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Research article

Adaptive internal model guidance law for weaving maneuvering target

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ABSTRACT

For the terminal phase guidance problem of the missile intercepting weaving maneuvering target, an adaptive internal model guidance laws in the three-dimensional (3-D) engagement space is proposed in this paper. The guidance law adopts the disturbance rejection theory by treating the target weaving maneuvering accelerations as external disturbance, which comprises of nominal part and adaptive part. The nominal part based on feedback linearization method ensures the whole guidance system stable and the adaptive part based on internal model principle is used to recover the disturbance signals on-line to reject the target maneuver asymptotically. The algorithm guarantees the whole guidance system with satisfying performance both in transient and steady state on the effect of target maneuver on guidance system. The stability analyses and theory proof are provided in this paper. At last, numerical simulations are carried out to illustrate the effectiveness of the proposed guidance law.

1. Introduction

An air-to-air missile guidance procedure can be divided into boost phase, midcourse phase and terminal phase [1]. During the terminal phase, the guidance law for a missile plays an important part in realizing the precise guidance, which is used to render missile to intercept target with miss distance as small as possible. The most known and used guidance laws are proportional navigation (PN) [4] and many kinds of its variants such as augmented proportional navigation (APN) [3], true proportional navigation (TPN) [6,7], pure proportional navigation [5], biased proportional navigation (BPN) [2], optimal guidance law (OGL) [8,9], generalized proportional navigation (GPN) [10], ideal proportional navigation (IPN) [11] and realistic true proportional navigation(RTPN) [12,13]. Traditional PN guidance law is inherent simplicity and ease of implementation, which is an optimal algorithm for a non-maneuvering target. However, for the situation of the target with maneuverability, the performance of PN guidance laws is degraded and they cannot assure satisfying guidance precision. On the other hand, PN-variants guidance laws for instance, OGL and APN guidance laws can improve guidance precision, which largely depend on *a prior* information about target maneuver, missile acceleration and so on.

Recently, to deal with the aforementioned problem, many researchers have developed various kinds of guidance laws using advanced control theory, such as sliding mode control (SMC) [14,16], nonlinear H_∞ method [17], nonlinear geometric method [18], L_2 gain control [19], differential game method [21], etc. Especially, SMC has been widely used to solve the problem of external disturbances and the uncertainties of the system due to its robustness. In the implementation of the SMC, the sliding mode guidance law assumes that the upper bound of external disturbance or target maneuvering is known. However, in real applications, the upper bound of external disturbance is hard to obtain actually. It needs assuming a bound of the disturbance of the guidance system, which might be degraded the control performance accordingly.

Disturbance rejection theory as one of the fundamental control problems has been intensively studied for both linear system and nonlinear system in recent years. One of the approaches to deal with the problem is based on internal model principle. For the case that models of both the controlled system and the external disturbance are known exactly, this problem has been addressed by disturbance observers method [20]. The estimated disturbance is used to compensate external disturbance on the system asymptotically. With the development of disturbance rejection theory, the problem of parameterized disturbance rejection has been solved successfully [22,23]. Through constructing an adaptive disturbance observers, the closed-loop system does not effect by the possible parametric uncertainties of both the system and external disturbance generator.

In this paper based on 3-D interception model of missile and target with maneuver [15], a novel adaptive guidance laws using internal model principle is developed. The unknown target acceleration is treated as external disturbance generated by

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exosystem with known order but unknown frequencies. Adopting internal model principle, two adaptive observers are used to recover the disturbance signals on-line. The target maneuver effects on the miss distance of guidance system are completely rejected by virtue of estimation method. By doing so, the required guidance precision as well as satisfying performance can be guaranteed.

The rest of the paper is organized as follows. Section 2 describes the modeling of the 3-D relative kinematics between the missile and the target. In Section 3, the nonlinear guidance law with adaptive internal model principle is proposed. In the following section, the stability of the missile guidance system is analyzed. In Section 5 numerical simulation is carried out to illustrate the satisfying performance of the proposed guidance law. The conclusions are given in Section 6.

2. Problem formulation

In this section, we will give the kinematics of the relative motion between the missile and the target by 3-D vectors and the associated spatial coordinates. 3-D interception geometry of missile and target is shown in Fig. 1. The missile and the target are denoted by M and T, respectively. $Oxyz$ denotes the inertial reference frame. A line-of-sight(LOS) coordinate system which its origin at mass center of the missile is denoted by $Ox_Ly_Lz_L$. In this coordinate system, the x_L-axis is represented as a direction of LOS and its positive direction is originated from the missile and to the target; the y_L-axis is in the vertical plane; the z_L-axis is decided by the right-hand rule. The distance between the missile and the target is denoted by the R. In addition, q_ε denotes LOS elevation angles; q_β denotes LOS azimuth angles.

The 3-D relative motion between the missile and the target in Fig. 1 is described by the following three two-order differential equations,

$$\begin{aligned}\ddot{R} &= R\dot{q}_\varepsilon^2 + R\dot{q}_\beta^2\cos^2 q_\varepsilon + a_{Tr} - a_{Mr}\\ \ddot{q}_\varepsilon &= -\frac{2\dot{R}}{R}\dot{q}_\varepsilon - \dot{q}_\beta^2 \sin q_\varepsilon \cos q_\varepsilon + \frac{a_{T\varepsilon} - a_{M\varepsilon}}{R}\\ \ddot{q}_\beta &= -\frac{2\dot{R}}{R}\dot{q}_\beta + 2\dot{q}_\varepsilon\dot{q}_\beta \tan q_\varepsilon - \frac{a_{T\beta} - a_{M\beta}}{R\cos q_\varepsilon}\end{aligned} \tag{1}$$

where a_{Mr}, $a_{M\varepsilon}$ and $a_{M\beta}$ denote the projections of the missile's accelerations on axis Ox_L, Oy_L and Oz_L, respectively. Similarly, a_{Tr}, $a_{T\varepsilon}$ and $a_{T\beta}$ represent the projection of the target's acceleration on axis Ox_L, Oy_L and Oz_L, respectively.

