Chinese Journal of Aeronautics, (2016), 29(4): 984–994

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Trajectory reshaping based guidance with impact time and angle constraints

Zhao Yao, Sheng Yongzhi *, Liu Xiangdong

School of Automation, Beijing Institute of Technology, Beijing 100081, China
Key Laboratory for Intelligent Control and Decision of Complex Systems, Beijing Institute of Technology, Beijing 100081, China

Received 12 September 2015; revised 29 February 2016; accepted 10 April 2016
Available online 22 June 2016

KEYWORDS

Guidance;
Homing missiles;
Impact angle;
Impact time;
Trajectory reshaping

Abstract This study presents a novel impact time and angle constrained guidance law for homing missiles. The guidance law is first developed with the prior-assumption of a stationary target, which is followed by the practical extension to a maneuvering target scenario. To derive the closed-form guidance law, the trajectory reshaping technique is utilized and it results in defining a specific polynomial function with two unknown coefficients. These coefficients are determined to satisfy the impact time and angle constraints as well as the zero miss distance. Furthermore, the proposed guidance law has three additional guidance gains as design parameters which make it possible to adjust the guided trajectory according to the operational conditions and missile's capability. Numerical simulations are presented to validate the effectiveness of the proposed guidance law.
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1. Introduction

A major objective of terminal guidance is to achieve a minimum miss distance.[1,2] Current guidance applications, however, also require to impose additional terminal constraints like impact angle and impact time to improve the guidance performance. In order to enhance the effectiveness of the warhead, a particular terminal impact angle should be specified. By comparison, the impact time constraint is imposed to achieve a salvo attack or a cooperative attack for homing missiles, which can greatly enhance the survivability of the missile against advanced defense systems. Due to these important reasons, the guidance laws with multiple terminal constraints have been extensively studied in the past few decades.

Since the concept of impact angle guidance was initially reported in 1973,[3] a large amount of work has been performed towards solving this problem. As a typical work in this area, modified proportional navigation guidance (PNG) laws were investigated to fulfill the impact angle constraints.[4–8] Except for the modified PNG, some other control methods, such as optimal control,[9–11] suboptimal control[12–14] and sliding mode control (SMC),[15–18] have also been utilized to derive the impact angle constrained guidance laws. Compared with the impact angle control laws, the studies on the impact time control guidance law are relatively rare.[19–22]

* Corresponding author. Tel.: +86 10 68912460.
E-mail addresses: shine3y9r@126.com (Y. Zhao), shengyongzhi@bit.edu.cn (Y. Sheng), xdliu@bit.edu.cn (X. Liu).

Peer review under responsibility of Editorial Committee of CJA.

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http://dx.doi.org/10.1016/j.cja.2016.06.012
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The guidance scheme proposed in Ref.[23] initiated the research area where both impact angle and impact time are constrained. From then on, there have been some valuable contributions made in this field.[24–27] Through a combination of line-of-sight (LOS) rate shaping process and a second-order SMC approach, an impact time and angle (ITA) guidance law was developed in Ref.[24] for engaging a modern warfare ship. A closed-form ITA guidance law was presented in Ref.[25], where a feedback term was added to a specially constructed biased PNG to satisfy the ITA constraints. In Ref.[26], an optimal ITA guidance scheme for the nonlinear missile model was derived, which not only ensured the ITA requirements but achieved the minimum integral square control efforts as well. Based on the polynomial guidance law analyzed in Refs.[28,29], an augmented polynomial guidance law was devised in Ref.[27] to solve the ITA guidance problem. With the proper selection of the guidance gains, the generated homing trajectory turned out to be quite similar to the optimal solution.

In this paper, a new closed-form ITA guidance law is developed for homing missiles. The focus is first placed on engaging a stationary target. To derive the proposed guidance law, a trajectory reshaping process is introduced. This process results in defining a specific polynomial function with two unknown coefficients. One is tuned to adjust the length of the homing trajectory so as to achieve the impact time requirement. The other is determined to make the polynomial function equal to zero at each time step, so that the terminal impact angle constraint as well as the zero miss distance can be satisfied. Using the obtained solutions of the two coefficients, the guidance command can be expressed as a combination of an impact angle control law and a bias term, which is incorporated to annul the impact time error. After well developed, the guidance law is further extended to deal with maneuvering targets using the notion of predicted interception point (PIP). The associated modification in the guidance command with respect to a maneuvering target is also illustrated.

