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Collision risk assessment in Flying Ad Hoc aerial wireless networks

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ABSTRACT

A stochastic model is introduced that accurately models collisions in Flying Ad Hoc wireless Networks (FANETs) where Unmanned Aerial Vehicles (UAVs) are flying within the same shared 3D airspace. The model has two input parameters, the number of flying UAVs and the average time for an arbitrary UAV to come into contact with another UAV (the inter contact time). Using only these two parameters, we provide simple, yet accurate closed-form expressions for different collision related metrics such as safety periods, survival probabilities and number of collisions. Two scenarios are particularly considered. The first assumes that UAVs are equipped with perfect collision detection and avoidance capabilities. This is essentially to answer the question of whether detection and resolution tools are required for a given UAVs fleet to accomplish its mission. The second scenario assumes that small UAVs cannot satisfy the requirements of collision detection and avoidance equipage due to their size, weight or power constraints.

While the number of deployed UAVs is easily known, the setup of the inter contact time is rather problematic for the end user (space controller) of the system. To this end, we developed a generic simple expression of the inter contact time to ease the administration task. This generic expression is then instantiated to two mobility models. Extensive simulations based on OMNeT++ are used to validate the obtained analytical results. The simulation results are shown to be in a remarkable agreement with those of the conducted mathematical analysis.

1. Introduction

Recent technological and scientific advances in communication, navigation and computer processing have generated a worldwide interest in Unmanned Aerial Vehicles (UAVs) (Mahjri, 2017; Austin, 2011; Li et al., 2016; Tuna et al., 2014). This rising popularity is notably attributed to their reduced cost and their adequacy for dangerous operations that cannot be performed by manned airplanes. UAVs are being used in various applications such as search and rescue (Khan et al., 2015), surveillance (Nigam et al., 2012), coverage (Sharmaa et al., 2017) and relay nodes (Saleem et al., 2015), and reconnaissance (Minaeian et al., 2016), disaster areas monitoring and hazardous materials handling (Vachtsevanos and Valavanis, 2015). Many of these applications require the deployment of many UAVs in the same shared airspace.

In the design of multi-UAV systems, communication is crucial for cooperation and collaboration between UAVs. Communications between UAVs of a given system may be through a central infrastructure, such as a ground base or a satellite, or directly among the UAVs through ad hoc networking. Infrastructure based communication architecture restricts the span and the capabilities of the multi-UAV system. Ad-hoc networking between UAVs solves the problems (Bekmezcia et al., 2013; Mahjri et al., 2018). In this paper, we consider a shared 3D space populated by UAVs relating to one or many systems using ad hoc networking.

Flying swarms are appealing to provide better efficiency and reliability in shorter times (Hung and Givigi, 2017) where several rather single flying vehicles could combine and conjugate their forces to perform the required mission. However, individual flight trajectories may interfere within such a shared space leading to tacit collisions. Collision risks must be efficiently assessed and quantified ahead in order to

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achieve safety and reduce accidents.

In this paper, we introduce a stochastic model that accurately models collisions in a swarm of UAVs flying within the same shared 3D airspace. Unlike most of the existing stochastic models, our proposed model is simple, generic and depends only on two input parameters: the number of flying airplanes N and the parameter λ describing the rate at which two randomly chosen UAVs come into contact with each other. While the number of flying UAVs is usually known in advance, the parameter λ depends on the flying space volume, the relative speed and the contact range. The question naturally arises as how to estimate or compute this parameter. We shall provide a generic (i.e.; independent from the mobility model) closed form expression for this parameter and then instantiate it for two considered mobility models. The major contributions of this paper can be summarized as follows:

- Based only on two parameters (N and λ), we provide simple yet accurate closed-form expressions for various collision related metrics. Collision related metrics are metrics quantifying the risks of collisions, and consequently the safety within the swarm of UAVs. We particularly derive and discuss the expressions of the expected number of collisions, survival probabilities and safety periods.
- The parameter λ, characterizing the inter-contact time between a pair of UAVs, may be difficult to obtain experimentally. We hence provide a generic explicit expression of λ. The obtained generic expression is then instantiated for two widely used mobility models: the random waypoint and the random direction mobility models.
- We validate the obtained analytical expressions through extensive simulations using OMNeT++.

The main goal of our stochastic model is to assist the UAVs swarm designer in taking well-founded and safe (with reduced collision risks) design decisions, understanding the UAVs system evolution and last but not least answering many questions regarding the collisions risks. To the best of our knowledge, this is the first paper to characterize the inter-contact time for three-dimensional mobility. No other work has characterized the inter-contact time neither for artificial nor for realistic three-dimensional mobilities.

