM control scheme is then applied to the guidance law of missiles with impact angle constraints, where extended state observer is designed to estimate the target acceleration. Simulation results are presented to validate the proposed guidance law.

1. Introduction

To fulfill the growing requirement of intercepting maneuvering targets, the modern control theories have been widely used to design guidance laws of missiles in recent years [1–4]. The most important theory is sliding mode control (SMC), which is simple to design and robust to matched uncertainties of system [5–7]. In conventional SMC systems, the system states are asymptotically convergent to equilibrium point due to the linear sliding mode (LSM) surface, which means the convergence time is infinity. To achieve finite-time convergence and high precision control of system, terminal sliding mode (TSM) control was developed [8,9].

Conventional TSM controller has been successfully applied in rigid robots control [9,10], spacecraft attitude tracking control [11,12], and guidance law of missile [13], but the common drawback is the singularity problem caused by nonlinear term in sliding mode. The possible singularity problem may lead to control saturation and limit the applications of TSM control. A useful strategy to avoid the singularity problem is indirect method, such as the approach of switching the sliding mode [14], or transferring system trajectory to a pre-specified region [15]. Another strategy is known as nonsingular TSM (NTSM) control [16–18], which could completely avoid this problem while maintaining the advantages of conventional TSM control. The NTSM control is first employed to design guidance law of interceptor with impact angle constraints against stationary and constant velocity targets in [19]. A similar design against maneuvering targets can be seen in [20], which shows that interception does not depend on initial condition. However, the conventional NTSM control is not strictly convergent in the whole phase plane, and in [20], the lateral acceleration of target is treated as uncertainty, which is conservative and may cause chattering.

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In this paper, a strictly convergent novel NTSM (NNTSM) guidance law for missiles with impact angle constraints is proposed, where extended state observer (ESO) is designed to estimate the lateral acceleration of target. The rest of the paper is organized as follows: the planar missile–target engagement kinematics and objective of interception are stated in Section 2. The strictly convergent NNTSM control method and convergence analysis are described in Section 3. In Section 4, NNTSM based guidance laws of missiles with impact angle constraints and extended state observer are designed. Simulation results to validate the performance of the proposed guidance law are presented in Section 5. Finally, conclusions and future work are discussed in Section 6.

2. Problem formulation

For the sake of simplicity, missile and target are assumed to be point masses, and the planar engagement geometry between them is show in Fig. 1. The kinematic engagement equations of guidance system can be given by

$$\begin{cases} \dot{r} = V_T\cos(\gamma_T-\theta) - V_M\cos(\gamma_M-\theta) \\ r\dot{\theta} = V_T\sin(\gamma_T-\theta) - V_M\sin(\gamma_M-\theta) \\ \dot{\gamma}_M = \dfrac{a_M}{V_M} \\ \dot{\gamma}_T = \dfrac{a_T}{V_T} \end{cases} \tag{1}$$

where, r is the relative distance between missile and target, θ is line of sight (LOS) angle, V_T, γ_T and a_T are velocity, flight path angle, and lateral acceleration of target, V_M, γ_M and a_M of missile, respectively.

Assuming V_T and V_M are constants, then differentiating the second equation in Eq. (1) with respect to time yields

$$\ddot{\theta} = -\frac{2\dot{r}\dot{\theta}}{r} + \frac{\cos(\gamma_T-\theta)}{r}a_T - \frac{\cos(\gamma_M-\theta)}{r}a_M \tag{2}$$

The design object of guidance law in this paper is to guarantee the missile hits target with desired impact angle within finite time, which can be achieved by driving the LOS angular rate to zero. Let θ_d be as the desired LOS angle, and denote $x_1 = \theta - \theta_d$, $x_2 = \dot{x}_1$, Eq. (2) can be written as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\dfrac{2\dot{r}x_2}{r} - \dfrac{\cos(\gamma_M-\theta)}{r}a_M + d \end{cases} \tag{3}$$

where $d = \frac{\cos(\gamma_T-\theta)}{r}a_T$.

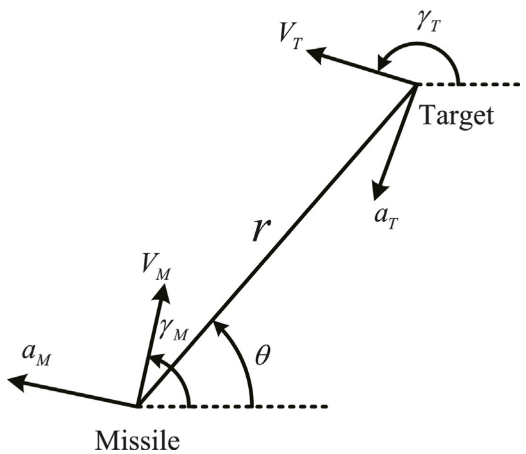

Fig. 1. Planar engagement geometry of interception.