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Flight safety measurements of UAVs in congested airspace

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Abstract Describing spatial safety status is crucial for high-density air traffic involving multiple unmanned aerial vehicles (UAVs) in a complex environment. A probabilistic approach is proposed to measure safety situation in congested airspace. The occupancy distribution of the airspace is represented with conflict probability between spatial positions and UAV. The concept of a safety envelope related to flight performance and response time is presented first instead of the conventional fixed-size protected zones around aircraft. Consequently, the conflict probability is performance-dependent, and effects of various UAVs on safety can be distinguished. The uncertainty of a UAV future position is explicitly accounted for as Brownian motion. An analytic approximate algorithm for the conflict probability is developed to decrease the computational consumption. The relationship between safety and flight performance are discussed for different response times and prediction intervals. To illustrate the applications of the approach, an experiment of three UAVs in formation flight is performed. In addition, an example of trajectory planning is simulated for one UAV flying over airspace where five UAVs exist. The validation of the approach shows its potential in guaranteeing flight safety in highly dynamic environment.

1. Introduction

With increasing numbers of unmanned aerial vehicles (UAVs) and expanded operations into complex mission scenarios, aviation safety is facing a new challenge caused by high-density air traffic in limited airspace. Emergency rescue and formation flying usually suffers in congested airspace. The same problem is encountered by civil aviation when reducing flight separation to improve transportation efficiency and increase airspace capacity, and also by certain innovative techniques under development, such as autonomous risk avoidance and free flight. In order to accomplish complicated military missions safely and effectively, coordinated formation flight (CFF) has been investigated by many researchers. The increase of collision risk among UAVs results in flight safety problems more serious than ever.[1] Fundamentally, an intuitive representation of airspace safety and, especially its tendencies are crucial to solving

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this issue. This leads to the requirement for timely and credible constructs of safety in congested airspace.

The complexity of air traffic dense flight lies in environmental dynamics; therefore, the airspace situation varies dynamically. There are often many maneuvers in low altitude flight, especially for UAVs, and the highly dynamic motions result in difficulty for risk assessment of flight routes. In civil aviation, reliable risk assessment approaches for fixed routes have been developed by Reich[2–4] and Brooker.[5] These methods employed historical statistics to assess the long-term longitudinal, lateral and vertical conflict risks. Assessing airspace complexity in a mid-term horizon has recently attracted more research interest since timely identification of dangerous encounters requiring evasive maneuvers can lead to more efficient air traffic control (ATC) system operations.[6] Sridhar et al. describe airspace complexity by the predicted dynamic density.[7] Prandini et al. present an analytic model of air traffic complexity in three dimensional airspace.[8] Due to the presence of flight errors, approaches to evaluate conflict probability involve predicting future aircraft trajectories and computing the probability that two aircraft get closer than a minimum required separation based on these trajectories.[9–13] Usual methods focus on mid-term conflict prediction via the geometric analysis of aircraft relative position. The Monte Carlo approach is a popular method for conflict resolution in the presence of uncertainty in aircraft dynamics,[14–16] though it takes a great amount of computation. Nevertheless, these methods are a posteriori and not appropriate for dynamic and congested airspace. In this work, the occupancy distribution of the airspace, which is represented with conflict probability between spatial positions and UAVs, is proposed as the determinant of airspace safety. In this way, one can have explicit awareness about airspace congestion for a predicted time interval.

In maneuvering flight, aircraft need to frequently perform conflict prediction and resolution; at present, flight routes are varied, and separation minima is difficult to maintain. In conflict prediction, aircraft may encounter intruders from any direction, thus the minimal safe separation is replaced by a protected zone around aircraft (the REICH model is actually a cuboid protected zone). Due to the different kinetic characteristics and flight performance between various types of aircraft, the prescribed protected zone for conflict prediction should relate to aircraft performance. Some research methods, such as the computation of reachable sets, have been developed for this issue. The mathematical formulation of protected zones is generally related to the reachability analysis of aircraft dynamic systems. The analysis attempts to divide the airspace into two parts: those that are reachable from the initial conditions and those that are not. Recently, some contributions have dealt with the mathematical description of reachable sets and their numerical computation.[17–21] Considering that the encounter model is key for assessing conflict probability, we present the safety envelope as the protected zone that should not be penetrated by intruders. It indicates the maximum range that a UAV could reach in a specified response time, then relates the UAV performance to conflict probability.

