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Cooperative target pursuit by multiple UAVs in an adversarial environment

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ABSTRACT

This paper presents the development of a cooperation strategy for multiple UAVs to pursue a target moving in an adversarial environment where threat exposure should be minimized, and obstacles and restricted areas should be avoided. A probabilistic approach is used to model the adversarial environment. A cost function is defined to quantify placement of UAVs around the target in formation in terms of threat exposure level and distance to the target. The cost function is used to develop a cooperation strategy for a team of UAVs to follow the target such that the total threat exposure of the team and the average distance to the target throughout the pursuit are minimized according to the weighting coefficients specified. The cooperation strategy has the feature of collision avoidance as well as data-fusion-based estimation of the target trajectory based on noisy measurements. Simulation results have demonstrated that the cooperation reduces the risk of losing the target during the pursuit while avoiding obstacles and restricted areas. Further, the UAVs guided by the cooperation strategy can follow the target closer without increasing the total threat exposure level as compared to cases where the UAVs pursue the target without cooperation.

1. Introduction

Consider that a team of UAVs (Unmanned Aerial Vehicles) is tasked to pursue a ground target moving in an adversarial area of operation. "Adversarial" implies that the area has obstacles, restricted-areas and no-fly zones to be avoided by each UAV and various sources of threat/risk, exposure to which by the entire team needs to be minimized. We assume that each UAV is equipped with a sensor suit that measures the position of the target as long as the target is within its sensing range. We further assume that there is a communication range in which the UAVs can share information on target measurements and their own states. The problem is assumed to be two-dimensional and thus the UAVs fly at the same altitude. This requires collision avoidance to be taken into consideration. The objective is to develop an algorithm that guides each UAV in a cooperative manner so that the target remains within the sensing range of at least one UAV at all time while the total threat exposure level of the entire team is minimized throughout the mission. The minimum threat exposure includes the requirement that the UAVs avoid the obstacles and restricted areas.

Cooperative behavior of UAVs is defined as coordinated action of multiple vehicles to optimally perform a given task. Cooperative planning with application to robotics has been studied for a long time [1]. In recent years, cooperation among UAVs has also been a subject of research in areas such as formation flying of UAVs [2–6], cooperative path planning [7–12], cooperative rendezvous [13–16], coordinated target assignment and intercept [17–19] and cooperative target tracking [20–24]. In most cooperative path planning and rendezvous problems when the area of operation has risk regions to avoid, a single cost function represents the total threat cost for the entire team. This reduces the problem to calculating the path and velocity profile for each UAV that will minimize the total cost function for the team. In some applications, fuel cost [14,13], team power (number of UAVs per target) and the spread of the intercepted targets (number of targets to be intercepted) [19] are added to the cost function. This type of cooperation problem is set up as an optimization problem over the entire area of operation of the cost function and involves searching through an infinite number of solutions. For practical purposes, the search space of the optimization is reduced by considering only a finite number of paths. The optimization must be carried out prior to the mission or when changes occur in the area of operation. A recently-studied application relevant to cooperative target tracking is convoy protection [20–22]. Since both the convoy and the environment are considered to be friendly, the UAVs fly directly over the target and cooperation is provided through formation control. In another study [23], a hostile target is considered and thus the tracking is performed from a stand-off distance. A cooperative scheme is employed through relative phase angles between the UAVs to maximize sensor coverage. In these Refs. [20–23], no threat, obstacle or restricted area is considered and no cost function is used to define cooperation for the team.

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This paper presents the development of a cooperation strategy for a team of UAVs to pursue a mobile ground target in an adversarial area of operation. This paper builds upon the work reported in Refs. [25,26] and expands it in two aspects. (1) While Refs. [25,26] present rule-based intelligent guidance algorithms for a "single" UAV to follow a target in an adversarial environment, this paper solves the problem of cooperation among multiple UAVs that are to perform a common task as a team. (2) This paper expands the modeling of the adversarial environment to include time-dependency in addition to position. PTEM (Probabilistic Threat Exposure Map) was introduced in Refs. [25,26] to model the adversarial area of operation as a function of position. As an original contribution, this paper introduces the probability of becoming disabled as a function of both position and time. This is to account for the amount of time UAVs stay in the adversarial area in addition to the lengths of the flight paths. The algorithm developed in Refs. [25,26] compute commanded heading and speed for a UAV to stay within a "proximity circle" centered at the estimated target position while minimizing threat exposure or to avoid obstacles and restricted-areas. A theoretical contribution of this paper is to define a cost function for the entire team of UAVs by defining a proximity disk for each UAV in a formation such that the target stays in the intersection of all the proximity disks and the UAVs are placed, within their proximity disks, at the position with the minimum threat exposure. The main practical contribution is the development of a cooperation strategy that minimizes the cost function over the radii of the proximity disks. The study presented in this paper demonstrates the benefit of formulating what "cooperation" means given the mission requirements and systematically developing a strategy to implement the defined cooperation. In the implementation of this cooperation strategy, the algorithm developed in Ref. [26] is used for guiding each UAV to follow the point with the minimum threat exposure on its proximity disk that moves as the target moves and whose radius is adjusted by the cooperation strategy.

