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A novel guidance law using fast terminal sliding mode control with impact angle constraints

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ABSTRACT

This paper is concerned with the question of, for a missile interception with impact angle constraints, how to design a guidance law. Firstly, missile interception with impact angle constraints is modeled; secondly, a novel guidance law using fast terminal sliding mode control based on extended state observer is proposed to optimize the trajectory and time of interception; finally, for stationary targets, constant velocity targets and maneuvering targets, the guidance law and the stability of the closed loop system is analyzed and the stability of the closed loop system is analyzed, respectively. Simulation results show that when missile and target are on a collision course, the novel guidance law using fast terminal sliding mode control with extended state observer has more optimized trajectory and effectively reduces the time of interception which has a great significance in modern warfare.

1. Introduction

With the rapid development of missile technology in modern warfare, anti-aircraft missile, one of the most important weapons of defense, whose performance requirement has become increasingly prominent is difficult to design in order to meet high demands of damage ability. Missile is not only required to get the minimum miss distance, but also required to have a better impact angle at the time of interception, which achieves the best damage effect by making warheads efficient. A guidance law with impact angle constraints is a law which makes the performance of anti-aircraft missile significantly improved by changing the impact angle to a constant angle. Using guidance law with impact angle constraints, anti-aircraft missile can significantly improve damage ability to enhance capability of the missile. Therefore, impact angle constraints is an important part of evaluation indicator for missile design [1–6].

There are many researches on impact angle constraints, in case of stationary targets [7], nonstationary nonmaneuvering targets [8], maneuvering targets [9] and so on. [10] explored the guidance law against maneuvering targets with intercept angle constraint, in which the target acceleration was estimated and analyzed. [11] proposed a guidance law that guaranteed imposing a predetermined impact angle relative to a maneuvering target's flight direction under the existence of unknown target acceleration. [12] presented an adaptive neuro-fuzzy sliding mode control guidance law with impact angle constraint to intercept non-maneuvering targets. A partial integrated guidance and control design for an interception with terminal impact angle constraints in three-dimensional space was presented in [13], in which a Monte Carlo study was conducted to test the robustness to aerodynamic uncertainties. Zhou et al. used a dynamic surface control method to design a sliding mode guidance law to intercept maneuvering targets with impact angle constrained flight trajectories under the assumption of ideal missile autopilot [14]. In [15], a new impact time and impact angle control guidance law for homing missiles against a stationary target was proposed and the corresponding simulations were given to validate the algorithm.

Terminal sliding mode control (TSMC) was first proposed in [16–18], which introduced nonlinear function into the sliding surface, and could meet fast response requirement in finite time. Wu designed a terminal sliding mode control for uncertain dynamic systems, which achieved a good performance [19]. Feng discussed the design of nonsingular terminal sliding mode controller, and applied the control method in robots [20]. Tao used fuzzy rules to design a TSMC switch, which could adjust the switch gain adaptively by the adaptive fuzzy adjustment, to achieve

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Notation

r	The relative distance between the missile and the target
r_0	The initial relative distance between the missile and the target
r_x	The level relative distance between the missile and the target
r_y	The vertical relative distance between the missile and the target
θ	The line of sight angle
θ_f	The line of sight angle at the time of interception
θ_{imp}	The desired impact angle
a_m	The missile lateral acceleration
a_t	The target lateral acceleration
a_m^{eq}	The equal missile lateral acceleration
a_m^{disc}	The discontinuous missile lateral acceleration
$\bar{a}_m$	The bound of missile lateral acceleration
γ_m	The flight path angle of the missile
γ_{mf}	The flight path angle of the missile at the time of interception
γ_t	The flight path angle of the target
γ_{tf}	The flight path angle of the target at the time of interception
v_m	The missile velocity
v_t	The target velocity

terminal sliding mode control for linear systems with mismatched time-varying uncertainties [21].

