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Integrated cooperative guidance framework and cooperative guidance law for multi-missile

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Abstract An integrated cooperative guidance framework for multi-missile cooperatively attacking a single stationary target is proposed in this paper by combining both the centralized and decentralized communication topologies. Once missiles are distributed into several groups, missiles within a single group communicate with the centralized leader-follower framework, while the leaders from different groups communicate using the nearest-neighbor topology. To implement the integrated cooperative guidance framework, a group of Finite-Time Cooperative Guidance (FTCG) laws considering the saturation constraint on FOV (FTCG-FOV) are firstly derived within the centralized leader-follower framework to satisfy the communication topology of missiles in a single group. Then, an improved sequential approach is developed to adapt the FTCG-FOV to satisfy the communication topology between groups. The numerical simulations demonstrate the effectiveness and high efficiency of the integrated cooperative guidance framework and the cooperative guidance laws, as well as the superiority of the developed sequential approach.

1. Introduction

In modern military operation, it is a challenging task for the missile to attack a land target or a surface ship that is equipped with an antiair defense system.[1] To penetrate the antiair defense system, the missile should be capable of terminal evasive maneuvering, which would induce increasing cost.[2] An alternative way is to conduct a cooperative attack, i.e., multiple missiles coming from different directions attack a single target simultaneously, which has been regarded as a cost-effective and efficient way to address the threat of the defense system.[3] Therefore, the research on cooperative attack has gained increasing interest in recent years. Considering that a land target or a surface ship is either stationary or moving at a relatively low speed, the target in the cooperative attack problem in this paper is considered to be stationary as is commonly done in practice.

To achieve cooperative attack, one can perform an open-loop cooperative guidance, i.e., a common impact time is gen-

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erated for all member missiles in advance, and thereafter each missile tries to arrive at the target on time independently.[4–7] However, a suitable common impact time is difficult to be generated in advance, since some missiles may not be able to satisfy the impact time constraint due to their specific initial conditions and limited speed. In addition, the open-loop guidance is also lack of robustness to external disturbance during engagement.[8] Actually, the open-loop cooperative guidance simply formulates the many-to-one cooperative attack problem as multiple one-to-one attack problems considering the impact time constraints, which cannot be considered as a genuine multi-missile cooperative guidance.[9]

Alternatively, with the closed-loop cooperative guidance approach, the missiles communicate to each other to synchronize the impact time.[10–12] As a well-known closed-loop cooperative guidance method, the Finite-Time Cooperative Guidance (FTCG) has gained much attention due to its fast convergence rate and high accuracy of the time-to-go errors of missiles. To attack a maneuvering target, Song et al.[13] proposed a FTCG law with impact angle constraints. In Ref. 1, two distributed FTCG laws are developed based on different time-to-go estimation methods. However, in addition to the normal acceleration command, the tangential acceleration was also required with both FTCG laws, causing extra difficulties in implementation. To address this problem, a more effective FTCG law employing a hierarchical framework was proposed in Ref. 14, which requires only the normal acceleration command.

For the closed-loop guidance laws introduced above, either a centralized or decentralized communication topology is utilized. However, both communication topologies are far from the optimum,[15] and their drawbacks shown as follows will become much more prominent if more missiles are involved in the cooperative attack. With the centralized communication topology, one or a few missiles should be designated, which can communicate with all the rest missiles. Clearly, the distances between the designated missile and the rest ones are subject to their communication capability, which incurs extra difficulty in designing the commands for cooperative missiles. In addition, poor penetration capability and system reliability would be induced if only one missile is designated, while unacceptable computational burden would be induced if more than one missile are designated. In contrast, with the decentralized communication topology, missiles can communicate only with their neighbors to reduce the computational burden, while the global information of the missile cluster cannot be obtained, causing great difficulty in making optimal decision for cooperative missiles. Moreover, it takes long time to achieve the consensus of time-to-go and some necessary conditions[16] are always hard to be satisfied. In addition, due to the limitation of the detective capability of seekers, the saturation constraint on Field-of-View (FOV) should be considered in the closed-loop cooperative guidance, which however has been rarely seen in the existing works. And the existing FOV-constraint guidance for the common one-to-one missile-target engagement scenario[17–21] cannot be directly applied to the closed-loop cooperative guidance.

To address the issues above, a novel integrated cooperative guidance framework is proposed in this paper, in which missiles are distributed into several groups, and then missiles within a single group communicate by means of the centralized leader-follower framework, while the communication between groups employs the nearest-neighbor topology among leaders. The contributions of this paper lie in: (A) the centralized and decentralized communication topologies are combined and integrated into the proposed framework effectively; (B) to implement the proposed integrated cooperative guidance framework, a group of FTCG laws considering the saturation constraint on FOV (FTCG-FOV for short) are designed in this paper by extending the FTCG law in Ref. 21 to a group of FTCG laws and introducing a bias term to satisfy the FOV constraint; (C) the sequential approach in Ref. 21 is improved, which is then employed to make the FTCG-FOV satisfy the requirement of communication between groups.

The rest of this paper is organized as follows. In Section 2, the many-to-one missile-target interception engagement along with the proposed integrated cooperative guidance framework is introduced. In Section 3, a group of FTCG-FOV are developed, of which the working process in the integrated cooperative guidance framework is presented in detail. Simulation results are presented and analyzed in Section 4. Conclusions are made in the last section.

2. Preliminary

2.1. Problem formulation

It is considered that n missiles M_i $(i = 1, 2, \ldots, n)$ are followers and one M_1 is the leader, cooperatively attacking a stationary target T. The engagement scenario is shown in the inertial reference coordinate OXY in Fig. 1, in which the variables with the subscripts i and 1 represent the states of the follower i and the leader, respectively. Furthermore, V, a, θ, q, η and r denote the speed, normal acceleration, heading angle, Line-of-Sight (LOS) angle, lead angle, and rang-to-go, respectively.

In this work, the following assumptions are made to simplify the design and analysis process of the proposed guidance method:

(1) Missiles and target are regarded as mass points in the yaw plane.
(2) Velocities of missiles are constant.
(3) Compared with the guidance loop, the dynamic lags of autopilots and seekers can be ignored.
(4) The Angle-of-Attack (AOA) is small and can be neglected.
(5) The lead angle of each missile is small when the range-to-go of the missile is small enough.

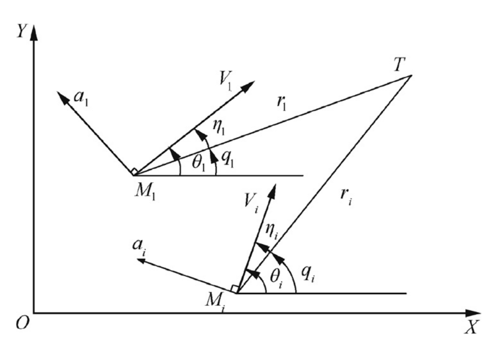

Fig. 1 Guidance geometry on many-to-one engagement scenario.