Chinese Journal of Aeronautics, (2016), 29(1): 202–214

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Three-dimensional guidance law based on adaptive integral sliding mode control

Song Junhong, Song Shenmin *

Center for Control Theory and Guidance Technology, Harbin Institute of Technology, Harbin 150001, China

Received 19 May 2015; revised 23 June 2015; accepted 3 August 2015
Available online 23 December 2015

KEYWORDS

Adaptive control;
Finite-time convergence;
Integral sliding mode control;
Missile;
Three-dimensional guidance law

Abstract For the terminal guidance problem of missiles intercepting maneuvering targets in the three-dimensional space, the design of guidance laws for non-decoupling three-dimensional engagement geometry is studied. Firstly, by introducing a finite time integral sliding mode manifold, a novel guidance law based on the integral sliding mode control is presented with the target acceleration as a known bounded external disturbance. Then, an improved adaptive guidance law based on the integral sliding mode control without the information of the upper bound on the target acceleration is developed, where the upper bound of the target acceleration is estimated online by a designed adaptive law. The both presented guidance laws can make sure that the elevation angular rate of the line-of-sight and the azimuth angular rate of the line-of-sight converge to zero in finite time. In the end, the results of the guidance performance for the proposed guidance laws are presented by numerical simulations. Although the designed guidance laws are developed for the constant speed missiles, the simulation results for the time-varying speed missiles are also shown to further confirm the designed guidance laws.

1. Introduction

The terminal guidance law design is the basis to realize the precise guidance of missile. The aim of a terminal guidance law is to allow missiles to intercept targets with minimum miss distances.[1] Proportional navigation (PN) guidance law and its variants have been well-known guidance laws, thanks to its high efficiency and ease of implementation in a large variety of interception engagements. However, for the situation of intercepting the targets with a larger maneuverability, PN guidance laws are not able to intercept the targets under the required precision.[2] In order to deal with the maneuverable targets effectively, many researchers have developed various modern robust guidance laws based on different nonlinear control methods, such as H_∞ control,[3] L_2 gain control,[4] differential game,[5] sliding mode control,[6–8] etc.

So far, the sliding mode control (SMC) has been widely used to design controllers because of its good robustness to external disturbances and the uncertainty of the system parameters. The conventional sliding mode control,[9–11] whose sliding mode manifold is a linear function, can only finish the

* Corresponding author. Tel.: +86 451 86402204 8212.
E-mail addresses: hitsjh@163.com (J. Song), songshenmin@hit.edu.cn (S. Song).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2015.12.012
1000-9361

asymptotic convergence in infinite time in the sliding phase. In order to achieve the finite time convergence in the sliding phase, one of the solutions is to apply the terminal sliding mode control (TSMC) whose sliding mode manifold is a nonlinear function.[12,13] In addition, the TSMC can also guarantee that the convergence of the system states is faster, the convergence precision is higher and the system has a better disturbance rejection performance than the traditional linear sliding mode control (LSMC). Therefore, the TSMC has been widely applied to the missile guidance law design problem.[14–18] Another good method is to finish the convergence in finite time by applying the integral sliding mode control (ISMC). A finite time convergent ISMC was proposed by Ref.[19] for a kind of higher order systems, and has been successfully used in the field about the design of the guidance law.[20,21]

In the implementation of the SMC, the switching gain selection is a difficult problem. Generally speaking, for completing the sliding mode reaching condition, we should choose the switching gain larger than the upper bound of external disturbance. So, a necessary assumption is that the disturbance has upper bound and that its upper bound needs to be known in Refs.[13,17]. However, in practical applications, the upper bound of external disturbance is hard to know. To resolve the above-mentioned problem, the adaptive sliding mode control has been studied in much literature.[22–27] The advantage of the adaptive sliding mode control is that it adaptively tunes the switching gain by designing an adaptive law to estimate the value of the upper bound of the disturbance. So, we do not need to know the upper bound on the disturbance in advance.

In practice, the relative motion of target and missile takes place in the three-dimensional (3D) space, and the mathematical model that accurately describes the relation of relative motion of target and missile is complicated nonlinear strong-coupled equations. While designing the guidance law for the missile, the usual method is to decouple the 3D motion into two two-dimensional motions. There exist many researches that designed the guidance laws in the two-dimensional space.[15–17,20,21] However, the method based on the traditional decoupling will lose the guidance information during decoupling and result in a negative effect on terminal guidance accuracy. So, it would be close to reality if the terminal 3D guidance law is developed under the condition of not neglecting the couple among the channels of nonlinear dynamics of target-missile relative movement in the 3D space.

