

A Risk Assessment Method for Mid-Air Collisions in Urban Air Mobility Operations

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Abstract—This paper proposes a method to systematically assess the risk of mid-air collisions in Urban Air Mobility (UAM) operations, considering unique flight characteristics, mission requirements, and the evolving airspace dynamics. The method encompasses three pivotal phases: the encounter leading to collision, the loss of control post-collision, and the resulting harm to third parties on the ground or in the air. Instead of focusing solely on the collision risk, this method quantifies potential harms, introducing the metric of "fatalities per flight hour" akin to conventional aviation. Three main barriers, strategic mitigation, tactical mitigation, and collision avoidance, are modelled to calculate the probability of mid-air collisions. The gas model evaluates the probability of strategic mitigation failure, while an encounter timeline concept determines the probability of tactical mitigation failure. This paper concludes with Monte Carlo simulations validating the proposed model and a real-world case study demonstrating its applicability for regulators, operators, and stakeholders in ensuring the safety and efficiency of future UAM operations.

Index Terms—Urban Air Mobility (UAM), Mid-Air Collision, Risk Assessment, Monte Carlo Simulation

I. INTRODUCTION

The current airspace system has been evolving from manned aviation to further include new entrants such as unmanned aerial vehicles (UAV) and, in particular, urban air mobility (UAM) that seems a promising solution for future air transportation in urban areas. In the deployment of UAM, safety is paramount. Potential threats to UAM flight safety include strong winds, aircraft malfunctions, and the risk of collisions caused by nonconforming aircraft [1]. The flight characteristics of new airspace entrants may differ significantly from traditional manned aircraft, thus requiring a careful understanding of their associated collision risk and the way for risk mitigation.

In the literature, the risk assessment for UAV or UAM to urban ground events have been extensively studied. Ancel, et al. uses Bayesian Belief Networks to assess the risk of UAV to pedestrians on the ground in real time [2]. Bertrand,

et al. investigates the feasibility of a long-range inspection mission of railways by UAVs from a risk point of view. The ground risk for the population of inhabited areas is assessed for this mission [3]. Similarly, Bertrand, et al. also propose a new method to assess the risk to the road network by UAV operations [4]. Pang, et al. proposes an integrated risk assessment model to capture the comprehensive risk of urban ground environments including fatality risk, property damage risk and societal impact risk, then develops a 3D risk-based path planning algorithm EDA-FRA* for low-risk UAV flight plan [5]. Su, et al. investigates a quantitative ground risk assessment method for UAM. The method assesses the risk of UAM to urban areas and generates a risk-cost map, which is used to guide the generation of low-risk UAM flight plans [6]. These hazardous events used for risk assessment are mainly focused on damage caused on the ground.

In terms of risk assessment for mid-air collisions, there are two models including the Reich model and the gas model, which have been studied for decades in the field of manned aviation [7]. The Reich model is used by the International Civil Aviation Organization (ICAO) Airspace Planning Manual to determine separation criteria [8]. For manned aircraft, the model can be used to analyse the collision in any region of the airspace consisting of parallel corridors [9]. On the other hand, the Reich model has been also studied for unmanned aircraft [10]. For airspace where both manned aircraft and unmanned aircraft are in operation, McFadyen, et al. used the Reich model to determine the risk of their vertical collision between them [11].

Another widely used mid-air collision risk model in manned aviation is the gas model. In this model, aircraft invading airspace are assumed to move in unpredictable trajectories, similar to free-moving gas molecules. Under this simplified assumption of aircraft behaviours, it can be used to estimate the risk of mid-air collisions for manned aircraft [12]. In the UAM deployment, the model was used to calculate the probability of UAS collision with a large commercial aircraft [13], and defined perception and avoidance requirements for UAS using the target level of safety approach [14]. [15] also used model to consider the collision risk between UAV and general aviation.