The remainder of the paper is organized as follows. Section 2 presents the probabilistic approach used to quantify likelihood for a UAV to become disabled in the adversarial area of operation. Section 3 describes PTEM and the gradient search. Section 4 lays out the procedure for finding the minima of PTEM on a closed disk. In Section 5, the formulation of the cooperation, the development of the cooperation strategy and its additional features and implementation are presented. Section 6 summarizes the implementation of the cooperation strategy in simulation along with guidance and estimation algorithms. Section 7 presents the simulation results. The paper is completed with conclusions in Section 8.

2. Probabilistic approach

When a UAV is flying in an area with multiple threats, the risk of the UAV becoming disabled is characterized by the probability of the UAV becoming disabled at a certain location, specified by its x- and y- coordinates relative to a frame of reference, (x, y) at a certain time t. In this paper, "threat" is used as a broad term to describe the risk or cost for a UAV to occupy a given location at a given time as well as obstacles and restricted regions in the area of operation. To be able to construct the problem in a probabilistic framework, several events are defined and their probabilities are determined.

Let $E_i(x, y, t)$ be the event that the UAV becomes disabled by the ith source of threat at the position of (x, y) at time t in the area of operation. $E(x, y, t)$ is the event that the UAV becomes disabled by at least one of the threat sources at position (x, y) at time t. Then, let $f_{p,i}(x, y)$ and $f_{t,i}(t)$ be probability density functions (*pdf*) such that the probability of the UAV becoming disabled by the ith threat source at the neighborhood of (x, y) at time t is

$$p_i(x, y) = f_{p,i}(x, y) f_{t,i}(t) \Delta x \Delta y \Delta t, \tag{1}$$

where Δx and Δy are to define the area of a neighborhood of (x, y) and Δt is to define a neighborhood of t. Note that, $f_{p,i}(x, y)$ models the dependency of becoming disabled on position and $f_{t,i}(t)$ models the dependency of becoming disabled on time. In this paper, $f_{p,i}(x, y)$ is characterized by a Gaussian probability density function *(pdf)*, which specifies the concentration point (location) of the threat by the mean value and the level of penalty of flying close to it by the variance. Any other *pdf* can also be used provided it is differentiable. Regarding the time dependency of becoming disabled, various possible *pdf* s can be used for $f_{t,i}(t)$. For example, a uniform *pdf* for $f_{t,i}(t)$ means that the threat exposure level of the UAV at a given position does not depend on time itself but the amount of elapsed time in the neighborhood of that position. If the level of exposure of the UAV to threats increases as it stays longer in the area of operation, then an increasing probability density function of time should be defined for $f_{t,i}(t)$. If there are, in the area of operation, threats that become less effective in disabling a UAV or the UAV becomes less vulnerable to threats, then $f_{t,i}(t)$ should be defined as a decreasing probability density function of time. Note that, in this case, the probability of a UAV becoming disabled still increases as it stays in the area of operation, however the rate of increase becomes smaller.

Now, let $S(x, y, t)$ be a certain event that the UAV follows trajectory S to reach (x, y) at time t. Then, the conditional probability of the event that the UAV becomes disabled by the ith source of threat at the position (x, y) at time t under the condition that the UAV follows trajectory S is defined as

$$\begin{aligned} p_{S,i}(x, y, t) &= P[E_i(x, y, t) | S(x, y, t)] \\ &= \int_t f_{p,i}(x, y)\, f_{t,i}(t)\, l_1(x, y, t)\, l_2(x, y, t)\, \mathrm{d}t, \end{aligned} \tag{2}$$

where l_1 and l_2 are used to define the neighborhood at a point on trajectory S (e.g. radar signature area of the vehicle). Also note in Eq. (2) (x, y) are functions of time and thus $f_{p,i}$ is also a function of time.

If there are N number of sources of threat in the area of operation, then the conditional probability of the UAV becoming disabled by at least any one of the sources of threat at the position of (x, y) at time t under the condition that it follows trajectory S is

$$p_S(x, y, t) = P[E(x, y, t) | S(x, y, t)]. \tag{3}$$

Since

$$E(x, y, t) = \bigcup_{i=1}^{N} E_i(x, y, t) \tag{4}$$

and $E_i(x, y, t)$ are not necessarily disjoint events,

$$\begin{aligned} p_S(x, y, t) &\le \sum_{i=1}^{N} p_{S,i}(x, y, t) \\ &= \sum_{i=1}^{N} \left[\int_S f_{p,i}(x, y)\, f_{t,i}(t) l_1(x, y, t) l_2(x, y, t) \mathrm{d}t \right] \end{aligned} \tag{5}$$

by Union Bound [27]. Thus we can easily compute an upper bound on the probability of a UAV becoming disabled if it follows a certain trajectory in an area with multiple threat sources. If l_1 and l_2 are assumed to be constant for any position and time on the trajectory and $f_{t,i}(t)$ is the same for all threat sources, then

$$p_S(x, y, t) \le l_1 l_2 \int_t f_t(t) \left[\sum_{i=1}^{N} f_{p,i}(x, y) \right] \mathrm{d}t, \tag{6}$$

since $f_{p,i}(x, y)$ and $f_t(t)$ are probability density functions and therefore integrable.