At present, many 3D guidance laws have been developed. For example, a few 3D PN guidance laws were developed in Refs.[28–30]. However, for intercepting a strong maneuvering target, the robustness of such guidance laws is not so well. Based on a geometric method, a 3D guidance law considering angle constraints was developed for the non-maneuvering targets in Ref.[31]. In Refs.[32,33], a 3D guidance law was proposed for maneuvering targets based on a nonlinear backstepping control approach. Note that in Refs.[32,33], the guidance laws were designed for maneuvering targets, but the proposed guidance laws could not guarantee that the system states converge in finite time. Then, in Refs.[34,35], SMC-based 3D guidance laws considering impact angle constraints were proposed. However, in Ref.[34], the guidance law was designed for stationary targets. Although the guidance law was proposed for maneuvering targets in Ref.[35], the information of the target acceleration bound needs to be known in advance. Hence, for the guidance problem in the terminal phase when the missiles intercept the high-speed maneuvering targets, to study the finite time convergent 3D guidance law without any information about the upper bound of the target acceleration is not only theoretically challenging but also practical requirement.

For the guidance problem in the terminal phase when the missiles intercept the high-speed maneuvering targets, the main contribution of this paper is to develop a non-decoupling and finite time convergent 3D guidance law and without the knowledge of the bound on the target acceleration in advance. First of all, based on the ISMC, a new 3D integral sliding mode (ISM) guidance law is put forward in the 3D environment, which can guarantee the finite time convergence of guidance system states. Then, a novel 3D adaptive integral sliding mode (AISM) guidance law with the finite time convergence is proposed by combination of the ISMC and adaptive control technique which is used to estimate the unknown upper bound of the target acceleration.

2. Formulation of guidance model

In this section, the target-missile relative motion equations for the 3D guidance system are presented. Fig. 1 shows the 3D interception geometry. T denotes the target, M the missile, $Oxyz$ a inertial reference frame, $Ox_1y_1z_1$ a line-of-sight (LOS) frame and R the relative distance between the target and missile; q_ε and q_β are the elevation and azimuth angles of the LOS, respectively.

Regard the missile and the target as point mass in designing guidance laws and the velocities of the missile and the target; $V_{\rm M}$ and $V_{\rm T}$, are assumed to be constants. 3D relative motion geometry of missile and target, as given in Fig. 1, can be expressed by the following differential equations[17]:

$$\ddot{R} - R\dot{q}_\varepsilon^2 - R\dot{q}_\beta^2\cos^2 q_\varepsilon = a_{{\rm T}R} - a_{{\rm M}R} \tag{1}$$

$$R\ddot{q}_\varepsilon + 2\dot{R}\dot{q}_\varepsilon^2 + R\dot{q}_\beta^2 \sin q_\varepsilon \cos q_\varepsilon = a_{{\rm T}\varepsilon} - a_{{\rm M}\varepsilon} \tag{2}$$

$$-R\ddot{q}_\beta \cos q_\varepsilon - 2\dot{R}\dot{q}_\beta \cos q_\varepsilon + 2R\dot{q}_\varepsilon\dot{q}_\beta \sin q_\varepsilon = a_{{\rm T}\beta} - a_{{\rm M}\beta} \tag{3}$$

where $\boldsymbol{a}_{\rm M} = \left[a_{{\rm M}R}, a_{{\rm M}\varepsilon}, a_{{\rm M}\beta}\right]$ and $\boldsymbol{a}_{\rm T} = \left[a_{{\rm T}R}, a_{{\rm T}\varepsilon}, a_{{\rm T}\beta}\right]$ are the vectors of the missile's acceleration and target's acceleration in the LOS frame, respectively.

From Eqs. (2) and (3), it can be obtained that there exist serious cross couplings between the elevation and the azimuth channels of the LOS.

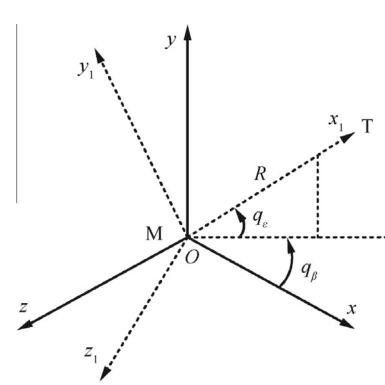

Fig. 1 Three-dimensional interception geometry.