The Reich model is ideal for structured airspace with fixed flight paths, providing efficient airspace usage without overly conservative risk estimates compared to the gas model. However, it falls short in unpredictable airspace situations. Conversely, the gas model excels in quantifying evenly distributed collision risks across an area without needing to ac-

This work was partially funded by the SESAR JU under grant agreement No 101017702, as part of the European Union's Horizon 2020 research and innovation programme: AMU-LED (Air Mobility Urban - Large Experimental Demonstrations). The opinions expressed herein reflect the authors view only. Under no circumstances shall the SESAR Joint Undertaking be responsible for any use that may be made of the information contained herein. (*Corresponding author: Yan Xu.*)

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count for specific flight paths. But it lacks explicit parameters for an aircraft's communication, navigation, and surveillance capabilities, ignoring related uncertainties.

In addition to the above two collision models, researchers have proposed some mid-air collision assessment methods for UAM. [16] proposed a performance-based UAM collision risk model and a risk assessment framework. The model considers communications, navigation and surveillance (CNS) infrastructure and system requirements for both low and high altitude future airspace. [17] used fault trees and event diagrams for evaluating and solving UAM mid-air collision Problems. [18] and [19] applied Bayesian Belief Networks (BBN) to calculate the probability of mid-air collision for UAS deployed in precision agriculture. [20] proposed a model for determining the mid-air collision risk based on the physical parameters of UAV and the parameters of a general aviation. [21] defined an air risk map based on the theory of [20] to visualise mid-air collision risk in urban areas.

The following research gaps have been identified, including (a) The future airspace will incorporate many new concept aircraft. The characteristics of these new aircraft differ from traditional aircraft, and little research has been performed to combine the structural strength and flight performance of the new aircraft with their operational risk assessment; (b) For the current mainstream risk assessment models, the Reich model is applicable to structured airspace, while the gas model does not take into account the influences of communication navigation, etc. in real missions; (c) Most existing research on aircraft collision risk primarily emphasises the potential threat to air or ground property, overlooking a comprehensive risk assessment of the entire mid-air collision process. Yet, this process encompasses various stages, including the initial encounter and collision of the aircraft, subsequent crash and impact with ground property, as well as the resulting damage to ground property following the collision.

To address the research gaps mentioned above, it will be useful to develop a method to systematically analyse mid-air collisions for UAM operations and assess the air and ground risks incurred from those collisions. It must take into account UAM vehicle performance including sensor errors on board, various external environmental factors, and different air and ground risk events, as well as multiple safety barriers to mitigate the risk throughout the whole process. It should also be convenient to ensure a real-time risk assessment during the mission that can quickly determine how an intruder poses a threat even without knowing its exact flight path (but only current flight status, such as velocity and heading).

As a result, the main contributions of this paper are summarised as follows:

- Compared to [13] and [16] which focuses on the occurrence of Mid-Air Collision (MAC), we consider not only MAC itself, but also the potential harms caused by the collision. Specifically, we divide the process into three main phases: first, UAM vehicles encounter leading to a collision; then the vehicle loses control after the collision,

crashing with ground or air events; and finally fatal injury is caused to third parties on the ground or in the air.

- Compared to the qualitative analysis of [17], we introduce a quantitative approach by proposing a metric similar to the one used in conventional manned aviation, namely "fatalities per flight hour", to quantify the risk of MAC for UAM operations, which bridges the MAC probability estimation and ground/air risk assessment. Compared to the theoretical analysis of [20], this research also compares the model calculation results with Monte Carlo simulation data to verify the validity of the model.
- To comprehensively capture the relevant risk events, a number of elements are modelled at each phase, including UAM vehicle performance, strategic and tactical mitigation barriers, and collision avoidance maneuvers during the encounter process.
- Compared to the collision studies [18] and [19], which were conducted for specific agricultural scenarios, this research addresses urban low altitude mission scenarios where UAM is more widely used. Various external factors that could have a crucial role in assessing MAC risk are considered, such as the airborne sensor errors, pilot responding time and wind impact and population distribution and traffic on the ground at the time of the mission.

The paper is organised as follows: in section II, the structure and basic definitions of the mid-air collision risk assessment model are presented; section III presents the mid-air collision probability model; section IV introduces the encounter timeline and defines the time range for each encounter stage; section V assesses the probability of collided UAM hitting and causing fatality to property; section VI sets the simulation scenarios for the proposed model and performs Monte Carlo simulation; section VII illustrates a real-world case study and analyses the simulation results; finally, section VIII presents a summary of the study.

