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Research Article

Analytical impact time and angle guidance via time-varying sliding mode technique

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ABSTRACT

To concretely provide a feasible solution for homing missiles with the precise impact time and angle, this paper develops a novel guidance law, based on the nonlinear engagement dynamics. The guidance law is firstly designed with the prior assumption of a stationary target, followed by the practical extension to a moving target scenario. The time-varying sliding mode (TVSM) technique is applied to fulfill the terminal constraints, in which a specific TVSM surface is constructed with two unknown coefficients. One is tuned to meet the impact time requirement and the other one is targeted with a global sliding mode, so that the impact angle constraint as well as the zero miss distance can be satisfied. Because the proposed law possesses three guidance gain as design parameters, the intercept trajectory can be shaped according to the operational conditions and missile's capability.

To improve the tolerance of initial heading errors and broaden the application, a new frame of reference is also introduced. Furthermore, the analytical solutions of the flight trajectory, heading angle and acceleration command can be totally expressed for the prediction and offline parameter selection by solving a first-order linear differential equation. Numerical simulation results for various scenarios validate the effectiveness of the proposed guidance law and demonstrate the accuracy of the analytic solutions.

1. Introduction

Advanced guidance techniques for homing missiles have been extensively studied in the past decades. In addition to the minimal miss distance, the terminal constraints such as impact angle and time are of equivalent importance. The impact angle is a critical factor in the homing guidance application as it has considerably great effect on the lethality of the warhead. For example, the top attack is preferable in the anti-tank application since tanks are vulnerable from the top. By comparison, the lateral impact is required for maximum destruction in the anti-ship missiles application. The impact time constraint does also take the key role in homing missiles for salvo attacks or cooperative attack missions, in which multiple missiles are commanded to simultaneously hit a target. Hence, the impact angle and time can greatly enhance the survivability of the missiles against advanced defense systems of warships.

In terms of the guidance technique for homing missiles, the emphasis was initially concentrated on the impact angle guidance. Since 1973, when Kim and Grider reported the concept of impact angle guidance, great achievements have been obtained regarding this practical research area [1]. The proportional navigation guidance (PNG) technique was one of the most popular methods in tackling such problems because of the ease of mechanization due to less information demand [2,3]. The PNG method has been applied for the interception of stationary targets with fixed impact angles [4,5]. The former was essentially a 3-D adaptive guidance method which took full nonlinear point-mass dynamics into consideration, while the latter focused on the planar engagement by capturing all possible impact angles and was further extended to cope with constant velocity targets in [6]. As a variant of PNG, the biased PNG approach has also been pointed out to derive impact angle constrained guidance laws by adding one biased term to the original PNG [7,8]. Sliding mode control (SMC), as a variable structure control, has shown the advantages in the missile guidance due to its robust performance [9,10]. Furthermore, a new smooth second-order sliding mode control approach was proposed and its application was accordingly demonstrated for missile guidance and control system design [11,12]. The SMC was further combined with a backstepping approach so that it

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achieved a robust guidance law with impact angle constraint [13]. With the switching surfaces defined by the line-of-sight (LOS) angle, the guidance law was reported to hit the maneuvering targets from a wide range of directions [14,15]. Based on the integral sliding mode control and nonlinear disturbance observer technique, the novel guidance law was presented to intercept maneuvering targets with terminal impact angle constraints [16]. This approach was further investigated with the consideration of the first-order-lag autopilot [17]. On the other hand, another methodology extensively studied is the optimal control theory.

In [18], an optimal guidance law was derived for arbitrary-order linear missile dynamics, which was dependent on zero-effort miss distance and a new variable denoted zero-effort angle. A generalized form of energy optimal guidance law was proposed with the effective time-to-go calculation method in [19]. This guidance law was extended by considering the optimal control problem with the time-to-go weighings in the cost function [20]. It should be noted that some suboptimal control methods, such as the state-dependent Riccati equation and the recent model predictive static programming technique, have also been applied to the impact angle guidance law design [21–23].

