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Distributed three-dimensional cooperative guidance via receding horizon control

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Abstract The paper presents a new three-dimensional (3D) cooperative guidance approach by the receding horizon control (RHC) technique. The objective is to coordinate the impact time of a group of interceptor missiles against the stationary target. The framework of a distributed RHC scheme is developed, in which each interceptor missile is assigned its own finite-horizon optimal control problem (FHOCP) and only shares the information with its neighbors. The solution of the local FHOCP is obtained by the constrained particle swarm optimization (PSO) method that is integrated into the distributed RHC framework with enhanced equality and inequality constraints. The numerical simulations show that the proposed guidance approach is feasible to implement the cooperative engagement with satisfied accuracy of target capture. Finally, the computation efficiency of the distributed RHC scheme is discussed in consideration of the PSO parameters, control update period and prediction horizon.

1. Introduction

In the last decade, autonomous guidance approaches have already been developed to improve the performance of the interceptor missiles for minimum energy control, minimum time control, impact time control and impact angle control.[1–4] For a single interceptor missile, the above objectives have been achieved with satisfied accuracy of target capture. Recently, many researches start to focus on the design of the guidance approaches for the multiple missiles, because the cooperative engagement can have better performance than a single interceptor missile in detecting the maneuvering targets, penetrating the defense systems and surviving the threats.[5–7] However, it is more difficult to achieve the impact time control and impact angle control for a group of multiple missiles, because each interceptor missile may have different initial conditions as well as possible communication limit with other members.[8,9]

In the current literature, two typical classes of impact time control guidance approaches have been proposed for the multi-missile salvo attack. The first class integrates the impact-time constraints into the design of the control commands for interceptor missiles. In Ref.[10], the closed form of the impact time control guidance law is developed based on the proportional navigation (PN), which can guide a group of interceptor missiles to intercept a stationary target at a desirable time. In Ref.[11], a time-varying navigation gain is proposed to coordinate the impact time of each interceptor

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missile. Then, an extension of the impact time control guidance law is used to control both the impact time and impact angle.[12] The above algorithms require that the global information of the time-to-go is available to each interceptor missile in the group. Therefore, the distributed control architecture is developed on the basis of consensus protocols to improve the performance of the time-constrained guidance law.[13] In addition, the PN-based distributed coordination algorithms are proposed to perform the cooperative engagement against both the stationary and maneuvering target.[14,15]

The second class uses the leader–follower model to describe the cooperative engagement of interceptor missiles. In Ref.[16], a nonlinear state tracking controller is developed to the design of the leader–follower strategy in order to achieve the impact time control guidance. Then, the consensus protocol is integrated into the leader–follower model, in which the final impact time of each follower converges to the leader in the finite time.[17] In Ref.[18], a heterogeneous leader–follower guidance approach is also proposed for a group of interceptor missiles by using the traditional PN algorithm. Furthermore, the virtual leader scheme is used to achieve cooperative engagement by transforming the time-constrained guidance problem to the nonlinear tracking problem.[19]

More recently, Ghosh et al.[20] develop a recursive time-to-go estimation method for three-dimensional (3D) engagement of a Retro-PN guided interceptor against higher speed non-maneuvering target. They present a navigation gain scheduling algorithm to achieve the interception at a pre-specified time. Ghosh et al.[21] also propose 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 studies are the first efforts to solve the cooperative guidance problem against moving target in 3D engagement.

The purpose of this paper is to propose a new solution framework for the 3D cooperative engagement problem. The receding horizon control (RHC) technique is employed to achieve the impact time control guidance for interceptor missiles. The main contribution of the paper is delineated in the following part: (1) the distributed RHC scheme is developed to coordinate the impact time of the interceptor missiles, each of which only shares the information with neighbors and solves its own local finite-horizon optimal control problem (FHOCP); (2) the swarm intelligence method is integrated into the distributed RHC framework with enhanced equality and inequality constraints. The feasibility and computation efficiency are demonstrated by some numerical simulations. The rest of the paper is organized as follows: Section 2 presents the preliminaries to the constrained particle swarm optimization (PSO) algorithm. The problem formulation of cooperative engagement is described in Section 3. In Section 4, the distributed RHC framework is developed to achieve the cooperative time-constrained guidance. In Section 5, the numerical results of the proposed approach are discussed in detail. Finally, the concluding remarks are presented in Section 6.

