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A distributed cooperative guidance law for salvo attack of multiple anti-ship missiles

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Abstract The consensus problem of impact time is addressed for multiple anti-ship missiles. A new distributed cooperative guidance law with the form of biased proportional navigation guidance (BPNG) is presented. The proposed guidance law employs the available measurements of relative impact time error as the feedback information to achieve the consensus of impact time among missiles and, by exploiting the special structure of the biased cooperative control term, it can handle the seeker's field-of-view (FOV) constraint. The proposed scheme ensures convergence to consensus of impact time under either fixed or switching sensing/communication network, and the topological requirements are less restrictive than those in the existing results. Numerical examples are provided to illustrate the effectiveness of the proposed guidance law.

1. Introduction

Modern warships are usually equipped with a variety of defense systems against anti-ship missiles, such as air defense missile systems and close-in weapon systems (CIWS). These have been great obstacles for anti-ship missiles to complete their missions. On the other hand, salvo attack, which is regarded as a cost-effective and efficient countermeasure for anti-ship missiles to penetrate the formidable defensive systems, has drawn much attention in recent years.[1–11] Here, salvo attack means that multiple missiles attack a single ship simultaneously to induce a many-to-one engagement scenario.

In the literature, a variety of guidance laws have been reported to realize salvo attack of multiple missiles. As one of the initial efforts in this field, an impact time control guidance (ITCG) law for anti-ship missiles to intercept stationary target with the prescribed impact time is presented in Ref.[1]. As an extension of Ref.[1], a guidance law to control both the impact time and impact angle was presented in Ref.[2]. While Ref.[2] used the jerk as the control command, Ref.[3] employed the missile's normal acceleration as the control command directly and designed a guidance law to control both the impact time and impact angle as well. To handle the seeker's field-of-view (FOV) constraint while adjusting the impact time, a switching logic-based guidance scheme is presented in Ref.[4], which consists of the ITCG law proposed in Ref.[1] and a constant target look angle guidance law. In Ref.[5], another sliding

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mode-based guidance law also enables interception of either stationary or constant velocity targets at the prescribed impact time.

Note that, though the guidance laws mentioned above can be applied to salvo attack, they suffer from the disadvantage that a common suitable impact time must be prescribed to all members before the homing phase begins. Thus, this individual homing-based approach to achieve salvo attack is an open-loop control one, and is not robust to external disturbance, as pointed out by Ref.[6]. As another approach to achieve salvo attack, cooperative homing guidance exhibits valuable robustness to external disturbance. In Ref.[6], a two-level cooperative guidance architecture was proposed and a cooperative guidance law was designed based on the ITCG law proposed in Ref.[1]. This guidance law is not a distributed one but a centralized one in essence, since a bi-directional communication is assumed between each missile and a common center controller. To relax the topological requirements on sensing/communication network, under the assumption of nearest-neighbor sensing/communication topology, the centralized cooperative guidance law is decentralized by using the consensus protocol to obtain the distributed cooperative guidance law in Ref.[7]. Furthermore, this coordination strategy is extended to cater for the case of attacking maneuvering targets in Ref.[8] and for the case of cooperative guidance for multiple missile groups in Ref.[9]. While in Refs.[6–9], only fixed sensing/communication topology is considered, the consensus problem of impact time under switching but strongly connected and balancing sensing/communication network is studied in Ref.[10], based on the same coordination strategy presented in Ref.[7] again.

All the cooperative guidance laws in Refs.[6–10] depend on the so-called weighted-average consensus algorithm to determine the desired time-to-go for each missile. However, as pointed out by Ref.[10], the weighted-average consensus algorithm is asymptotically convergent, but not finite time convergent. Hence, a suitable period of convergence must be chosen carefully. Otherwise, the maximum disagreement of impact time among the group of missiles cannot converge below a satisfactory level before impact occurs, leading to failure of salvo attack. In Ref.[11], by introducing the concept of time-to-go variance of multiple missiles, the authors presented a cooperative proportional navigation guidance (CPNG) law to adjust the impact time of missiles directly. More recently, the authors of Ref.[12] presented a scheme to achieve consensus of impact time by using the special sensing/communication topology of "leader–followers", where the switching of sensing/communication network and network latency were considered. Ref.[13] also proposed an integrated guidance and control law, in which the cooperative strategy was expressed by the desired target look angle command and it was assumed implicitly that the sensing/communication network is fully-interconnected.

It should be pointed out that to achieve the consensus of impact time, the cooperative guidance relies on the sensing/communication network to exchange information. However, missiles have to fly in a adversarial environment, where serious electromagnetic interference (EMI) and interception of anti-air missile can be expected. Hence, the exchange of information among the missiles is usually limited and occurs only locally and intermittently. Consequently, the topology of sensing/communication network is time-varying and cannot be predicted or prescribed or known a priori. In such a context, it is of paramount importance to relax the topological requirement on sensing/communication network. Besides relaxing the topological requirement on sensing/communication network, maintaining the seeker's lock-on condition is another key issue needed to be addressed when applying the cooperative guidance laws. This is because to adjust the impact time, the trajectory of missile may be highly curved. And in the highly curved engagement, the seeker may lose the target since its field-of-view is usually limited.

The cooperative guidance laws mentioned above are all derived with rather restrictive sensing/communication topological requirements (i.e., strongly connected and balanced,[10] fully-interconnected,[11] or leader–followers[12]), which limits their application in practical environment of battlefield. And none of them is able to deal with the seeker's FOV constraint. In this paper, we have designed a new distributed cooperative guidance law for salvo attack of multiple anti-ship missiles under a less restrictive condition on the connectivity of time-varying sensing/communication networks. It reveals that if the directed sensing/communication networks are sequentially irreducible (defined later in Section 2.2), then the consensus of impact time can be guaranteed under mild assumptions. Compared with the listed literature, the main contribution of this paper is twofold: (1) the sensing/communication topological requirements are relaxed so that the cooperative guidance law is more feasible in practice; (2) the cooperative guidance law can be extended easily to cater for the cases where the seeker's FOV is limited, without using the switching logic.

2. Problem formulation and preliminaries

2.1. Problem formulation

Consider that n missiles (M1, M2, …, Mn) attack a stationary warship, as shown in Fig. 1, in which R_i, θ_i, q_i and φ_i are the range-to-go, heading angle, line-of-sight (LOS) angle and lead angle of the ith missile Mi, respectively. The missiles exchange information each other during the engagement. But the exchange of information occurs only locally and intermittently due to some reasons such as the limitation of communication distance, the electromagnetic interference in a hostile environment, the requirement of silent flight, and so on.

For the ith missile, the velocity V_i is assumed to be constant during the engagement, and the dynamics of engagement can be expressed in terms of R_i and φ_i as follows:[11,12]

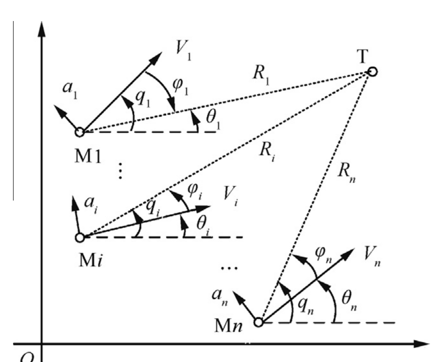

Fig. 1 Geometry of salvo attack.