Chinese Journal of Aeronautics, (2015), **28**(4): 1104–1120

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Three-dimensional cooperative guidance laws against stationary and maneuvering targets

Zhao Jiang *, Zhou Rui, Dong Zhuoning

School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China

Received 28 November 2014; revised 25 February 2015; accepted 24 March 2015
Available online 21 June 2015

KEYWORDS

Coordination algorithms;
Maneuvering target;
Missile guidance;
Multiple missiles;
Three-dimensional (3-D)

Abstract This paper presents the cooperative strategies for salvo attack of multiple missiles based on the classical proportional navigation (PN) algorithm. The three-dimensional (3-D) guidance laws are developed in a quite simple formulation that consists of a PN component for target capture and a coordination component for simultaneous arrival. The centralized algorithms come into effect when the global information of time-to-go estimation is obtained, whereas the decentralized algorithms have better performance when each missile can only collect information from neighbors. Numerical simulations demonstrate that the proposed coordination algorithms are feasible to perform the cooperative engagement of multiple missiles against both stationary and maneuvering targets. The effectiveness of the 3-D guidance laws is also discussed.

1. Introduction

Numerous advanced guidance laws have been presented in the last decade to improve the performance of traditional proportional navigation (PN) algorithm for some specific objectives such as the minimum time control, minimum energy control, impact time control and impact angle control.[1–4] For a single missile, the above objectives have already been achieved with satisfied accuracy of target capture.[5–7] Therefore, many researchers start recently on the development of cooperative guidance laws for salvo attack of multiple missiles because they may have better performance than the individual missile system in detecting the maneuvering targets, penetrating the defense systems, and surviving the threats.[8–11] However, it is more difficult to achieve a simultaneous attack against the maneuvering target in the light of different initial conditions and the communication limitation between each missile.[12–14]

In the current literature, two typical classes of approaches have been proposed to develop the cooperative guidance laws for the multimissile salvo attack. The first class investigates the design of the impact-time constraint for the coordination of the time-to-go. Jeon et al.[15] introduced the closed form of impact time control guidance (ITCG) law based on the linear formulation. It can guide a group of missiles to simultaneously intercept a stationary target at a desirable time. Later, Lee et al.[16] presentd an extension of the ITCG guidance law to control both the impact time and the impact angle. Regarding the two algorithms above, it is required that the global information of the time-to-go is available to each group member. To improve the performance of the ITCG, Zhao and Zhou[17]

* Corresponding author. Tel.: +86 10 82316849.
E-mail addresses: jzhao@buaa.edu.cn (J. Zhao), zhr@buaa.edu.cn (R. Zhou), dongzhuoning@buaa.edu.cn (Z. Dong).

Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2015.06.003
1000-9361

proposed the distributed control architecture based on the consensus protocols. Peng et al.[18] also applied the consensus theory to design the cooperative guidance laws by using the discrete topology model to feature the desired impact time.

The second class of approaches employs the leader–follower model to describe the multimissile salvo attack. Based on the traditional PN guidance law, Zhang et al.[19] developed a leader–follower strategy to achieve the simultaneous attack of multiple missiles, in which the rang-to-go and heading angle error of the leader are selected as the reference state variables. Zhao et al.[20] proposed a virtual leader scheme that achieves the impact time control indirectly by transforming the time-constrained guidance problem to the nonlinear tracking problem. In addition, Sun et al.[21] designed the cooperative guidance law by feedback linearization to drive the impact time of each follower to converge to the leader in finite time.

More recently, Ghosh et al.[22] developed a recursive time-to-go estimation method for three-dimensional (3-D) engagement of a retro-PN guided interceptor with higher speed non-maneuvering targets. They presented a navigation gain scheduling algorithm to achieve the interception at a pre-specified time. Later, Ghosh et al.[23] discussed a cooperative strategy for the lower speed interceptors guided by Retro-PN guidance law to perform the salvo attack against a higher speed target. These are early efforts to solve the cooperative guidance against moving targets in 3-D engagement.

Most of the current studies such as Refs.[15–21] only take into account the planar pursuit situation to design the guidance laws for cooperative engagement. It is more difficult to develop the cooperative strategies in 3-D engagement like Refs.[22,23]. In addition, there remain rare studies on the decentralized coordination algorithm for the interceptor missiles to achieve a simultaneous attack against a maneuvering target. Therefore, we focus on the design of 3-D cooperative strategies for multi-missile salvo attack. The contribution of the paper is described as follows: (1) the paper modifies the time-to-go expression in Ref.[24] for an extension to the 3-D engagement. Considering the heading errors between the missile and target, the time-to-go estimation is enhanced for interceptor missiles against the maneuvering targets; (2) the cooperative strategies are developed in a simple formulation that consists of a PN component and a coordination component. The centralized algorithms come into effect when the global information of time-to-go estimation is available, whereas the decentralized algorithms have better performance when the interceptor missiles can only collect information from neighbors.

2. Preliminaries

2.1. Basic assumptions

To perform the complete missile-target engagement, the nonlinear dynamics of 3-D pursuit situation is considered in this paper. We assume the following conditions to facilitate the capturability analysis of the cooperative guidance laws:

(1) The angle of attack of the missile is small enough to be neglected.
(2) The total velocities of the missile and target are set to constant values.
(3) The missile and target are considered as point masses moving in the 3-D space.
(4) The seeker and autopilot dynamics of the missile are fast enough in comparison with the guidance loop.