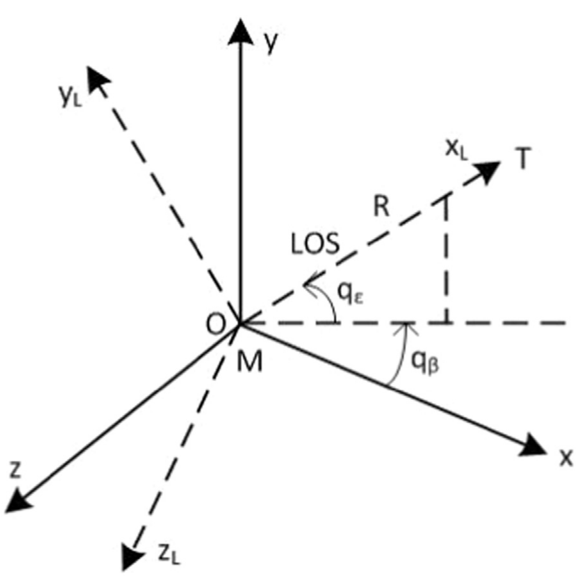

Fig. 1. 3-D interception geometry of the missile and target.

To solve guidance law problem, it needs nullifying the LOS angular rates, i.e., $\dot{q}_\varepsilon$ and $\dot{q}_\beta$ converge to zero by designing the guidance law input $a_{M\varepsilon}$ and $a_{M\beta}$. Then, satisfying miss distance can be guaranteed.

To convenient the guidance law design, we rewrite 3-D relative motion equations (1) in state-space form. Let us define $x_1 = q_\varepsilon$, $x_2 = \dot{q}_\varepsilon$, $x_3 = q_\beta$, $x_4 = \dot{q}_\beta$, then the last two equation of Eq. (1) can be rewritten as follows,

$$\begin{aligned}\dot{x}_1 &= x_2\\ \dot{x}_2 &= -\frac{2\dot{R}}{R}x_2 - x_4^2 \sin x_1 \cos x_1 - \frac{1}{R}(a_{M\varepsilon} - a_{T\varepsilon})\\ \dot{x}_3 &= x_4\\ \dot{x}_4 &= -\frac{2\dot{R}}{R}x_4 + 2x_2x_4 \tan x_1 + \frac{1}{R\cos x_1}(a_{M\beta} - a_{T\beta})\end{aligned} \tag{2}$$

In practice applications, the target's acceleration $a_{T\varepsilon}$ and $a_{T\beta}$ are always treated as external disturbances since the target's accelerations are not easy to obtain and their bounds are used to design controller. In this paper, we address on the target acceleration satisfying weaving maneuver, where $a_{T\varepsilon}$ and $a_{T\beta}$ actually are two unknown sinusoidal signals, generated by the following two unknown exosystem

$$\dot{\chi} = S\chi,\quad \mu_i = l_i^T\chi \tag{3}$$

with $\mu_1 = a_{T\varepsilon}$, $\mu_2 = a_{T\beta}$ and $i=1,2$. $\chi \in \mathbf{R}^q$ is the generator state vector with initial condition $\chi(0)$; $S \in \mathbf{R}^{q\times q}$ is an unknown constant coefficient matrices and l_i is a constant vector of suitable size.

Remark 1. For a target taking weaving maneuver, the maneuver can be decomposed into two sinusoidal motion on axis Oy_L and Oz_L, respectively.

For weaving maneuver of the target, the following assumption holds which is the condition generating sinusoid signal.

Assumption 1. The eigenvalues of S are with zero real parts and distinct, and l_i, $i=1,2$, is a constant vector of suitable size. The pair (S, l_i^T) is observable.

3. Design of guidance law

In this section, a guidance law is presented to ensure stability of the closed-loop system as well as the disturbance rejection of the 3-D guidance system Eq. (2). The design process of guidance law adopts the following routine. Firstly, we design a state feedback nominal guidance law $\bar{\alpha}(x)=[\alpha_1(x), \alpha_2(x)]^T$ which ensures stability of the guidance system with disturbance-free. Secondly, in order to reject the effect of target's maneuver on system performance, an adaptive internal model observer $\hat{\mu}=[\hat{\mu}_1, \hat{\mu}_2]^T$ is designed to estimate $\mu=[\mu_1, \mu_2]^T$, the target acceleration of the guidance system, asymptotically. Combining the above two part guidance laws, we obtain the final guidance law as follows

$$u = [u_1, u_2]^T = \bar{\alpha} + \hat{\mu} \tag{4}$$

where $u_1 = a_{M\varepsilon}$, $u_2 = a_{M\beta}$; $\bar{\alpha} = [\alpha_1, \alpha_2]^T$ and $\hat{\mu} = [\hat{\mu}_1, \hat{\mu}_2]^T$ will be defined later.

3.1. The design of the nominal guidance law $\bar{\alpha}$

When the target has no maneuver, i.e., target acceleration is zero, we design state feedback guidance law to stabilize the guidance system in this subsection. Now, the dynamic of the guidance system (2) will be divided into two subsystems, i.e., (x_1, x_2) and (x_3, x_4), for guidance law design.