Chinese Journal of Aeronautics, (2017), xxx(xx): xxx–xxx

CSAA

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Distributed cooperative guidance for multiple missiles with fixed and switching communication topologies

Qilun Zhao [a], Xiwang Dong [a], Zixuan Liang [b,*], Chen Bai [c], Jian Chen [d], Zhang Ren [a]

[a] *Science and Technology on Aircraft Control Laboratory, School of Automation Science and Electronic Engineering, Beihang University, Beijing 100083, China*
[b] *School of Astronautics, Beihang University, Beijing 100083, China*
[c] *China Academy of Launch Vehicle Technology, Beijing 100076, China*
[d] *College of Engineering, China Agricultural University, Beijing 100083, China*

Received 23 July 2016; revised 6 January 2017; accepted 25 March 2017

KEYWORDS

Consensus;
Cooperative guidance;
Directed topology;
Missile guidance;
Multiple missiles;
Switching communication topologies

Abstract This study investigates cooperative guidance problems for multiple missiles with fixed and switching directed communication topologies. A two-step guidance strategy is proposed to realize the simultaneous attack. In the first step, a distributed cooperative guidance law is designed using local neighboring information for multiple missiles to achieve consensus on range-to-go and leading angle. The second step begins when the consensus of multiple missiles is realized. During the second step, multiple missiles disconnect from each other and hit the target using the proportional navigation guidance law. First, based on the local neighboring communications, a sufficient condition for multiple missiles to realize simultaneous attack with a fixed communication topology is presented, where the topology is only required to have a directed spanning tree. Then, the results are extended to the case of switching communication topologies. Finally, numerical simulations are provided to validate the theoretical results.

1. Introduction

Numerous advanced control methods on one single aircraft have been investigated in the last decade.[1,2] Recently, cooperative control of multi-agent system[3,4] and multiple unmanned aerial vehicles (UAVs)[5–7] have received considerable interest. This is partly because a group of well-organized and low-cost UAVs may have better performance than a single

* Corresponding author.
E-mail address: aliang@buaa.edu.cn (Z. Liang).
Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2017.06.009
1000-9361

Please cite this article in press as: Zhao Q et al. Distributed cooperative guidance for multiple missiles with fixed and switching communication topologies, *Chin J Aeronaut* (2017), http://dx.doi.org/10.1016/j.cja.2017.06.009

advanced and high-cost UAV. Similarly, multiple missiles also possess the same characteristic. To saturate a target's defenses, survive the threats and increase the kill probability, simultaneous attack of multiple missiles is proposed. Simultaneous attack means that a group of missiles launched from different positions hit the target simultaneously.

In the current literature, works regarding simultaneous attack of multiple missiles can be classified into two categories. The first category is individual homing, in which a guidance law is investigated for each missile to reach the target at a designated time.[8–13] Although the above guidance laws can be used to realize simultaneous attack, they suffer from the disadvantage that a suitable impact time must be preprogrammed manually for each missile before launching. In other words, simultaneous attack cannot be achieved autonomously.

The second category is cooperative homing (i.e., cooperative guidance), in which multiple missiles communicate with each other to synchronize the impact time. Jeon et al.[14] proposed a cooperative guidance law called cooperative proportional navigation (CPN). CPN has a time-varying navigation gain that can be adjusted via time-to-go (i.e., the remaining time of impact) estimation. In Ref. 15, a cooperative guidance law for controlling both the impact time and impact angle was derived. The cooperative guidance laws in Refs. 14,15 require that global information on time-to-go estimation is available to each missile, which may lead to a high communication cost and a high computational load. Distributed cooperative guidance based on local information exchange has arisen to cope with this problem. Zhao and Zhou[16] developed a two-level guidance architecture and obtained a decentralized cooperative guidance law. Derived from neighbor-to-neighbor communication, cooperative guidance was extended to the cases of maneuvering target intercept,[17,18] obstacle avoidance,[19,20] finite time control,[21,22] particle swarm optimization[23] and leader-follower structure.[24] Wang et al.[25] normalized the dynamic equations of a multi-missile system into a quasi-double integrator model and proposed a two-stage control strategy.