II. RISK ASSESSMENT FRAMEWORK

The purpose of this research is to develop an assessment model to quantitatively predict the value of risk due to a UAM mid-air collision. It is divided into three parts, namely, the probability of a mid-air collision, the probability of an aircraft falling to the ground and colliding with property on the ground after a collision, and the probability of property damage after a collision. For this risk assessment model, the research focused on the first component, which is the probability of a mid-air collision of an aircraft. This probability is modelled using the Swiss-Cheese model, which is further subdivided into three phases, namely Strategic Mitigation Failure, Tactical Mitigation Failure, and Collision Avoidance Failure. The Swiss-Cheese model was proposed in 1990 by Reason [22]. It describes a series of interactions that lead to the failure of a well-defended system. The three mitigation phases are inspired by the SESAR ATM Barrier Model [23].

A mid-air collision is considered to occur when all three phases fail. The probability of an air collision is judged by the

probability of all three phases occurring. We consider three steps through which an UAM MAC incident develops to a harm, and thus its risk (R) is defined as Eq. (1):

$$R = P_{MAC} \cdot P_{IM|MAC} \cdot P_{FA|IM} \quad (1)$$

In Eq. (1), we suggest that the damage caused is the result of a series of conditions that are satisfied simultaneously. The equation describes the mid-air collision risk by the multiplication of three components, and the relationship between them is based on conditional probabilities. The division of three risk stages is inspired by previous research [6], [24]. In the equation, R is the risk cost, which is defined as the number of fatalities per flight hour. P_{MAC} is the mid-air collision occurring probability; $P_{IM|MAC}$ is the probability of an impact occurring under the condition that a mid-air collision occurs; and $P_{FA|IM}$ is the probability of causing fatalities in the case of UAM impacting an object, which is mainly associated with the function of kinetic energy.

According to [25], defences, barriers and safeguards occupy a key position in the system approach. For instance, high-tech systems usually have a number of layers of defence: some are by design (e.g., alarms, physical barriers), others rely on people (e.g., pilots, air traffic controllers), and others on procedures and management controls. Their function is to protect potential victims and assets from local hazards. For the most part, they work effectively, but there are always weaknesses.

As elaborated in the SESAR ATM Barrier Model for mid-air collision [23], there are different mitigation layers to prevent a strategic conflict (SC) successively degenerating into a tactical conflict (TC) and then a near-mid-air collision (NMAC). Thus, mid-air collisions are considered to occur only when an aerial encounter passes through strategic conflict resolution (SCR), tactical conflict resolution (TCR), and collision avoidance (CA), as the main mitigation barriers.

Strategic mitigation occurs before the execution of a flight plan. Its purpose is to predict potential conflicts and make adjustments during the flight planning phase based on known information about the mission area and existing flight plans that share the same airspace. This includes adjustments to the flight plan to ensure that there is no (or little) overlap between the flight trajectories in space and time. The mitigation process may also occur while the flight plan is generated in order to avoid specific areas of potential conflict.

Tactical mitigation occurs during the flight execution phase. In this phase, unexpected operations can invade mission airspace, or some experiencing contingency events require forced landing, which is not covered by strategic mitigation. In this case, tactical mitigation can be divided into two main types: conflict mitigation through ground-based separation services provided by airspace managers, such as the U-space service provider, or self-mitigation performed by remote pilots.

Collision avoidance occurs during flight execution as the final mitigation barrier, which includes measures triggered by visual detection and those provided by Detect-And-Avoid

(DAA) devices. In this paper, collision avoidance is initiated immediately by the onboard flight computer when both strategic and tactical mitigation measures have failed. During the process, the flight will be able to manoeuvre with the maximum load that its structure can withstand.

Following the description above, an air encounter will progress to a mid-air collision if all three mitigation barriers have failed. In previous Eq. (1), P_{MAC} is the probability of a mid-air collision. Inspired by SESAR ATM Barrier Model [23], the mid-air collision risk is defined as Eq.(2).

$$P_{MAC} = P_{TC|SC} \cdot P_{CA|TC} \cdot P_{providence} \quad (2)$$

where $P_{TC|SC}$ represents the probability that, after strategic mitigation, tactical mitigation is still required. $P_{CA|TC}$ is the probability that, after tactical mitigation, collision avoidance is still needed as emergency action. After taking collision avoidance, the probability that a mid-air collision remains materialised is regarded as providential $P_{providence}$. As it is rather infeasible to accurately model “providence”, we assume a worst-case scenario where a collision must occur if the aircraft are no longer able to perform manoeuvres by the maximum load that they can withstand, i.e. $P_{providence}$ is 1 in such a case.