The paper is organized as follows. Section 2 reviews the related literature and discusses the advantages of our proposal in comparison with earlier methods. Section 3 presents our analytical model. We particularly consider two scenarios. In the first scenario, we assume that UAVs have perfect collision detection and avoidance capabilities. In the second scenario, we assume that UAVs are deprived of any collision detection and avoidance capabilities due to size, weight or power constraints.

Section 4 validates the analytical results by comparing them against simulation results obtained under the random waypoint and the random direction mobility models. The simulation results are found to be in an excellent agreement with the analytical result. Besides, we derive an explicit generic expression for the parameter λ, we instantiated for the two considered mobility models and validated through simulations. Section 5 concludes the paper.

2. Related work

Given the system safety critical nature, collision risk assessment has become an active area of research in the field of both manned and unmanned aerial vehicles (Mahjri et al., 2015). Collision risk assessment techniques could be temporal, spatial or probabilistic. Temporal and spatial approaches (Muñoz et al., 2015; Munoz et al., 2013) compute the time and space coordinates of potential collisions. Probabilistic approaches (Liu and Hwang, 2011; Hardy and Campbell, 2013) use analytic, numerical approximation and simulation techniques to diagnose collision risks. The author of Belkhouche (2013) proposed a mathematical modeling and estimation of the collision risk between a pair of UAVs. The collision risk is expressed in terms of kinematic inequalities based on both the bearing and the collision cone angles. Such a formulation simplifies the collision risk assessment as it does not explicitly require the use of the two UAVs speeds and orientations. The suggested approach is, on the other hand, limited to the determination of whether the two airplanes are on a collision course. It provides no information about the upcoming collision such as its coordinates and time of occurrence. The authors in Mahjri et al. (2016, 2018) used the instantaneous position and velocity vectors in order to predict the 4D coordinates (time and the three dimensional space coordinates) of future collisions in a swarm of UAVs flying in a 3D airspace.

The authors in Sahawneh et al. (2015) proposed an approach to estimate the probability of a collision risk between a pair of UAVs flying in a close proximity at the same fixed altitude. The proposed method has a short runtime which makes it attractive for real-time collision risk assessment on board of small UAVs but has also a limited applicability due to the restrictive assumption that all aircrafts cruise at the same constant altitude. Authors in Leven et al. (2011) developed a generic mathematical model predicting the rate of collisions that would occur in a 2D swarm of UAVs when no collision avoidance mechanism is implemented. The collision rate is expressed as a function of many parameters that must be defined by the swarm designer and identified based on a priori knowledge of the behavior of vehicles. As a result, the unavailability or the lack of a priori estimates of these parameters is detrimental to the practical use of the proposed model.

The authors in Dentler et al. (2018) proposed a UAV collision avoidance technique and analysed its performance in a scenario composed of three UAVs. The UAVs mobility was represented based on a real quadrotor dynamics. This technique is nevertheless not scalable to scenarios with more than three UAVs. Paper (Yang et al., 2017) introduced a multi-aircraft conflict detection and resolution approach based on the concept of probabilistic reach sets. A probabilistic reach set includes all the states that the system can reach with a probability higher than a predefined small value. The reach sets were computed by formulating a chance-constrained optimization problem, which is then solved using a simulation-based method. A conflict corresponds to the intersection of different airplanes reach sets. Conflicts are solved by readjusting the airplanes trajectories while minimizing the travelled distance and separating the reach sets. The deterministic and hence non flexible conflict resolution method, the use of specific stochastic models to describe the aircraft motion as well as the requirement of running a high number of simulations of the aircraft trajectories are the main limits of this approach.

The work in Blom et al. (2006) and Stroeve et al. (2009) used Monte Carlo methods for the assessment of collision risks in air traffic scenarios. While Monte Carlo approaches represent a powerful tool to deal with nonlinear systems, their computation time may be very large making them inefficient for any real-time collision warning. Monte Carlo approaches also do not guarantee a non-underestimation of the collision risk resulting in violations of the safety requirements.

Authors in Patil et al. (2012), Kahn et al. (2017) and Lambert et al. (2008) proposed formulations to compute the probability of collision between a moving vehicle and a set of static obstacles. In Patil et al. (2012), the vehicle is assumed to be operating under the Gaussian motion with uncertainties. The estimates of the collision probability are based on a priori distribution of the vehicle along a given plan. The proposed method ensures conservative estimates: the probability of collision is never underestimated in order to guarantee the safety requirements. However, this approach assumes a precise sensing of all the obstacles in the environment which may not hold true in real world applications.

In Kahn et al. (2017), the authors proposed an uncertainty-aware collision prediction model for a robot evolving in an a priori unknown environment. The proposed model takes as input the current state and observations of the robot as well as a sequence of controls and outputs the probability of a collision between the robot and the surrounding obstacles. To avoid the predicted collisions the robot must experience low speed collisions until it gains confidence. Such collisions limit the