Especially, Shashi et al. designed a nonsingular terminal sliding mode guidance law with impact angle constraints, and discussed the impact angle constraints situations for stationary targets, constant velocity targets and maneuvering targets situation and for different initial engagement geometries and impact angles. The relative control theory was derived rigorously and proved in each situation, which gave a great performance and was convincing [22]. But the method used in [22] has a long path length and a long strike time. Based on this, a novel composite control scheme based on fast terminal sliding mode control and extended state observer is proposed in this paper, and the proposed control method can optimize the trajectories obviously with a short path length and a short strike time, both of which are important evaluation indices in missile performance.

In this paper, we will consider the missile guidance problem with impact angle constraints. A vary function is introduced in sliding mode surface. The function is not simply the state of the system and causes the coupling of sliding mode surface. But the introduced function can make the strike time shorter, which take an important position in missile strike. The rest of this paper is organized as follows. The missile interception with impact angle constraints is modeled in Section 2. The design of guidance laws is given in Section 3. The simulation results are given in Section 4 and the conclusion is summarized in Section 5.

2. Modeling of missile interception with impact angle constraints

A three dimension engagement between a missile and a target can be analyzed as a planar engagement which is confirmed by the velocities of the missile and the target. A planar engagement between a missile and a target is shown in Fig. 1. v_m and v_t are the missile velocity and the target velocity respectively, and a_m and a_t denote their lateral accelerations, respectively. The relative distance between the missile and the target is represented by r and the line-of-sight (LOS) angle by θ. In this paper, v_m and v_t are assumed as fixed constants, the kinematic engagement equations are given by

$$\begin{aligned} \dot{r} &= v_t \cos \theta_t - v_m \cos \theta_m \\ r\dot{\theta} &= v_t \sin \theta_t - v_m \sin \theta_m \\ \dot{\gamma}_m &= \frac{a_m}{v_m} \\ \dot{\gamma}_t &= \frac{a_t}{v_t} \end{aligned} \tag{1}$$

where $\theta_t = \gamma_t - \theta$ and $\theta_m = \gamma_m - \theta$.

θ_{imp} is the desired impact angle, which is the angle between the velocity vectors of the interceptor and target at the time of interception, and can be defined as

$$\theta_{imp} = \gamma_{tf} - \gamma_{mf} \tag{2}$$

where γ_{tf} and γ_{mf} are the flight path angles of the target and the missile at the time of interception, respectively.

As is shown in Fig. 1(c), at the time of interception, LOS angle is denoted by θ_f. The relation between the missile and the target can be established by (3) when the missile and the target are on a collision course.

$$v_m \sin \theta_{mf} = v_t \sin \theta_{tf} \tag{3}$$

where $\theta_{mf} = \gamma_{mf} - \theta_f$ and $\theta_{tf} = \gamma_{tf} - \theta_f$. And at this situation, from (1), we have $r\dot{\theta} = 0$.

From (1)–(3), we have

$$\theta_f = \gamma_{tf} - \tan^{-1}\left(\frac{\sin \theta_{imp}}{\cos \theta_{imp} - \eta}\right) \tag{4}$$

where $\eta = \frac{v_t}{v_m}$. It is obvious that $v_t < v_m$.

Actually, if we give different θ_{imp}, it can be found that θ_f and θ_{imp} have the one-to-one correspondence to each other [22], which is important for further research. Especially, $\theta_{imp} = n\pi, \ n = \pm 1, \pm 2, \ldots$ mean the head-on and tail-chase scenarios.

3. Design of guidance laws

3.1. Extended state observer

Extended state observer (ESO) is proposed in the research of the active disturbance rejection control (ADRC) [23,24] and widely used in many significant field [25–27]. The ESO treats the system model uncertainties and external disturbances as an extended state which can be equally compensated in the controller to realize the linearization of dynamic compensation.

Consider a nonlinear time-varying dynamic system [28]·

$$y^{(n)}(t) = f(y^{(n-1)}(t), y^{(n-2)}(t), \ldots y(t), w(t)) + gu(t) \tag{5}$$

where u and y are input and output of the system, respectively, w is the external disturbance and g is a given coefficient. Assume that $f(y^{(n-1)}(t), y^{(n-2)}(t), \ldots y(t), w(t))$ is differentiable and denoted as f, which represents the nonlinear time-varying dynamics of the

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