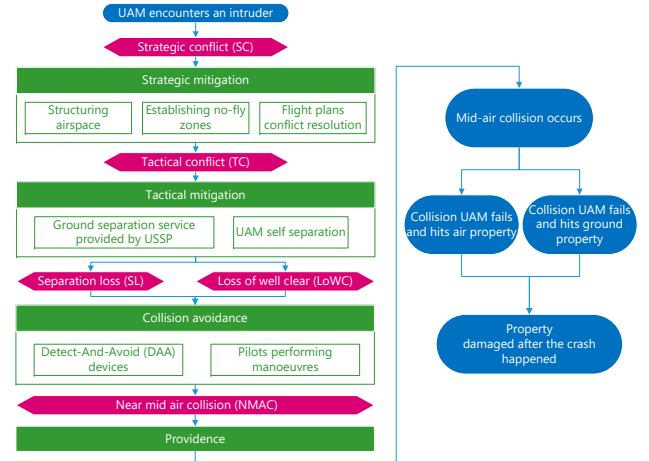


Fig. 1. Relationship diagram of the risk factors considered in the mid-air collision risk assessment model.

In general, the whole process discussed above can be appreciated from Fig. 1. In the next sections, we will first introduce how to estimate the MAC probability. Then, we focus on the tactical phase, elaborating the encounter timeline, followed by computing the threshold of approach time to determine the effectiveness of collision avoidance. Finally, the connection between MAC probability and ground and air risk will be investigated to understand the potential harms caused by the collision.

III. MAC PROBABILITY

In this section, the mid-air collision probability P_{MAC} for UAM operations is modelled in detail, and each part is presented with the definitions around Eq. (2) given above.

A. UAM risk envelope

Following the risk model proposed in the project BUBBLES [26], [27], this paper defines the concept of an aircraft risk envelope that takes into account the aircraft's own shape and its in-flight uncertainty. An MAC is considered to have occurred when the risk envelopes of two aircraft overlap. The risk envelope is defined as a circle area, as shown in Fig. 2. The size of the envelope is defined as in Eq. (3).



Fig. 2. UAM aircraft risk envelope considering size and uncertainty buffer.

$$L_{envelop} = L_{aircraft} + L_{uncertainty} \quad (3)$$

Where $L_{envelop}$ is the radius of the aircraft enveloping circle area, which consists of the maximum length of the aircraft ($L_{aircraft}$) in the horizontal projection and the flight uncertainty buffer ($L_{uncertainty}$).

Referring to [28] and considering the uncertainty caused by the influence of external factors, this research creates a virtual risk envelope around the aircraft. The flight uncertainty distance $L_{uncertainty}$ of the aircraft risk envelope can be defined by Eq. (4).

$$L_{uncertainty} = L_{nav} + L_{wind} \quad (4)$$

Where L_{nav} is the navigation error, which may arise from various factors such as atmospheric propagation phenomena, equipment limitations, the geometric distribution of the satellite relative to the receiver, and bias and noise of the accelerometer and gyroscope. L_{wind} represents the wind error. The uncertainty in wind composition at the same location and time can vary under different weather conditions. Without losing generality, this paper assumes that these can be combined into a single uncertainty buffer.

Wind field uncertainty and sensor uncertainty are independent of each other, and there is no direct link between them. Therefore, we use a worst-case estimation that superimposes the maximum wind field effect at the maximum navigation error to obtain the uncertainty boundary.

B. Strategic mitigation failure

Strategic mitigation sits in the pre-flight phase, which may include the organisation and management of airspace, demand and capacity balancing, strategic conflict resolution for the

flight plans. However, during actual mission execution, unexpected events may still occur, for example, mission airspace is invaded by an aircraft that has suffered a malfunction and needs emergency landing, or by an aircraft taking off without flight authorisation. The probability of occurrence of the above scenarios is defined as $P_{TC|SC}$. These intruding aircraft appear unexpectedly in the course of a mission, and thus their flight plans or trajectories cannot be easily determined. Therefore, the widely studied gas model is better suited to describe this situation than the Reich model that is more applicable to structured airspace.

