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Fault tolerance of cooperative interception using multiple flight vehicles

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Abstract

Cooperative interception of a moving target by multiple vehicles is studied. The main contributions of research work presented in this paper include: (1) cooperative interception is achieved for multiple vehicles to reach the target simultaneously at a finite time, by proposing and solving for a novel finite-time consensus problem and (2) in addition, the cooperative interception is investigated with tolerance of actuator or network failures, where novel fault tolerant consensus protocols are proposed to address actuator failures (or loss of effectiveness) and network failures, respectively. The maximum fault tolerance against network failures can be estimated. Simulations of a three-against-one interception case are presented to demonstrate the effectiveness of the proposed design approaches.

1. Introduction

Multi-vehicle systems have great potential in various applications such as tracking and interception, search and rescue, surveillance and cooperative monitoring [1–4]. In interception missions, a strategy of multi-vehicle systems against one target (many-to-one) becomes a more favorable strategy over the traditional one-by-one engagement approach, as the latter may have a failed interception. Specifically in the many-to-one mission, it is important that multiple flight vehicles reach the target simultaneously [5–7].

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Some many-to-one engagements especially for a static or low-speed target are studied in [5,7,8]. Jeon et al. [5] proposed an impact-time-control guidance (ITCG) law, whose impact time must be calculated in priori and set into all vehicles off-line. Since the vehicles do not exchange information during the guidance, the ITCG-based approach is a static guidance strategy. By taking advantage of the communication among the vehicles, a cooperative proportional navigation for many-to-one engagement was proposed in [8]. However, the proposed centralized control law in each vehicle requires real-time update of global information of the entire system. Zhao and Zhou [7] extended the work of [8] to a two-level hierarchical architecture for the cooperative guidance, where the centralized and decentralized frames are constructed based on the impact-time. However, these studies only aimed at a static or low-speed target. To the authors' best knowledge, the study of a single moving target intercepted by multiple flight vehicles is rare. A cooperative interception problem, defined as that multiple flight vehicles intercept a single moving target simultaneously, is desirable.

An implicit constraint in cooperative interception is that the engagement must be completed in finite time. This imposes a finite-time cooperation problem. There are some studies on the finite-time stability and cooperation. Bhat et al. addressed the sufficient condition of finite-time stability in [9,10] and proposed a design method for state feedback controller. Furthermore, an output feedback controller was proposed in [11] by Hong et al. to stabilize the nonlinear systems in finite time. With the development of cooperative control, the finite-time consensus of multi-agent systems is attracting more and more attentions from researchers such as Cortes [12], Xiao et al. [13,14] and Wang et al. [15]. Two finite-time consensus protocols for continuous-time systems are proposed in [12], both of which are discontinuous. Xiao and Wang developed a finite-time consensus protocol in [13,14] that incorporates continuous state feedback. However, most studies on finite-time consensus protocols ignore the possible failures such as actuator failures and network failures. These failures deteriorate the consensus performance that will jeopardize the cooperative interception mission. Although Wang and Xiao considered the switching communication topology as the network failures in [15], the maximum tolerance of network failures for a time-decay system is hard to estimate.

Motivated by the limitations discussed above, we are proposing a novel formulation for cooperative interception, with emphasis on fault tolerance. This formulation is based on the finite-time consensus. Specifically, the relative kinematics between individual flight vehicle and the target is constructed in the line-of-sight (LOS) frame. The guidance law design is then divided into two stages. In the first stage, the command acceleration is designed to guarantee that the relative distance converges to zero, i.e., the individual interception is guaranteed. The second stage is to ensure that all the vehicles reach the moving target simultaneously. By introducing a novel dynamic consensus variable, denoted by *time-to-go*, to represent the time required for interception, the second stage is formulated as a dynamic finite-time consensus problem. Two novel consensus protocols are proposed with the special emphasis on their fault tolerances to possible failures such as actuator failures and network failures.

The main contributions are summarized as follows:

1. For the first protocol, we show that for the vehicle endowed by head or tail actuators, it can tolerate either one of the failures. In other words, the cooperative interception can still be accomplished if some actuators become partially effective. In addition, we also show that if some actuators have partial loss of effectiveness (i.e., the operation range is limited), the cooperative interception is still guaranteed.