The rest of the paper is organized as follows: in Section 2, the definitions of UAV safety envelope and airspace safety are introduced; a probabilistic approach for the measure of airspace safety is presented. In Section 3, we analyze the effect of UAV flight performance on conflict probability and construct the airspace safety field. In Section 4, two applications based on airspace safety are presented. In Section 5, conclusions are drawn.

2. Airspace safety

2.1. UAV safety envelope model

The safety envelope is used to characterize the space range that a UAV can reach in a certain time frame. It is an enclosed space determined by UAV flight performance and prescribed time frame. In Fig. 1, the six axes a, b, c, d, e, f represent the maximum range that UAV A is able to reach in each direction during the time frame $[0, \tau]$. The safety envelope $E(\boldsymbol{X}^A)$ is composed of eight different one-eighth ellipsoids. The axes e and f are equal due to the bilateral symmetry of UAV flight performance. However, axes a, b, c and d are different. The specified response time is denoted as τ, and V_f, V_b, V_a, V_d, V_l are the maximum forward velocity, the maximum backward velocity, the maximum vertical ascending velocity, the maximum vertical descending velocity and the maximum horizontal lateral velocity of a UAV, respectively. Hence, we have the maximum range in each direction

$$\begin{cases} a = V_\mathrm{f} \times \tau \\ b = V_b \times \tau \\ c = V_\mathrm{a} \times \tau \\ d = V_\mathrm{d} \times \tau \\ e = f = V_\mathrm{l} \times \tau \end{cases} \tag{1}$$

In the inertia coordinate system O-xyz (see Fig. 1), for UAV A whose position is $\boldsymbol{X}^A = [x^A, y^A, z^A]^\mathrm{T}$, we define the safety envelope $E(\boldsymbol{X}^A)$ as the region centered at $\boldsymbol{X}^A$

$$E(\boldsymbol{X}^A) = \begin{cases} \boldsymbol{X} \in \mathbf{R}^3 | (\boldsymbol{X} - \boldsymbol{X}^A)^\mathrm{T} \boldsymbol{M}_1 (\boldsymbol{X} - \boldsymbol{X}^A) \leqslant 1 \quad x \geqslant x^A, \quad z \geqslant z^A \\ \boldsymbol{X} \in \mathbf{R}^3 | (\boldsymbol{X} - \boldsymbol{X}^A)^\mathrm{T} \boldsymbol{M}_2 (\boldsymbol{X} - \boldsymbol{X}^A) \leqslant 1 \quad x \geqslant x^A, \quad z < z^A \\ \boldsymbol{X} \in \mathbf{R}^3 | (\boldsymbol{X} - \boldsymbol{X}^A)^\mathrm{T} \boldsymbol{M}_3 (\boldsymbol{X} - \boldsymbol{X}^A) \leqslant 1 \quad x < x^A, \quad z \geqslant z^A \\ \boldsymbol{X} \in \mathbf{R}^3 | (\boldsymbol{X} - \boldsymbol{X}^A)^\mathrm{T} \boldsymbol{M}_4 (\boldsymbol{X} - \boldsymbol{X}^A) \leqslant 1 \quad x < x^A, \quad z < z^A \end{cases} \tag{2}$$

where $\boldsymbol{M}_i \in \mathbf{R}^{3\times 3}$ $(i = 1, 2, 3, 4)$ is a diagonal matrix given by

$$\begin{cases} \boldsymbol{M}_1 = \mathrm{diag}\left(\frac{1}{a^2}, \frac{1}{e^2}, \frac{1}{c^2}\right) \\ \boldsymbol{M}_2 = \mathrm{diag}\left(\frac{1}{a^2}, \frac{1}{e^2}, \frac{1}{d^2}\right) \\ \boldsymbol{M}_3 = \mathrm{diag}\left(\frac{1}{b^2}, \frac{1}{e^2}, \frac{1}{c^2}\right) \\ \boldsymbol{M}_4 = \mathrm{diag}\left(\frac{1}{b^2}, \frac{1}{e^2}, \frac{1}{d^2}\right) \end{cases} \tag{3}$$

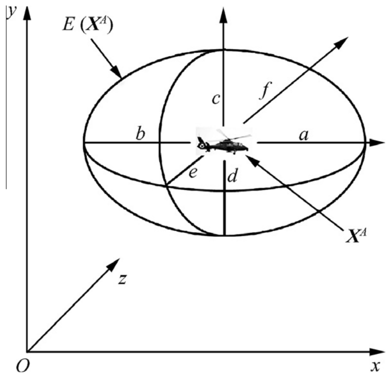

Fig. 1 Safety envelope of UAV A.

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