Specifically, the aircraft is considered as a mass wrapped in a circular envelope of the aircraft. According to [8], the circular envelope is used to evaluate the aircraft in potentially intersecting orbits and can greatly simplify subsequent calculations. A collision between two aircraft corresponds to the intersection of the corresponding areas. When assessing the risk of collision between two aircraft with a circular envelope, it can be equated to the problem of the intersection of a circular envelope of superimposed area and a mass of negligible size. The collision can be seen as the entry of the masses into a given envelope area. That is, one of the aircraft envelopes will have an area that is the sum of the aircraft envelope sizes, while the other not.

The schematic diagram of the gas model is shown in Fig. 3 where the yellow area is the area swept by the UAM at a certain time. Assuming that the intruders are similar to gas molecules randomly distributed in the mission airspace, the possible conflicting intruders are the molecules overlapping the swept area, as shown by the red dots, and the rest of the non-conflicting intruders are shown with the green dots.

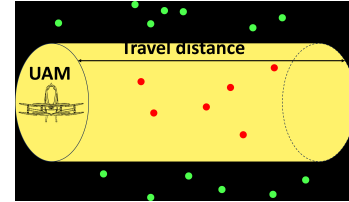


Fig. 3. Schematic diagram of the gas model, where red dots are conflicting intruders and green dots represent non-conflicting intruders.

$$A_{SC} = 2 \cdot L_{TC} \cdot L_{mission} \quad (5)$$

As shown in Eq. (5), A_{SC} represents the area swept by the envelope in the mission airspace during the mission time for the aircraft to be evaluated, and $L_{mission}$ is the length of the flight path of the aircraft. As both the size and the trajectory of the intruder aircraft in the mission area are unknown, it is assumed that the intruder aircraft and the aircraft to be assessed are of the same size, and the relative velocity between them is the absolute velocity of the aircraft to be assessed. We consider twice the area of the aircraft envelope sweeping through the area, as there is also an envelope around the intruder.

The density of intruding aircraft in the airspace that requires tactical mitigation is shown in Eq. (6).

$$\rho_{aircraft} = \frac{N_{aircraft}}{A_{mission}} \quad (6)$$

Where $\rho_{aircraft}$ represents the predicted density of the intruding aircraft at the mission altitude and $N_{aircraft}$ represents the total number of predicted aircraft in the airspace. This value can be estimated from the contemporaneous historical intruder aircraft records in the airspace. $A_{mission}$ represents the total area of the mission airspace. The probability of failure of strategic mitigation $P_{TC|SC}$ can be calculated from Eq. (7), where $t_{mission}$ represents mission flight time.

$$P_{TC|SC} = \frac{\rho_{aircraft} \cdot A_{SC}}{t_{mission}} \quad (7)$$

C. Tactical mitigation failure

After evaluating the probability of strategic mitigation failure $P_{TC|SC}$, the next step is to compute the probability of tactical mitigation failure $P_{CA|TC}$. This reveals the probability that, after the aircraft encounters the intruder aircraft whose strategic mitigation has failed, the tactical mitigation also fails, thus requiring the encounter to be handled by a collision avoidance system. The research [29], [30] consider the encounter timeline between the aircraft to be evaluated and the intruder.

$$P_{CA|TC} = \sum [(1 - \Phi(t))(1 - P_{DAA}) + P_{DAA}] \quad (8)$$

Where P_{DAA} is the probability of loss of well clear of DAA system. Eq. (8) suggests that the tactical mitigation failure and the encounter developing into a collision avoidance can be divided into two scenarios. The first situation is that the DAA system fails, whereas the second is that the DAA system operates normally but the predicted approach time for the aircraft to enter the collision avoidance area is less than the time taken between the aircraft detecting the intruder and performing the manoeuvre (i.e., the aircraft enters the collision avoidance area before it has time to complete the manoeuvre). Finally, the probabilities of all detected intruder aircraft will be summed. A detailed discussion of the encounter timeline will be given in section IV.

