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Sliding mode control based guidance law with impact angle constraint

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Abstract The terminal guidance problem for an unpowered lifting reentry vehicle against a stationary target is considered. In addition to attacking the target with high accuracy, the vehicle is also expected to achieve a desired impact angle. In this paper, a sliding mode control (SMC)-based guidance law is developed to satisfy the terminal angle constraint. Firstly, a specific sliding mode function is designed, and the terminal requirements can be achieved by enforcing both the sliding mode function and its derivative to zero at the end of the flight. Then, a backstepping approach is used to ensure the finite-time reaching phase of the sliding mode and the analytic expression of the control effort can be obtained. The trajectories generated by this method only depend on the initial and terminal conditions of the terminal phase and the instantaneous states of the vehicle. In order to test the performance of the proposed guidance law in practical application, numerical simulations are carried out by taking all the aerodynamic parameters into consideration. The effectiveness of the proposed guidance law is verified by the simulation results in various scenarios.

1. Introduction

For the case of the terminal guidance phase, the guidance laws are required to hit the target from a specific direction with high precision, as well as to achieve a minimal miss-distance. Traditional guidance laws, such as classical proportional navigation guidance (PNG),[1] are very popular in practical applications because of the ease of mechanization due to less information demand. Although such guidance laws can be used to attack the target accurately, they are usually silent on terminal angle constraint.

Since the concept of impact angle guidance is advanced in Ref.[2], great development has been achieved on this issue. A technique that has been commonly employed to derive such laws is using the PNG-based method. A biased PNG law is presented in Ref.[3], and the impact angle is guaranteed by adding a biased term to PNG. Similarly, in Ref.[4], an improved biased PNG law which is more simple and practical than Ref.[3] is proposed. An adaptive guidance is presented in Ref.[5], where nonlinear parameter adaptation laws are adopted in PNG to intercept a ground target. This guidance approach is effective and easy to implement. Moreover, the trajectories generated by this method are similar to the optimal trajectories. Another PNG-based guidance law, possessing the ability of intercepting a stationary target with various angles by

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varying the PN gains, is proposed in Ref.[6]. Afterwards, the method in Ref.[6] is further extended to deal with nonstationary nonmaneuvering targets in Ref.[7]. However, the control effort is not continuous at the instant of guidance law switching, which may increase the tracking difficulty for the flight control system.

In some recent work, the time-to-go (t_{go}) information is used to design the impact angle guidance laws. A guidance law on the basis of state dependent Riccati equation (SDRE) is proposed in Ref.[8]. The guidance problem turns to be a nonlinear regulator problem and a t_{go} based state-weighting matrix is used. A closed-form solution of a linear quadratic optimal control problem to cater for terminal angle constraint is developed in Ref.[9]. In addition, three kinds of method are introduced to calculate t_{go}. However, in practical applications, the precise estimation of t_{go} is usually a challenging work.

On the other hand, a computationally efficient technique which is called model predictive static programming (MPSP) is used to obtain impact angle constrained guidance laws. MPSP is based on nonlinear optimal control theory, and an effective trajectory optimization concept is integrated into the guidance laws. For more details, one can refer to Refs.[10,11].

Sliding mode control (SMC), as an effective method to tackle the uncertainties and disturbances, has drawn a good amount of attention from researchers around the world. In Ref.[12], a new guidance concept named intercept angle guidance is proposed. This guidance method which is implemented in the usage of sliding mode approach can be applied in three kinds of engagement scenarios, i.e., head-on, tail-chase and head-pursuit. Then, this guidance concept is further investigated in Ref.[13] with taking time-varying acceleration bounds into consideration. A novel sliding mode-based impact time and angle guidance law is presented in Ref.[14]. The line-of-sight (LOS) angle history is shaped to satisfy the needs of impact angle as well as impact time, then a backstepping based second-order sliding mode control is derived to track the pre-designed LOS angle. The method presented in Ref.[15] is a terminal SMC (TSMC)-based guidance and control law which can be used to intercept stationary, constant-velocity, and maneuvering targets with any impact angle, even under the circumstance of large initial heading errors. In spite of the effectiveness of the proposed method from the constant-velocity missile point of view, it is difficult to estimate its performance by taking all the aerodynamic parameters into consideration. In Ref.[16], a scheme of integrated guidance and control on the basis of an adaptive SMC algorithm is developed. In this work, the nonlinear dynamics is taken into account, and the robust characteristics of the algorithm are validated in the case of aerodynamic parameter perturbation; however, the range of available terminal angle is limited.

In this paper, an SMC-based guidance law is developed to hit a stationary target from a specified direction with high precision. The nonlinear point-mass dynamics in the pitch plane is used to evaluate the guidance law. As the sliding mode function is specially designed according to the terminal constraints, the associated sliding mode is established to guarantee the interception with the specified impact angle where the backstepping approach is utilized. Moreover, the closed-loop dynamics is insensitive to uncertainties and disturbances by the virtue of the strong robustness of SMC. The guidance law features in four characteristics. Firstly, aerodynamic characteristics are taken into account in the design of the proposed guidance law. As a result, the simulation results obtained from this method tally well with the actual situation. Secondly, there is a wide range of achievable impact angle in the usage of the guidance law. It guarantees the capability of the proposed guidance law to meet different mission requirements. Thirdly, the guidance scheme is quite robust to initial conditions as well as parameter perturbation. Finally, the guidance command is very smooth and it can be easily realized by the attitude control system.

2. Problem formulation

In this paper, a two-dimensional homing scenario is considered. To make it explicit, the engagement geometry in inertial coordinate frame is shown in Fig. 1. The missile and the target are represented by M and T; the missile's acceleration is denoted by u; the velocity and flight path angle of the missile are defined as V and γ respectively, with V_f and γ_f being their final values. In addition, the missile mass is represented by m and the gravity acceleration $g = 9.81$ m/s is treated as a constant.

The equations of motion in the terminal guidance phase can be given as

$$\dot{x} = V\cos\gamma \tag{1}$$

$$\dot{y} = V\sin\gamma \tag{2}$$

$$\dot{V} = -\frac{D}{m} - g\sin\gamma \tag{3}$$

$$\dot{\gamma} = \frac{L}{mV} - \frac{g\cos\gamma}{V} \tag{4}$$

where the position coordinates are x and y. The terms L and D are the aerodynamic lift and drag which are defined by

$$L = qSC_L \tag{5}$$

$$D = qSC_D \tag{6}$$

where $q = 0.5\rho V^2$ is the dynamic pressure which is dependent on the air density ρ and the velocity V; S is the reference area of the vehicle; the terms C_L and C_D are the lift and drag coefficients that are dependent on the angle of attack α and Mach number Ma.

Time t is taken as the independent variable in the equations of motion (1)–(4). However, the flight time of the terminal guidance phase is usually not the key question we are concerned about. In Ref.[17], the downrange x is used as the independent variable to land the reusable launch vehicle

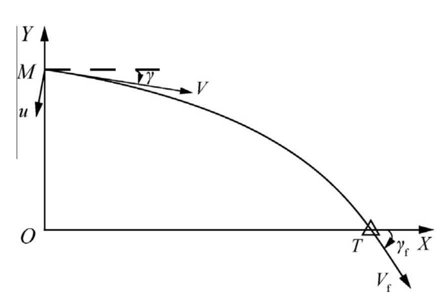

Fig. 1 Engagement geometry.