However, although the impact angle guidance can provide a lot of advantages in enhancing the killing probability, it is far away from enough in the engagement of a modern warfare ship. Modern warships are typically equipped with a number of self-defense systems against anti-ship missiles, such as surface-to-air missiles, electronic countermeasure (ECM) systems and close-in weapon systems (CIWS) which seriously intimidate the survivability of the conventional anti-ship missiles [24]. One feasible solution to this problem is the cooperative attack, which takes the impact time of missiles under control so as to ensure several homing missiles to hit the target simultaneously. Nevertheless, unlike the impact angle guidance methods, only few works have been performed to deal with the impact time control problem. An early contribution in this area was made that an impact time constrained guidance law was developed through a combination of PNG term and a feedback term of the impact time error [24]. By means of this method, a cooperative guidance scheme was further derived in [26]. In [27], the impact time control problem was transformed to a tracking problem using a virtual leader approach. A new guidance scheme was presented in [28] to intercept non-maneuvering targets at a desired impact time via SMC technique. In [29], a guidance approach initiated the researches to control both impact angle and time for homing problems. In the past two years, some valuable contributions in this field have also been made in [30–33]. A new sliding mode based impact time and angle (ITA) guidance law was developed in [30]. An LOS rate shaping process was firstly introduced to satisfy the terminal constraints and then a second-order sliding mode concept was further deployed to track the designed LOS rate profile. In [31], a numerical guidance strategy for the nonlinear missile model was derived, which not only guaranteed the impact time and angle requirements but minimized the integral square control efforts as well. An improved biased PNG law was proposed in [32], where the impact time and angle constraints were satisfied by adding a feedback control to a specially constructed biased PNG. In [33], a polynomial function with three unknown coefficients was introduced to design an impact time and angle guidance law. With the appropriate selection of the guidance gains, the generated acceleration command profiles turned out to be quite similar to the optimal solutions.

In this paper, a novel time-varying sliding mode (TVSM) based homing guidance law is proposed, which enables the missile to intercept the target at a specified impact time with a desired impact angle. In order to satisfy the ITA requirements, a specific sliding mode surface is designed with two unknown coefficients. One of these coefficients is tuned to adjust the homing trajectory so as to achieve the impact time requirement. The other one is determined to realize a global sliding mode so that the impact angle constraint as well as the zero miss distance can be satisfied.

The proposed ITA guidance method could provide several advantages over the published work in the following aspects. Firstly, although the control analysis was greatly simplified by the derived guidance law with the deployment of the linearized engagement dynamics in [24,29,33], these approximations were no longer valid with large pointing errors. This paper completely uses the nonlinear dynamics but no extra assumptions are made so that the proposed guidance law can provide more accurate results even in the presence of large heading errors. Secondly, the derivation of laws in [24,29,30,33] utilizes the downrange x as the independent variable, thus limiting terminal heading angles within the range between 90° and −90°. However, this study provides the solution to this problem by appropriately redefining the reference frame, which widely broaden the capture region of the desired impact angle. Thirdly, the analytic solutions of the impact time and angle guidance are obtained using nonlinear engagement dynamics, which is the first attempt within the knowledge of the authors. The analytic solutions can not only provide an insight into the behavior of the missile in advance, but also predict the prospective flight trajectory in real-time without time-consuming simulations. Fourthly, the laws in [29,32] would lead to certain homing trajectories as long as the engagement conditions are determined. The proposed method, however, has three guidance gains as design parameters, which can be employed to shape the intercept trajectory in relation to the missile's capability. Finally, compared with the work in [29,32,33], the main emphasizes of which were focused on stationary targets, the method presented in this study can also be applied for engaging a maneuvering target.

2. Problem formulation

In this paper, a two-dimensional homing engagement as shown in Fig. 1 is considered. The missile is assumed to be traveling at a constant velocity V in the horizontal plane and the target is supposed to be stationary. The positions of the missile and target in the inertial X–Y coordinate are represented by (x,y) and (x_f, y_f), respectively. The heading angle is denoted by θ. The acceleration command u is applied along the normal direction of the missile's velocity. The equations of the motion for the homing engagement are given as follows [24]

$$\dot{x} = V\cos\theta, \tag{1}$$

$$\dot{y} = V\sin\theta, \tag{2}$$

$$\dot{\theta} = \frac{u}{V}. \tag{3}$$

Recall that the design objective of the ITA guidance problem is to intercept the target with a given impact angle at a predetermined

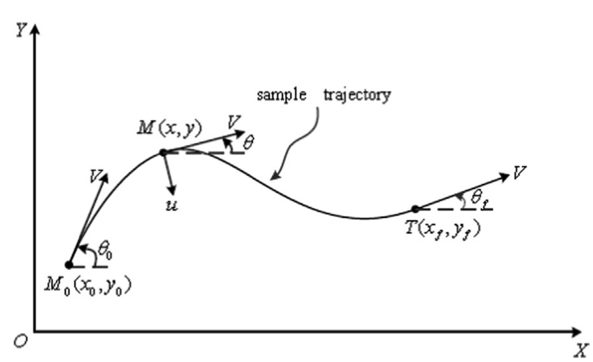

Fig. 1. Engagement geometry for homing guidance.