2.2. Guidance geometry

Under the prescribed assumptions, the guidance geometry on one-to-one engagement is depicted in Fig. 1, where M denotes the missile and T denotes the target; r is the missile-to-target range; V_{m} and V_{t} are the total velocities of the missile and target; the terms γ_{m} , γ_{t} , φ_{m} and φ_{t} are Euler angles in the inertial reference frame, whereas the angles θ_{m} , θ_{t} , ψ_{m} and ψ_{t} are defined with respect to the line-of-sight frame; γ_{L} and φ_{L} are the line-of-sight angles in the inertial reference frame.

The 3-D point-mass equations of motion for the missile and target can be derived from the classical principles of dynamics[25,26]

$$\dot{r} = V_{\mathrm{m}}(\rho\cos\theta_{\mathrm{t}}\cos\psi_{\mathrm{t}} - \cos\theta_{\mathrm{m}}\cos\psi_{\mathrm{m}}) \tag{1}$$

$$r\dot{\lambda}_y = V_{\mathrm{m}}(\sin\theta_{\mathrm{m}} - \rho\sin\theta_{\mathrm{t}}) \tag{2}$$

$$r\dot{\lambda}_z = V_{\mathrm{m}}(\rho\cos\theta_{\mathrm{t}}\sin\psi_{\mathrm{t}} - \cos\theta_{\mathrm{m}}\sin\psi_{\mathrm{m}}) \tag{3}$$

$$\begin{aligned}\dot{\theta}_{\mathrm{m}} = {} & a_{z\mathrm{m}}/V_{\mathrm{m}} + V_{\mathrm{m}}\tan\lambda_y\sin\psi_{\mathrm{m}} \\ & \times(\rho\cos\theta_{\mathrm{t}}\sin\psi_{\mathrm{t}} - \cos\theta_{\mathrm{m}}\sin\psi_{\mathrm{m}})/r \\ & - V_{\mathrm{m}}\cos\psi_{\mathrm{m}}(\rho\sin\theta_{\mathrm{t}} - \sin\theta_{\mathrm{m}})/r\end{aligned} \tag{4}$$

$$\begin{aligned}\dot{\psi}_{\mathrm{m}} = {} & a_{y\mathrm{m}}/(V_{\mathrm{m}}\cos\theta_{\mathrm{m}}) - V_{\mathrm{m}}\sin\theta_m\sin\psi_{\mathrm{m}} \\ & \times(\rho\sin\theta_{\mathrm{t}} - \sin\theta_m)/(r\cos\theta_{\mathrm{m}}) \\ & - V_{\mathrm{m}}(\rho\cos\theta_{\mathrm{t}}\sin\psi_{\mathrm{t}} - \cos\theta_{\mathrm{m}}\sin\psi_{\mathrm{m}})/r \\ & - V_{\mathrm{m}}\sin\theta_{\mathrm{m}}\cos\psi_m\tan\lambda_y(\rho\cos\theta_{\mathrm{t}}\sin\psi_{\mathrm{t}} \\ & - \cos\theta_{\mathrm{m}}\sin\psi_{\mathrm{m}})/(r\cos\theta_{\mathrm{m}})\end{aligned} \tag{5}$$

$$\begin{aligned}\dot{\theta}_{\mathrm{t}} = {} & a_{z\mathrm{t}}/(\rho V_{\mathrm{m}}) + V_{\mathrm{m}}\tan\lambda_y\sin\psi_{\mathrm{t}}(\rho\cos\theta_{\mathrm{t}}\sin\psi_{\mathrm{t}} \\ & - \cos\theta_{\mathrm{m}}\sin\psi_{\mathrm{m}})/r - V_{\mathrm{m}}\cos\psi_{\mathrm{t}}(\rho\sin\theta_{\mathrm{t}} - \sin\theta_{\mathrm{m}})/r\end{aligned} \tag{6}$$

$$\begin{aligned}\dot{\psi}_{\mathrm{t}} = {} & a_{y\mathrm{t}}/(\rho V_{\mathrm{m}}\cos\theta_{\mathrm{t}}) - V_{\mathrm{m}}\sin\theta_{\mathrm{t}}\sin\psi_{\mathrm{t}}(\rho\sin\theta_{\mathrm{t}} \\ & - \sin\theta_{\mathrm{m}})/(r\cos\theta_t) - V_{\mathrm{m}}(\rho\cos\theta_{\mathrm{t}}\sin\psi_{\mathrm{t}} \\ & - \cos\theta_{\mathrm{m}}\sin\psi_{\mathrm{m}})/r - V_{\mathrm{m}}\sin\theta_{\mathrm{t}}\cos\psi_{\mathrm{t}}\tan\lambda_y(\rho\cos\theta_{\mathrm{t}}\sin\psi_{\mathrm{t}} \\ & - \cos\theta_{\mathrm{m}}\sin\psi_{\mathrm{m}})/(r\cos\theta_{\mathrm{t}})\end{aligned} \tag{7}$$

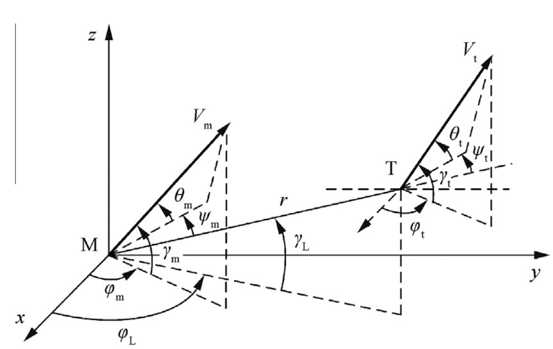

Fig. 1 Guidance geometry on one-to-one engagement.