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A joint mid-course and terminal course cooperative guidance law for multi-missile salvo attack

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Abstract Salvo attacking a surface target by multiple missiles is an effective tactic to enhance the lethality and penetrate the defense system. However, existing cooperative guidance laws in the mid-course or terminal course are not suitable for long- and medium-range missiles or stand-off attacking. Because the initial conditions of cooperative terminal guidance that are generally generated from the mid-course flight may not lead to a successful cooperative terminal guidance without proper mid-course flight adjustment. Meanwhile, cooperative guidance in the mid-course cannot solely guarantee the accuracy of a simultaneous arrival of multiple missiles. Therefore, a joint mid-course and terminal course cooperative guidance law is developed. By building a distinct leader-follower framework, this paper proposes an efficient coordinated Dubins path planning method to synchronize the arrival time of all engaged missiles in the mid-course flight. The planned flight can generate proper initial conditions for cooperative terminal guidance, and also benefit an earliest simultaneous arrival. In the terminal course, an existing cooperative proportional navigation guidance law guides all the engaged missiles to arrive at a target accurately and simultaneously. The integrated guidance law for an intuitive application is summarized. Simulations demonstrate that the proposed method can generate fast and accurate salvo attack.

1. Introduction

Since a many-to-one engagement is advantageous to increase the lethality and probability of penetration,[1] cooperative guidance is a technique which is certain to be widely applied in future missile systems. In fact, persistent efforts have been made to meet the increasing need of cooperative guidance of missiles.[1–14]

The common missile engagement timeline can be functionally partitioned into four phases.[15] launching, midcourse guidance, acquisition, and terminal guidance. Existing cooperative

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guidance strategies mostly focus on the terminal guidance phase of missiles, and they are based on the classic Proportional Navigation Guidance[16] (PNG) or the optimal guidance.[17] In 2006, Jeon et al. 1 derived a closed form of the Impact Time Control Guidance (ITCG) law based on a linear formulation. The ITCG law guides a missile to attack a stationary target at a presetting time. Lee et al. 2 extended the ITCG law to control both the impact time and the impact angle. In 2010, Jeon and Lee 3 proposed a Cooperative Proportional Navigation (CPN) for many-to-one engagements, which decreases the variance of the time-to-go (time left before hitting) of engaged missiles. Based on ITCG and consensus protocols, Zhao and Zhou 4 introduced an effective hierarchical cooperative guidance architecture including both centralized and distributed coordination algorithms. Zou et al. 5 proposed a distributed adaptive cooperative guidance law for multiple missiles with a heterogeneous leader–follower structure to implement a cooperative salvo attack. Similarly, Zhao et al. 6 proposed a virtual leader-based scheme that achieves impact time control indirectly by skillfully transforming the time-constrained guidance problem to a nonlinear tracking problem. Zhang et al. 7 designed a practical Three-Dimensional (3-D) impact time and impact angle control guidance law by using a two-stage control approach. Zhang and Ma et al. 8 designed a feasible Biased PNG (BPNG) law to control the impact time and the impact angle. Based on ITCG, a biased term with the cosine of weighted leading angle was used by Zhang et al. 9 to guarantee that the Field-Of-View (FOV) constraint is not violated during an engagement. Furthermore, Zhang and Wang et al. 10 proposed a distributed cooperative scheme to ensure a convergence to the same impact time under an either fixed or switching sensing/communication network. Zhao and Zhou 11 presented unified cooperative strategies for the salvo attack of multiple missiles, and developed guidance laws against both stationary and maneuvering targets. Lately, Zhao et al. 12 proposed an effective 3-D guidance law to perform cooperative engagements of multiple missiles against both a stationary target and a maneuvering one.

From another point of view, some scholars have concentrated on cooperative guidance in midcourse.[15,18–22] Morgan 15 addressed a midcourse guidance law which ensures a sufficiently small Zero Effort Miss (ZEM) at the handover moment and optimizes an energy cost function. Since a sooner attack is preferred in a battlefield, Indig et al. 18 presented near-optimal solutions for minimum-time midcourse guidance of missiles with an angular constraint in both planar and spatial cases. As shown in the simulations work of Indig et al., flight paths closely approximate the optimal Dubins path[19] which is the time-optimal path for vehicles with a constant velocity. Tanil 20 firstly made midcourse cooperative waypoint path planning for multi-missile salvo attack by adopting an evolutionary speciation approach. Obstacle avoidance and simultaneous arrival are equally emphasized in the work of Tanil, but the turning radius constraint is neglected. Shima et al. 21 solved a simultaneous interception problem of multiple vehicles, and proposed three path elongation algorithms, but all the elongated paths have curved turnings at the end of flights, which is not suitable for midcourse guidance. The acquisition phase is considered in our proposal, and all the elongated paths have straight headings toward a target at the end of flights. Yao et al. 23 presented elongated Dubins paths with bounded curvatures and preset lengths. However, the leader-follower scheme in our proposal ensures a soonest salvo attack.

The satisfactory effect of aforementioned guidance laws has been proven in either the mid-course or the terminal course. However, the two courses should not be considered separately in a cooperative guidance since a terminal guidance with a closed-loop command is indispensable for a precise attack. Meanwhile, the initial conditions of the terminal course are generated from the midcourse flight, and there are constraints on the initial conditions of the terminal course cooperation as follows:

(1) The detection range constraint of seeker: all participant missiles should be in certain ranges from the target at the moment when the cooperative terminal guidance starts.
(2) The FOV constraint of seeker: all the included angles between Line-Of-Sight (LOS) and missile headings should not violate the FOV constraints throughout the cooperative terminal course.

In short words, all the engaged missiles should have accomplished the acquisition and the handover process at the initial moment of the cooperative terminal guidance. Moreover, the Time-To-Go (TTG) differences among them should be small enough.

These initial constraints above are not innately satisfied without the mid-course cooperation, since the differences between the predicted flight times among the missiles cannot be eliminated from the launching moment to the terminal course. Therefore, the demand on a joint midcourse and terminal course cooperative guidance emerges. Besides, a joint cooperative guidance is required for long-range cruise missiles and those for stand-off attack. The joint mid-course and terminal course cooperative guidance at least has the following three advantages:

(1) Since missiles are relatively far from the target in the mid-course flight, the length adjustment for a missile's path has a much wider range as compared with that in the terminal phase.
(2) The heading of a missile is not constrained by the FOV in the midcourse.
(3) The terminal course flight is in the core defense area of the opponent. As compared with maneuvering in the terminal course, elongating a flight path in the midcourse has a lower risk.

Taking both multi-missile handover conditions and the soonest salvo attack into consideration, this paper utilizes Dubins paths and proposes a coordinated path planning method under a novel leader-follower framework. Unlike common leader-follower frameworks,[5,6] the framework built in this paper is for synchronizing the expected arrival time of all engaged missiles by path planning, rather than simply unifying the missile speed, heading error, and sight distance. The planned flight paths for all missiles not only follow the dynamics of these missiles, but also achieve a soonest salvo attack.

The innovations of this paper are as follows:

(1) To our best knowledge, it is the first time to propose a joint cooperative guidance law from the perspective of satisfying the constraints on the initial conditions of cooperative terminal guidance by incorporating mid-

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