For cooperative guidance, communication among multiple missiles plays an important role due to the requirement of obtaining neighboring information. Cooperative guidance laws in Refs. 21,22,25 are based on undirected communication topologies, which means that the information flow among multiple missiles is assumed to be bidirectional (i.e., undirected). This may consume twice communication and power resources compared with the unidirectional (i.e., directed) ones. Note that both communication and power resources are limited in the battlefield. In this situation, unidirectional communication is more practical than the bidirectional one and it is more convenient for each missile to obtain information from its nearest neighbors. Thus, it is meaningful to consider cooperative guidance using local neighboring directed communications. Furthermore, in practical battlefield, the communication between different missiles may be unreliable due to the existence of communication channel failures and new creations among multiple missiles. That is, the communication topology of missiles may be switching rather than fixed. Hence, it is necessary to investigate the influence of switching directed topologies on distributed cooperative guidance. Although switching topologies were considered by Zhang et al.,[26,27] their results are based on the time-to-go (i.e., the remaining time of impact) estimation. Actually, the time-to-go cannot be measured directly by any onboard devices.[27] Moreover, it is difficult to estimate time-go-to accurately, particularly in cooperative guidance problems.[13] Thus, the difficulty of time-to-go estimation restricts the application and development of cooperative guidance laws to some extent. To the best of our knowledge, distributed cooperative guidance problems for multiple missiles with switching directed communication topologies, which are independent of time-to-go estimation, are still open.

Inspired by the facts stated above, distributed cooperative guidance problems for multiple missiles are investigated in this study without using the time-to-go estimation. Both the fixed topology and switching topology cases are considered. A two-step guidance strategy for multiple missiles to realize simultaneous attack is presented. Based on the local neighboring communication and feedback linearization approach, a distributed cooperative guidance law (i.e., first step of the strategy) is derived to make the states (i.e., range-to-go and leading angle) of multiple missiles reach consensus. The second step is further adopted when the consensus of states is realized. In the second step, multiple missiles attack the target under proportional navigation (PN) guidance law. Next, sufficient conditions under which multiple missiles can achieve simultaneous attack with fixed and switching directed communication topologies are presented, respectively. Finally, numerical simulations are given to validate the theoretical results.

Compared with the existing works, the main features of the current study are threefold. First, the proposed guidance law is based on local neighboring directed communications, which are only required to have a directed spanning tree. That is, the requirement on communication network is more practical. In Refs. 14,15, communication topologies are assumed to be fully connected, and global information on time-to-go estimation is needed. In Refs. 21,22,25, it is assumed that the information exchange among multiple missiles is undirected. The case of general directed communication topologies is more challenging than that of undirected communication topologies, since the Laplacian matrix is not symmetric any more (see Ref. 28 for more details). Second, the communication topologies of multiple missiles can be switching, which is the more general case in implementation. In Refs. 14–23, the communication topologies are fixed. When communication topologies are switching, both the design and analysis become more complex and challenging than those for the fixed case.[29,30] Finally, the results in this study can be applied to achieving simultaneous attack autonomously. In Refs. 8–13, suitable impact time has to be manually preprogrammed for each missile.

The remainder of this study is organized as follows. In Section 2, preliminaries and problem formulation are presented. The main results are provided in Section 3. Section 4 provides numerical simulation results. Section 5 concludes the whole work.

2. Preliminaries and problem formulation

2.1. Preliminaries

It is supposed that $N(N \geqslant 2)$ missiles participate in a simultaneous attack. The communication topology of multiple missiles can be expressed by a weighted directed graph $D_N = \{M, E, W_N\}$, where $M = \{M_1, M_2, \ldots, M_N\}$ is the missile set, $E \subseteq \{(M_i, M_j): M_i, M_j \in M\}$ is the edge set and