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Research article

Three-dimensional impact angle constrained distributed guidance law design for cooperative attacks☆

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ABSTRACT

In this paper, a novel cooperative guidance law is proposed to make multiple missiles in the three-dimensional (3-D) space hit simultaneously the same target at pre-specified impact angles. Firstly, the normal accelerations which change the velocity direction (flight-path and heading angle) are designed such that all missiles will fly along the desired line of sight (LOS) after a given time which ensures the hit-to-kill interception at the desired impact angles; then the consensus variable is constructed using available information and can reach consensus under the proposed tangential acceleration which determines the velocity magnitude. Hence simultaneous hit-to-kill attack is achieved. Finally, some simulation studies are performed to verify the effectiveness of the proposed scheme.

1. Introduction

In the problem of missile interception, it is desired to obtain a minimum miss distance, and also satisfy terminal constraints such as impact angle and impact time. The motivation for achieving particular terminal impact angles stems from the requirement of increasing the lethality of the warhead [1]; for example, the top attack is preferable in the anti-tank application since tanks are vulnerable from the top [2]. As antimissile defence systems (such as close-in weapon systems (CIWS)) [38,39] have been developed, it may be crucial for a single missile to destroy a large target equipped with CIWS. Because CIWS features one-to-one engagement, a salvo attack that introduces a many-to-one scenario can be a promising strategy [3]. In salvo attack, multiple missiles hit the same target simultaneously. Hence to achieve a successful salvo attack against any target, control over time of interception (called the impact time) is necessary.

In this research area, the emphasis was initially concentrated on achieving a certain impact angle. Since 1973 when Kim and Grider [4] reported the concept of impact angle guidance, much has been achieved in this area [5–10]. A simultaneous attack of a group of missiles against a single common target can be achieved by two ways. The first approach is individual homing, in which a common impact time is commanded to all members in advance, and thereafter each missile tries to home on the target on time independently. The second is cooperative homing, in which the missiles communicate among themselves to synchronize the arrival time. The earlier results on individual homing were usually based on the linearized engagement dynamics under the small angle assumption of the missile's flight-path angle [11–14], which is called the linear approach; the nonlinear approach considering the full nonlinear engagement kinematics is based on the Lyapunov stability theory [15–18]. To the best knowledge of the authors, studies on the cooperative approach are rare [19,20].

It is noted that in Refs. [15–19] the time-to-go was used explicitly in the command formulas, and thus accurate estimation of the time-to-go is crucial to their performance. However, it is very difficult to accurately estimate time-to-go, especially in a salvo attack where the missile may employ various maneuvers (resulting in a curved trajectory) to achieve the simultaneous attack. In addition, the global information of the whole group is required to ensure cooperative attack in Ref. [19]. Using only the neighbours' information, a cooperative guidance law was designed in Ref. [20], however, the impact time angle

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constraint was not considered. In addition, the assumption that the heading error is small was made in Ref. [20]. More importantly, it is assumed that the missiles are moving in the plane in Refs. [11–20], however, in practice, the missiles fly in the 3-D space. To the authors' best knowledge, cooperative guidance law design for salvo attack in the 3-D space has not been reported.

In this paper, a distributed cooperative guidance law is proposed to make multiple missiles in the 3-D space attack the same target simultaneously at the desired impact angles. The whole design consists of two parts: Firstly, the normal accelerations are designed to make the elevation and azimuth LOS angle errors and theirs rates converge to zero at the given time. Thereafter all missiles will fly along the desired LOS and hence a hit-to-kill interception at the desired impact angles is ensured. Secondly, the tangential acceleration is designed to make the consensus variable defined using available information reach consensus, and hence the simultaneous attack is achieved. During the design of the tangential acceleration, only the neighbours' information not the whole information is used.

The structure of this paper is organized as follows. In Section 2, the problem formulation including model description, communication topology and interception strategy are given. Next design details (normal design and tangential design) are presented in Section 3. Finally, simulations are conducted in Section 4 and conclusions are drawn in Section 5.

2. Problem formulation

Consider the scenario that a group of n missiles attack a stationary target in the 3-D space (see Fig. 1). Denote $\lambda_{E,i}$ and $\lambda_{A,i}$ as the elevation and azimuth angle of LOS for the ith missile, respectively (which are defined as impact angles in this paper); their desired values are denoted as $\lambda^*_{E,i}$ and $\lambda^*_{A,i}$, respectively. The impact time of the ith missile is $T_{f,i}$. The main objective of this paper is listed as follows:

1. to have all missiles hit the stationary target simultaneously, namely $T_{f,i} = T_{f,j}$;
2. to have the impact angles reach the desired values, namely $\lambda_{E,i}(T_{f,i}) = \lambda^*_{E,i}$ and $\lambda_{A,i}(T_{f,i}) = \lambda^*_{A,i}$,

where $\lambda_{E,i}(T_{f,i})$ and $\lambda_{A,i}(T_{f,i})$ denote the impact angle of the ith missile at the impact time $T_{f,i}$.

