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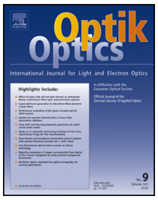

Original research article

Finite-time convergent terminal guidance law design based on stochastic fast smooth second-order sliding mode

Peng-fei Yang[a,*], Yang-wang Fang[a], You-li Wu[a], Xiao-ju Yong[b]

[a] *School of Aeronautics and Astronautics Engineering, Air Force Engineering University, Xi'an, 710038, China*
[b] *Air Force First Aviation College, Xinyang, 464000, China*

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ABSTRACT

A novel finite-time convergent terminal guidance law, based on stochastic fast smooth second-order sliding mode control theory, is proposed in order to handle the track imprecision caused mainly by inertial lag, model uncertainties and atmospheric environment disturbances, as well as the stochastic noise caused by target maneuver term. The missile-interceptor guidance system against targets performing evasive maneuvers is considered. The target maneuver model is employed to alleviate the dependence of the perfect knowledge of the range to target and the range rate as well as the limitation to target normal acceleration. Considering that the system is driven by additive noise, which do not have any equilibrium, a new concept of finite-time mean-square practical convergence is presented. And based on this concept, the finite-time convergence property of proposed guidance law is deduced. The availability and effectiveness of the proposed guidance law is illustrated through computer simulations. The results show that the proposed guidance law can realize finite-time convergence, and it has strong robustness against bounded uncertainties as well as the stochastic noise. The proposed guidance law does not has violent high-frequency chattering, which guarantees the tracking accuracy.

1. Introduction

The tracking accuracy as an important performance criterion of a homing missile is crucially dependent on guidance, navigation, and control [1]. The ever-increasing performance of the targets makes it an urgency to improve the terminal guidance law, which is used in the last stage of the attack. As the missile tracking the targets performing evasive maneuvers, convergence to zero of the line-of-sight (LOS) rate can make the terminal trajectory straighter and thus the missile needs smaller normal acceleration to track the target. However, traditional guidance laws cannot guarantee the LOS rate converge to zero, because the missile system is affected inevitably by the missile seeker measurement lag, guidance update rate limitation, missile rudder inertial delay, as well as model uncertainties and atmospheric environment disturbances [2].

Sliding mode control (SMC) is an effective approach in handling bounded uncertainties, disturbances and unmolded dynamics [3], therefore considerable efforts have been devoted to apply SMC to the homing missile guidance [4–6]. However, one disadvantage of classical SMC guidance is that the LOS rate cannot converges to the sliding surface in finite time [7]. Hence, Zhou [8] designed a new guidance law that can make the LOS rate converge to zero or its small neighborhood in finite time. Kumar [9] presented a guidance law intercepting targets at a desired impact angle in finite time using nonsingular

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[*] Corresponding author.
E-mail address: pfyang1988@126.com (P.-f. Yang).

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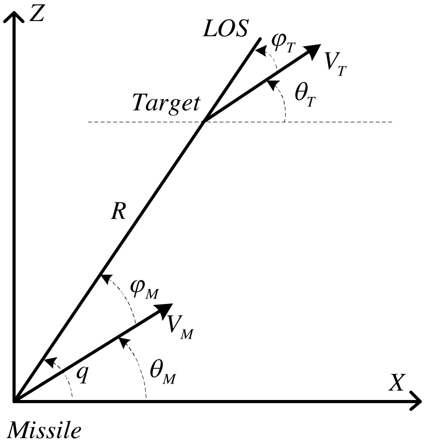

Fig. 1. Typical planar engagement geometry.

terminal sliding mode. However, the guidance laws in [8,9] were designed in the framework of first-order SMC. This lead to the following two deficiencies, one is that the system requires the relative degree equal to 1 with respect to the sliding variable, so it seriously restrict the choice of the sliding variable; another is the chattering effect in classical sliding mode controller, which is difficult to avoid [10,11]. These intrinsic difficulties of classical SMC are mitigated by the higher-order sliding mode (HOSM) controllers. A new smooth second-order sliding mode (SSOSM) control driven by uncertain sufficiently smooth disturbances was proposed and proved by Shtessel [12–14]. It exists the following several limitations, the first is the simplification of the missile-target engagement kinematics model; another is the dependences of the perfect knowledge of the range to target and the range rate, which is usually hard to get accuracy value; the last is the specific requirement of the target normal acceleration.

Aiming at the defects of the above mentioned research, an enhanced stochastic robust guidance law is achieved with a finite-time convergence in the presence of evasive target maneuvers, uncertainties, disturbances and stochastic noises. A novel stochastic fast smooth second-order sliding mode (SFS-SOSM) control is proposed and employed to design the terminal guidance law. A new concept of finite-time mean-square practical (FTMSP) stability is introduced to investigate the finite-time convergence of the stochastic sliding surface and the FTMSP convergence of SFS-SOSM control is proved using Itô's formula.

The rest of this paper is organized as follows: Section 2 is dedicated to formulating the missile-target engagement kinematics. The SFS-SOSM control algorithm is derived and its FTMSP convergence is proved in Section 3. A smooth guidance law based on SFS-SOSM control is presented in Section 4. In Section 5, the performances of designed guidance law are verified via several computer simulations.

2. Planar engagement model and intercept strategy

2.1. Problem formulation

Consider the planar homing case that the missile moves within the horizontal plane, a typical engagement scenario is presented in Fig. 1.

The planar missile-target engagement kinematics can be easily derived as

$$\dot{r} = V_T \cos(q - \theta_T) - V_M \cos(q - \theta_M) \tag{1}$$

$$r\dot{q} = -V_T \sin(q - \theta_T) + V_M \sin(q - \theta_M) \tag{2}$$

where q is the LOS angle; r is the range along LOS; V_T and V_M are target and missile velocity; θ_T and θ_M are target aspect angle and missile heading angle, respectively; $\phi_T = q - \theta_T$ and $\phi_M = q - \theta_M$ are target and missile's lead angle.

Denote $V_r = \dot{r}$, $V_q = r\dot{q}$ and substitute them into Eqs. (1) and (2), then differentiating both sides of Eqs. (1) and (2) with respect to time t to get

$$\begin{aligned} \dot{V}_r &= \dot{q}[-V_T \sin(\mathrm{q} - \theta_T) + V_M \sin(\mathrm{q} - \theta_M)] \\ &+ [\dot{V}_T \cos(\mathrm{q} - \theta_T) + V_T\dot{\theta}_T \sin(\mathrm{q} - \theta_T)] \\ &- [\dot{V}_M \cos(\mathrm{q} - \theta_M) + V_M\dot{\theta}_M \sin(\mathrm{q} - \theta_M)] \end{aligned} \tag{3}$$