D. Collision avoidance failure

The collision avoidance process occurs after tactical mitigation has failed and acts as the last barrier for the aircraft to avoid collisions. It is considered that the aircraft can take the maximum structural withstand load or the maximum pilot withstand load to perform an escape manoeuvre.

The maneuverability of aircraft directly affects this phase and thus the P_{MAC} . Flight envelopes from conventional aviation are inadequate for UAM due to the application of new concept aircraft like VTOL. The VTOL aircraft shows varying maneuverability in different flight states: vertical take-off and landing, conversion, and cruise [31]. In response, [32] proposed the concept of a 3D flight envelope for VTOL aircraft. However, in this research we focus on the risk of collision in the UAM during the cruise phase and do not

consider other flight modes. The maximum load is selected with reference to the UAM cruise flight envelope.

The forces applied when the aircraft makes a lateral maximum load turn are shown in Fig. 4, where n_n is the maximum load the aircraft can withstand, n is the maximum lateral turn load, g is the acceleration of gravity, and their relationship is shown in Eq. (9). Assuming that the maximum load n_n is known, then the maximum lateral turn load n can be expressed as Eq. (10), the maximum turn acceleration a_{turn} can be expressed as Eq. (11), and the minimum turn radius L_{turn} is expressed as Eq. (12), where v_{lr} is the relative lateral velocity.

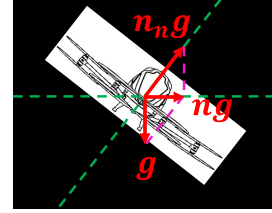


Fig. 4. Forces on aircraft performing the maximum lateral turn.

$$(ng)^2 = (n_n g)^2 + g^2 \quad (9)$$

$$n = \sqrt{n_n^2 - 1} \quad (10)$$

$$a_{turn} = ng = \frac{v_{lr}^2}{L_{turn}} \quad (11)$$

$$L_{turn} = \frac{v_{lr}^2}{g \cdot \sqrt{n_n^2 - 1}} \quad (12)$$

It is assumed that the aircraft will turn horizontally with the minimum turning radius L_{turn} as soon as the intruder is detected, as shown in Fig. 5. When the expected trajectory of the aircraft turning with the minimum turning radius L_{turn} intersects with the intruder's aircraft envelope, the distance of the aircraft from the intruder L_{CA} is defined as the lateral collision avoidance zone boundary. When the distance between the aircraft and the intruder L_{CA} is greater than that distance, the aircraft can avoid the intruder with a maximum load turn. O_{CA} is the centre of a circular trajectory with the minimum radius turn. When the circle with the minimum turning radius is tangent to the lateral aircraft envelope circle, L_{CA} can be calculated from Eq. (13) and Eq. (14), according to the geometry of the triangle with a right angle in Fig. 5.

$$(L_{envelop} + L_{turn})^2 = L_{CA}^2 + L_{turn}^2 \quad (13)$$

$$L_{CA} = \sqrt{L_{envelop}^2 + 2 \cdot L_{envelop} \cdot L_{turn}} \quad (14)$$

When the lateral relative distance between the aircraft and the intruder is less than the horizontal zone boundaries (L_{CA}), the aircraft is considered unable to avoid the near mid-air collision even with the maximum load turn. The probability of

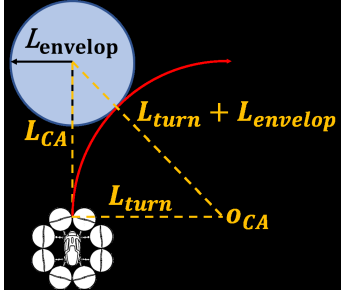


Fig. 5. Geometrical relationship between lateral collision avoidance zone boundary, minimum turning radius and aircraft envelope.

such a near collision developing into an actual collision at this point is subject to providence ($P_{providence}$). In this paper, we consider the most conservative case, i.e., $P_{providence}$ is 1, due to the unpredictability of providence in reality, but it could be further detailed in future work.

