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A novel cooperative mid-course guidance scheme for multiple intercepting missiles

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Abstract In the interception engagement, if the target movement information is not accurate enough for the mid-course guidance of intercepting missiles, the interception mission may fail as a result of large handover errors. This paper proposes a novel cooperative mid-course guidance scheme for multiple missiles to intercept a target under the condition of large detection errors. Under this scheme, the launch and interception moments are staggered for different missiles. The earlier launched missiles can obtain a relatively accurate detection to the target during their terminal guidance, based on which the latter missiles are permitted to eliminate the handover error in the mid-course guidance. A significant merit of this scheme is that the available resources are fully exploited and less missiles are needed to achieve the interception mission. To this end, first, the design of cooperative handover parameters is formulated as an optimization problem. Then, an algorithm based on Monte Carlo sampling and stochastic approximation is proposed to solve this optimization problem, and the convergence of the algorithm is proved as well. Finally, simulation experiments are carried out to validate the effectiveness of the proposed cooperative scheme and algorithm.

1. Introduction

With the progress of science and technology, modern defense system has been developed dramatically in recent years. For most of the invading targets such as exo-atmospheric ballistic missiles, an interception by direct hit has been realized as an efficient approach.[1] Since an early warning system can track these targets accurately, they are easily captured by the seeker of an intercepting missile at the handover point. Moreover, the handover error is consequently within the missile's maneuverability, which guarantees that the miss distance of a single missile is small enough to kill the target. However, some specific targets developed in recent years become more difficult to track by a ground-based radar or even a space-based target tracking system, such as supersonic cruise missile. Thus, in the mid-course guidance, an enough accurate prediction of the target's trajectory is not available to a missile any more.

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This leads to increasing handover errors, which accordingly result in a large terminal miss distance with the same maneuverability.

To achieve a successful interception, cooperation among multiple missiles becomes a promising alternative. On the one hand, the performance of target tracking is improved in the terminal guidance stage via information sharing among the intercepting missiles.[2,3] On the other hand, the intercept zone of the target can also be expanded,[4] which can alleviate the dilemma between improving the accuracy of an early warning system and the missile's maneuverability. According to specific combat missions, there are different cooperative schemes, such as the salvo attack and shoot-look-shoot. The salvo attack scheme is a mechanism in which multiple missiles cooperatively intercept and hit a target simultaneously.[5] This scheme is usually adopted in the scenario of attacking a marine target that moves in a relatively low speed.[6,7] In recent years, the salvo attack scheme has been applied to the interception of high-speed targets. In Ref. [8], two missiles were fired to intercept one invading target under a detection suffering from exorbitant errors and a cooperative guidance law was proposed to improve the interception probability. In Ref. [9], a guidance law for multiple missiles in near-space was designed to guarantee that all missiles hit the target simultaneously. The salvo attack scheme was applied to the interception with large handover errors in Ref. [10], wherein the optimal locations of missiles at the handover moment were designed to maximize the interception performance.

In the shoot-look-shoot scheme,[11] the intercepting missiles are launched and encounter with the target at different moments. The first group of missiles is launched once the invading targets are detected. Then after a damage assessment, another group of missiles is launched to intercept the targets that leak through the previous round of interception. If there is not sufficient time to perform the damage assessment, the successive group of missiles is launched before the previous round of interception is completed. This kind of scheme is referred to as shoot-shoot-look,[12] which is applied to protecting a battleship against a salvo of invading missiles in Ref. [13].

In more recent research,[12–15] the scheme of shoot-look-shoot or shoot-shoot-look is often used for intercepting multiple targets. The successive group of missiles is launched to intercept the targets that are missed in the previous round of interception. The transmission of target movement information between two successive rounds of interception is not taken into consideration. This information is definitely beneficial to improve the performance of the successive interceptions in the case where the early warning system cannot provide accurate movement information of a target. Inspired by this, we apply the shoot-shoot-look scheme for the mid-course guidance of multiple missiles to intercepting a target with large detection errors. The target movement information obtained by the early launched missiles will be transmitted to the successive group of missiles. In the light of this mechanism, the latter missiles can maneuver in advance to eliminate the guidance error. In order to make full use of the latter missiles' maneuverability, the time interval Δt between two rounds of interception should be as long as possible. However, since the target is moving, the error of the target movement information grows with the time interval Δt, which implies a larger Δt brings in bigger handover errors for the latter missiles. Thus, in this kind of cooperative scheme, the time interval between two rounds of interception needs to be designed properly. Based on the preliminary work in Ref. [16], a more general scenario is considered in this paper, and an algorithm based on Monte Carlo sampling and stochastic approximation[17–20] is proposed to obtain the optimal cooperative handover parameters.

The remainder of this paper is organized as follows: Section 2 presents the engagement process and the problem formulation of the cooperative handover parameter design. The proposed optimization algorithm and its convergence analysis will be introduced in Section 3 based on Monte Carlo sampling and stochastic approximation. Section 4 presents a series of simulation experiments to demonstrate the effectiveness of the proposed cooperative scheme and the optimization algorithm. Conclusions and potential applications of the proposed cooperative scheme are given in Section 5.

2. Problem formulation

In this section, a description of the cooperative engagement process will be presented first, and then the design of cooperative handover parameters is formulated into an optimization problem.

2.1. Engagement process

In the cooperative interception scheme, the intercepting missiles are launched at different moments. The launches at the same moment are called a round of interception. For each round of interception, one or several missiles are launched. We suppose that there are K rounds of interception, and the total number of missiles launched in the jth round of interception is denoted by N_j $(j = 1, 2, \ldots, K)$. Let F_i^j $(i = 1, 2, \ldots, N_j)$ denote the ith missile in the jth round of interception. The time schedule of the cooperative interception is shown in Fig. 1, where t_0^j, t_1^j and t_2^j are the launch, handover and end moments of missiles in the jth round of interception, respectively. Let $\Delta t_j = t_1^{j+1} - t_2^j$ denote the time interval between the terminal guidance of two consecutive interception rounds.

In this paper, we assume that the information is transmitted within two consecutive rounds of interception, i.e., when the missiles in the jth round of interception are in the terminal guidance, the target movement information will be transmitted to the missiles in the $(j+1)$th round, which are still in the mid-course guidance. Ignoring the boost stage, the process of the first round of interception can be divided into two stages according to the source of target movement information, i.e., the mid-course guidance and terminal guidance. However, the interception process of the missiles in the consecutive round of interception can be divided into three stages. For the first stage $t \in [t_0^j, t_1^{j-1}] (j > 1)$, F_i^j is guided by the early warning system, and the target movement information is contaminated with large errors. For the second stage $t \in [t_1^{j-1}, t_1^j]$, F_i^j is guided by the missiles in the previous round of interception and the target movement information is much more accurate than that in the first stage. For the last stage $t \in [t_1^j, t_2^j]$, F_i^j homes in on the target based on the information provided by the seeker system equipped on itself.