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Obstacle avoidance for multi-missile network via distributed coordination algorithm

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Abstract A distributed coordination algorithm is proposed to enhance the engagement of the multi-missile network in consideration of obstacle avoidance. To achieve a cooperative interception, the guidance law is developed in a simple form that consists of three individual components for target capture, time coordination and obstacle avoidance. The distributed coordination algorithm enables a group of interceptor missiles to reach the target simultaneously, even if some member in the multi-missile network can only collect the information from nearest neighbors. The simulation results show that the guidance strategy provides a feasible tool to implement obstacle avoidance for the multi-missile network with satisfactory accuracy of target capture. The effects of the gain parameters are also discussed to evaluate the proposed approach.

1. Introduction

As the need for highly adaptive guidance and control approaches is increasing, obstacle avoidance techniques have been proposed for the unmanned aerial vehicles,[1–3] ground vehicles,[4,5] unmanned surface vehicles,[6,7] autonomous underwater vehicles,[8,9] and mobile robots.[10,11] Considering that the group of interceptor missiles is guided in the complex environment, the threat avoidance and geopolitical restrictions are also indispensable to the development of guidance and control systems. For this reason, some studies have recently focused on the design of the reference routes[12] and guidance laws[13] for obstacle avoidance. However, only the single interceptor missile was considered in the above work. To improve the performance in detecting the targets and penetrating the defense systems, the implement of cooperative engagement for multi-missile network is required.[14–17] The difficult problem is an achievement of obstacle avoidance for multi-missile network with satisfactory accuracy of target capture as well as effective coordination of impact time between each member.[18–20]

In the current literature, many advanced cooperative guidance laws have been proposed for the multi-missile networks. The first class of approaches investigates the design of the impact-time constraints to achieve a simultaneous interception against the given target. In Ref.[21], the closed form of impact time control guidance law is developed on the basis of the linear formulation, which can guide a group of missiles to the target at a desirable time. Then, the time-varying navigation gain is used to coordinate the impact time of the multi-missile net-

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work.[22] The extensions of the time-constrained guidance law are also presented to control both the impact time and impact angle.[23,24] The above guidance strategies typically require that the global information of time-to-go is available to each interceptor missile. For this reason, the distributed control architecture of the impact-time constraint is proposed to enhance the cooperative engagement of multiple missiles.[25,26] The discrete topology model is also used to feature the desired impact time using the consensus theory.[27]

Another class of approaches employs the leader–follower model to formulate the cooperative guidance problem for the multi-missile network. In Refs.[28,29], a nonlinear state tracking controller and a state regulator are developed to solve the time-constrained guidance, respectively. Then, the consensus protocols are applied to the design of leader–follower strategy which guarantees that the impact time of each follower can converge to the leader in finite time.[30] To facilitate the heterogeneous multi-missile engagement, a distributed leader–follower model is proposed on the basis of proportional navigation (PN) guidance law.[31] Furthermore, the virtual leader scheme is also employed to achieve the impact time control by transforming the constrained guidance problem to the nonlinear tracking problem.[32]

Although the aforementioned design of the impact-time constraints[21–27] and leader–follower strategies[28–32] have promoted the development of the coordination algorithms for the multi-missile networks, the obstacle avoidance is not taken into account in these cooperative guidance approaches. Therefore, this paper presents an extension of the PN-based distributed guidance algorithm to enhance the engagement of the multi-missile network in consideration of obstacle avoidance. The contribution of the manuscript is summarized as follows: (1) the PN-based guidance law is developed in a simple form that consists of three individual components for target capture, time coordination and obstacle avoidance; (2) each member in the multi-missile network only requires the information of time-to-go from neighbors to perform a cooperative engagement; (3) the obstacle avoidance is achieved with satisfactory accuracy of target capture as well as effective coordination of impact time.

The rest of paper is organized as follows. Section 2 presents the basic assumptions and the engagement geometry. Section 3 describes the formulation of cooperative strategy in detail. In Section 4, the feasibility of the proposed guidance law is demonstrated by numerical simulation. Section 5 presents the performance evaluation by discussing the effect of gain parameters. Finally, concluding remarks are presented in Section 6.

2. Preliminaries

2.1. Basic assumptions

To simplify the nonlinear dynamics of the missile-target engagement, the pursuit situation in planar plane is considered in this paper. We assume some common conditions in the following part to facilitate the formulation of distributed coordination algorithm for the multi-missile network.

(1) Both the interceptor missile and the target are considered as the geometric points in the planar plane.
(2) The seeker and autopilot dynamics of each interceptor missile are much faster in comparison with the guidance loop.
(3) The velocity of each interceptor missile is constant and the acceleration input only changes its direction.

2.2. Engagement geometry

Suppose that n missiles participate in the multi-missile network to intercept a stationary target simultaneously. Under the prescribed assumptions, the two-dimensional geometry on many-to-one engagement is depicted in Fig. 1. Let M_i denote each interceptor missile and T denote the target, and then, the pursuit situation can be described by the following equations of motion[33,34]

$$\begin{cases} \dot{r}_i = -V_i \cos\theta_i \\ \dot{\lambda}_i = \dfrac{-V_i \sin\theta_i}{r_i} \\ \dot{\gamma}_i = \dfrac{A_i}{V_i} \\ \theta_i = \gamma_i - \lambda_i \end{cases} \tag{1}$$

where the subscript ($i = 1, 2, \ldots, n$) represents each member in the multi-missile network; r_i is the missile-to-target range; V_i is the total velocity of each missile; λ_i is the line-of-sight angle; the terms γ_i and θ_i represent the heading angles in the inertial reference frame and line-of-sight frame, respectively; the acceleration command is defined as A_i.

The problem studied herein is to find the coordination algorithm that can guide the group of missiles to the given target at the same time without obstacle collision, even if the initial conditions of each member are different.

3. Distributed coordination algorithm

Based on the traditional PN guidance law, this section focuses on the design of the coordination algorithm for the multi-missile network in the distributed formulation. The proposed cooperative guidance law consists of three individual components as

$$A_i = A_{\mathrm{p}i} + A_{\xi i} + A_{\mathrm{a}i} \tag{2}$$

where the terms $A_{\mathrm{p}i}$, $A_{\xi i}$ and $A_{\mathrm{a}i}$ are used for the target capture, time coordination and obstacle avoidance, respectively.

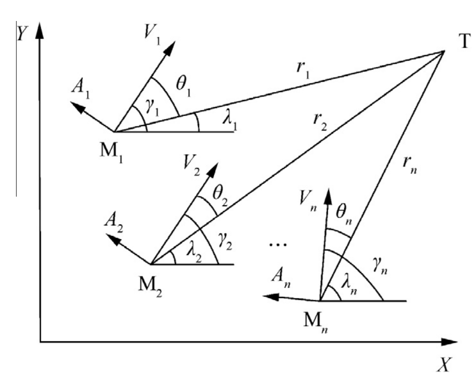

Fig. 1 Geometry on many-to-one engagement.