With respect to the previously published ITA guidance methods, the proposed guidance scheme could provide several advantages in the following aspects. Firstly, the approach developed in Ref.[24] requires an optimization routine to generate feasible LOS angle and rate profiles that meet the impact time and angle constraints, whereas such process is not needed in the implementation of the proposed ITA guidance law. Secondly, as long as the engagement conditions are determined, the guidance laws in Refs.[23,25] would result in certain homing trajectories. The proposed law, however, has three guidance gains as design parameters which can be utilized to shape the homing trajectory and command profile in accordance with the missile's capability. In particular, the guided trajectories could exhibit similar behavior to the energy optimal solutions by choosing proper guidance gains for a given engagement. Although the numerical guidance strategy investigated in Ref.[26] could minimize the integral square control efforts, it requires to solve the two point boundary value problem on line and additional computational burdens would be imposed on the missile-borne computer. So its practical application is limited. Thirdly, while the works in Refs.[23,25–27] just focused on stationary targets, this work also lays emphasis on engaging targets that are maneuvering.

2. System model and problem formulation

Consider a planar homing engagement between the missile M and the target T as depicted in Fig. 1. The missile is assumed to be traveling at a constant velocity V and the target is assumed to be stationary. The positions of the missile and the target in the inertial X–Y coordinate are denoted as (x, y) and (x_f, y_f), respectively. The missile's heading angle is represented by θ. The acceleration command u is applied normal to the missile's velocity vector.

The equations of motion for the homing engagement are given as[9]

$$\begin{cases} \dot{x} = V\cos\theta \\ x(t_0) = x_0,\ x(t_f) = x_f \end{cases} \tag{1}$$

$$\begin{cases} \dot{y} = V\sin\theta \\ y(t_0) = y_0, \quad y(t_f) = y_f \end{cases} \tag{2}$$

$$\begin{cases} \dot{\theta} = \dfrac{u}{V} \\ \theta(t_0) = \theta_0, \quad \theta(t_f) = \theta_f \end{cases} \tag{3}$$

where t_0 and t_f are the initial launch time and the designated impact time, respectively; θ_f is the desired impact angle. Note that the values of t_f and θ_f are determined before the missile is launched.

The design goal of the ITA guidance law can be summarized as follows. It is equivalent to designing a controller u such that

$$\lim_{t\to t_f} x \to x_f,\ \lim_{t\to t_f} y \to y_f,\ \lim_{t\to t_f} \theta \to \theta_f \tag{4}$$

It can be observed from Eqs. (1)–(3) that the equations of motion treat t as the independent variable. In terms of the homing guidance problem, however, the downrange x is a better choice for the independent variable due to the fact that x_f always corresponds to the target's location while t_f varies with different selections of impact time.[24] Hence, with respect to the independent variable x, a new set of equations of motion can be derived as

$$\begin{cases} y' = \tan\theta \\ y(x_0) = y_0, \quad y(x_f) = y_f \end{cases} \tag{5}$$

$$\begin{cases} \theta' = \dfrac{u}{V^2\cos\theta} \\ \theta(x_0) = \theta_0, \quad \theta(x_f) = \theta_f \end{cases} \tag{6}$$

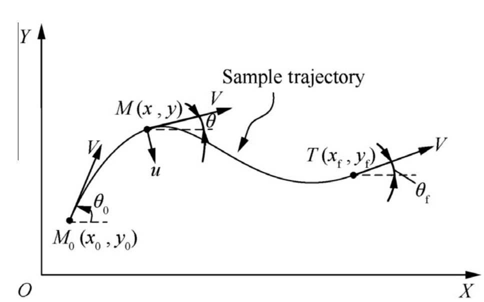

Fig. 1 Engagement geometry.

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