2.1. Model description

In Fig. 2 a schematic view of the 3-D interception geometry between the ith missile and the target is shown, where M and T denote the ith missile and target respectively. $o - x_I - y_I - z_I$ is a cartesian inertial reference frame fixed on the ground, $M - x_L - y_L - z_L$ and $M - x_V - y_V - z_V$ denote the LOS coordinate system and the velocity coordinate system, respectively, fixed on the missile. V_M, φ_M and γ_M denote the speed, heading angle and flight-path angle of

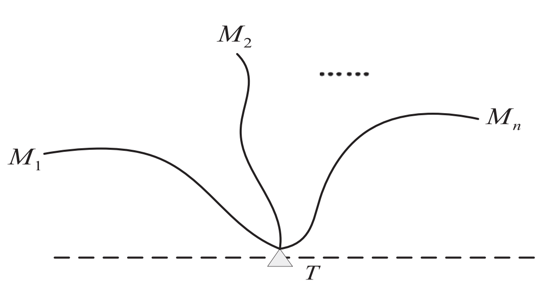

Fig. 1. n missiles attack a stationary target simultaneously.

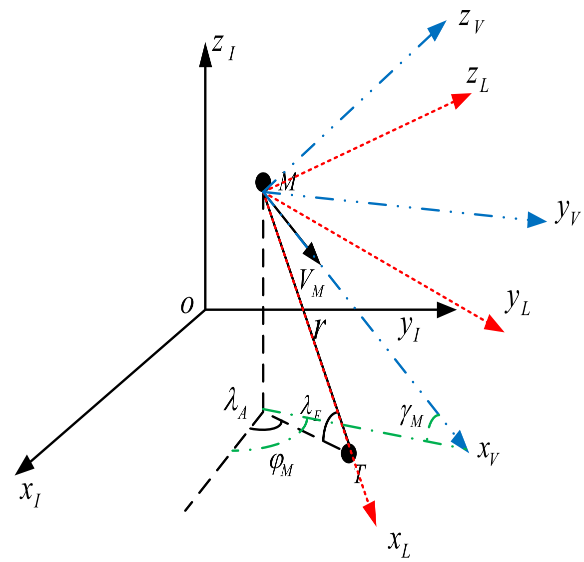

Fig. 2. 3-D interception geometry.

missile, respectively. Assume the target is stationary. λ_E and λ_A are the elevation and azimuth angle of LOS, respectively; r is the relative range between the missile and target (namely (remaining) range-to-go).

From Fig. 2, the engagement dynamics of the ith missile and target is given as [31]

$$\begin{aligned} &\ddot{r} - r\dot{\lambda}_E^2 - r\dot{\lambda}_A^2\cos^2\lambda_E = -a_r \\ &r\ddot{\lambda}_E + 2\dot{r}\dot{\lambda}_E + r\dot{\lambda}_A^2\sin\lambda_E\cos\lambda_E = -a_E \\ &-r\ddot{\lambda}_A\cos\lambda_E - 2\dot{r}\dot{\lambda}_A\cos\lambda_E + 2r\dot{\lambda}_E\dot{\lambda}_A\sin\lambda_E = -a_A \end{aligned} \tag{1}$$

where a_r, a_E and a_A are acceleration components of the ith missile in the LOS frame.

The coordinate transformation matrix between the inertial frame $o - x_I - y_I - z_I$ and the LOS frame $M - x_L - y_L - z_L$ is given by

$$L_1(\lambda_A, \lambda_E) = \begin{bmatrix} \cos\lambda_E\cos\lambda_A & \sin\lambda_E & -\cos\lambda_E\sin\lambda_A \\ -\sin\lambda_E\cos\lambda_A & \cos\lambda_E & \sin\lambda_E\sin\lambda_A \\ \sin\lambda_A & 0 & \cos\lambda_A \end{bmatrix} \tag{2}$$

The coordinate transformation matrix between the inertial frame $o - x_I - y_I - z_I$ and the velocity frame $M - x_V - y_V - z_V$ is given by

$$L_2(\varphi_M, \gamma_M) = \begin{bmatrix} \cos\gamma_M\cos\varphi_M & \sin\gamma_M & -\cos\gamma_M\sin\varphi_M \\ -\sin\gamma_M\cos\varphi_M & \cos\gamma_M & \sin\gamma_M\sin\varphi_M \\ \sin\varphi_M & 0 & \cos\varphi_M \end{bmatrix} \tag{3}$$

Denote the acceleration components of the ith missile in the inertial frame and the velocity frame as a_x, a_y, a_z and a_t, a_γ, a_φ, respectively, then from the coordinate transformation matrix L_1 and L_2, it follows that

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = L_1^{-1}\begin{bmatrix} a_r \\ a_E \\ a_A \end{bmatrix} \tag{4}$$

and

$$\begin{bmatrix} a_t \\ a_\gamma \\ a_\varphi \end{bmatrix} = L_2\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = L_2L_1^{-1}\begin{bmatrix} a_r \\ a_E \\ a_A \end{bmatrix} \tag{5}$$

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