IV. ENCOUNTER TIMELINE

The encounter timeline considers the succession of relatively independent events during the encounter. The time taken for each individual event varies depending on the on-board sensors, control method and system, ground equipment, etc. This paper refers to the encounter timeline concept proposed in previous work [33]. In this study, the following improvements and refinements have been made:

Depending on the type of air traffic participant, the collision avoidance process is refined into two scenarios, one in which the aircraft is not capable of autonomous collision avoidance and needs to rely on the separation service provided by the U-Space Service Provider (USSP), and the other in which the aircraft carries an on-board DAA system or is operated by a pilot and is capable of autonomously avoiding obstacles. These two cases correspond to different encounter timelines.

Then, the monitoring stages within the timeline are further subdivided according to the different surveillance methods used for the aircraft. This segmentation reduces the errors caused by using the same standard estimation for aircraft with different sensor types and communication service types.

Considering the scenario where an unknown intruder enters the airspace of a planned operations, the model calculates the motion based on the relative positions and individual velocity vectors of a pair of approaching aircraft. It predicts the process of movement leading up to a Separation Loss when such a close approach is detected.

In addition, when estimating the probability of Separation Loss using the encounter timeline, a more detailed motion model is built for calculating the approach time between a pair of encounter aircraft. The model incorporates the aircraft's flight dynamics and maximum load in its calculations.

A. Encounter timeline overview

As shown in Fig. 6, the events of the approach phase are divided into surveillance, separation, communication, responding, and manoeuvre execution steps. Among these, the

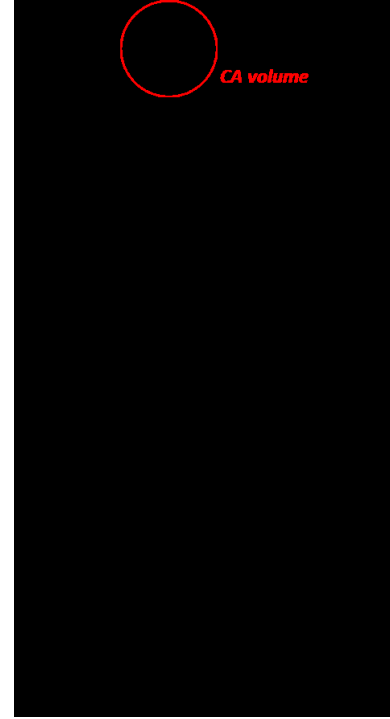


Fig. 6. Timeline of the process an aircraft goes through from encountering an intruder to performing an avoidance manoeuvre.

Surveillance step includes detection of intruding aircraft by airborne sensors or pilots, as well as tracking services provided by airspace management providers, such as U-space Service Providers (USSPs). The Separation step includes tactical separations that rely on USSP to provide separation services, or self separation using aircraft's own detection and avoidance systems or by pilot with see-and-avoid. The communication step refers to the process of transferring information resulting from the receipt of commands sent by the USSP when the aircraft utilises the separation service provided by the USSP. Having been given a separation command, the pilot will respond to the command. The speed of the response depends on the mechanism performing the response, which could be a flight computer or a human pilot. Once the control system has responded to the command, the aircraft starts to perform a manoeuvre to avoid collision.

The time required for these four steps (i.e., surveillance, separation, communication and responding) is not fixed and the statistics on the time spent on these stages generally show a normal distribution.

The reason for using the normal distribution is that it is better suited to modelling and analysing statistics such as response processes and human behaviour and that the four phases of data sources satisfy the law of normal distribution. However, it has the limitation that not all data can be well approximated by the normal distribution. Further research may divide the phases of the encounter timeline in more details, and different approach scenarios will be applied. The distribution of the data sources may not satisfy normal distribution,

meaning that other suitable probability distributions might be adopted to capture the data characteristics.

The total time of approach is defined as the sum of these individual times, which is also subject to a normal distribution. The expectation μ_{TC} and standard deviation σ_{TC} of this normal distribution are calculated from Eq. (15) and Eq. (16), where μ_{sur} , μ_{sep} , μ_{com} , μ_{pil} stand for the expectation of surveillance, separation, communication, responding respectively, and σ_{sur} , σ_{sep} , σ_{com} , σ_{pil} stand for the standard deviation for them respectively.