2. Preliminaries

The PSO is one of popular swarm intelligence methods.[22–24] In this paper, we use the global particle swarm because it is fast enough to find the optimal solution of the distributed RHC problem.

Assume that $\{p_1, p_2, \ldots, p_n\}$ are the n unknown parameters that have their own bounds in terms of

$$p_i \in [a_i, b_i] \quad i = 1, 2, \ldots, n \tag{1}$$

where a_i and b_i are the bounds of unknown parameters. The population is N_k. Each particle k has a position vector $\boldsymbol{p}(k)$ and a velocity vector $\boldsymbol{v}(k)$ as

$$\boldsymbol{p}(k) = [p_1(k), p_2(k), \ldots, p_n(k)]^{\mathrm{T}} \quad k = 1, 2, \ldots, N_k \tag{2}$$

$$\boldsymbol{v}(k) = [v_1(k), v_2(k), \ldots, v_n(k)]^{\mathrm{T}} \quad k = 1, 2, \ldots, N_k \tag{3}$$

where $\boldsymbol{p}(k)$ and $\boldsymbol{v}(k)$ refer to search space. The elements are represented by $p_i(k)$ and $v_i(k)$. According to the bounds of unknown parameters, the related position and velocity components are limited to

$$\begin{cases} a_i \leqslant p_i(k) \leqslant b_i \\ |v_i(k)| \leqslant |a_i - b_i| \end{cases} \quad i = 1, 2, \ldots, n; \ k = 1, 2, \ldots, N_k \tag{4}$$

Suppose that the PSO terminates at the iterations N_{ITER}. In a generic iteration j, the personal best position $\boldsymbol{p}_{\mathrm{best}}^{(j)}(k)$ and the global best position $\boldsymbol{g}_{\mathrm{best}}^{(j)}(k)$ can be determined. The velocity vector is described as[23]

$$\begin{aligned} \boldsymbol{v}^{(j+1)}(k) = {} & w\boldsymbol{v}^{(j)}(k) + c_1 r_1(0,1)(\boldsymbol{p}_{\mathrm{best}}^{(j)}(k) - \boldsymbol{p}^{(j)}(k)) \\ & + c_2 r_2(0,1)(\boldsymbol{g}_{\mathrm{best}}^{(j)}(k) - \boldsymbol{p}^{(j)}(k)) \quad k = 1, 2, \ldots, N_k \end{aligned} \tag{5}$$

where $\boldsymbol{p}^{(j)}(k)$ and $\boldsymbol{v}^{(j)}(k)$ are position and velocity vectors in each iteration; w is the inertial weight; c_1 and c_2 are cognitive and social components; r_1 (0, 1) and r_2 (0, 1) are random numbers. The update of the position vector is determined by[23]

$$\boldsymbol{p}^{(j+1)}(k) = \boldsymbol{p}^{(j)}(k) + \boldsymbol{v}^{(j)}(k) \quad k = 1, 2, \ldots, N_k \tag{6}$$

The optimal unknown parameters are contained in the position vector that relates to the objective function J. In general, the parameter optimization problem includes many equality and inequality constraints. For equality constraints, the most typical solution is to add a penalty term to the fitness function in the form of

$$J' = J + \sum_{p=1}^{m} \zeta_p |d_p(x)| \tag{7}$$

where $\zeta_p \geqslant 0$ (p = 1, 2,…, m) is weight factor; d_p (x) (p = 1, 2,…, m) represents the m quality constraints that relate to the n unknown parameters. Note that the values of the coefficients ζ_p depend on the actual problem. For inequality constraints, a simple solution is to set the fitness function to an infinite value if the particle k violates one of the inequality constraints, i.e., $J^{(j)}(k) = \infty$. The related velocity is also set to zero, i.e., $\boldsymbol{v}^{(j)}(k) = \boldsymbol{0}$, such that the velocity update is influenced only by the social and cognitive components.

3. Problem formulation

3.1. Basic assumptions

In this paper, the 3D nonlinear dynamics with a stationary target is used to design the guidance approach. The following conditions are assumed to describe the cooperative engagement.[25]