Compared to the simple single-step encounter timeline in [33], two types of separation methods are considered in this paper, including separation through the service provided by the USSP and self-separation. The main difference lies in that self-separation does not require communication process between the ground-based service provider and the airborne aircraft.

$$\mu_{TC} = \begin{cases} \mu_{sur} + \mu_{sep} + \mu_{com} + \mu_{pil} & (Sep \text{ service}) \\ \mu_{sur} + \mu_{sep} + \mu_{pil} & (Self \text{ sep}) \end{cases} \quad (15)$$

$$\sigma_{TC} = \begin{cases} \sqrt{\sigma_{sur}^2 + \sigma_{sep}^2 + \sigma_{com}^2 + \sigma_{pil}^2} & (Sep \text{ service}) \\ \sqrt{\sigma_{sur}^2 + \sigma_{sep}^2 + \sigma_{pil}^2} & (Self \text{ sep}) \end{cases} \quad (16)$$

The above calculation results in a normally distributed probability density function $f(t)$ of the time consumed by the aircraft between the discovery of the intruder and the avoidance manoeuvring, as shown in Eq. (17).

$$f(t) = \frac{1}{\sqrt{2\pi}\sigma_{TC}} \exp\left(-\frac{(t - \mu_{TC})^2}{2\sigma_{TC}^2}\right) \quad (17)$$

Integrating the probability density function $f(t)$ of the above normal distribution leads to a cumulative distribution function $\Phi(t)$ of that normal distribution, as shown in Eq. (18).

$$\Phi(t) = \frac{1}{2} \left(1 + \operatorname{erf} \left(\frac{t - \mu_{TC}}{\sqrt{2}\sigma_{TC}} \right) \right) \quad (18)$$

The independent variable of Eq. (18) is the predicted time t taken by the aircraft (seen as a particle) to enter the collision avoidance zone centred on the intruding aircraft from its current position, where it is assumed that the relative velocity magnitude and direction of the aircraft are constant during the approach. This cumulative distribution function $\Phi(t)$ represents the probability that the time taken by the aircraft between the detection of the intruding aircraft and the avoidance manoeuvre is less than the currently estimated time t . The calculation of this estimated time t is described in detail in the following sections.

B. Approach time estimation

The time t consumed from the detection of the intruding aircraft to a collision if no avoidance manoeuvre is taken needs to be evaluated. The positional relationship between the aircraft and the intruder is expressed in Fig. 7.

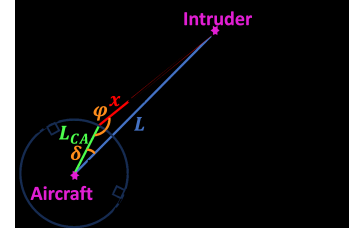


Fig. 7. The position and relative velocity vector relationship between the aircraft and the intruder.

As shown in Fig. 7, the aircraft speed direction is used as the reference base direction. v_1 represents the velocity of the aircraft, v_2 represents the velocity of the intruder, and v_3 is the relative velocity of the two. α is the azimuth of the intruder relative to the aircraft, β is the azimuth of the velocity v_2 of the intruding aircraft, and γ is the complementary angle of the relative velocity v_3 azimuth.

The velocity and position relationship between the aircraft and the intruder is also shown in Fig. 7. The relationship between the two velocity vectors is triangular, the velocity of the aircraft v_1 and the velocity of the intruder v_2 are known, and the angle of the direction of the intruder's velocity β is known, the relative velocity v_3 can be calculated using the cosine theorem, as shown in Eq. (19). After calculating the magnitude of the relative velocity v_3 , the complementary angle of the relative velocity v_3 azimuth γ can be calculated using the sine theorem, as shown in Eq. (20).

$$\|v_3\| = \sqrt{\|v_1\|^2 + \|v_2\|^2 - 2\|v_1\|\|v_2\|\cos(\beta)} \quad (19)$$

$$\gamma = \arcsin\left(\frac{\|v_2\|}{\|v_3\|} \cdot \sin(\beta)\right) \quad (20)$$

After the direction of the relative velocity v_3 is obtained, a collision is only possible if v_3 is within a certain range. v_3 is in the direction between the two tangent lines d_1 , d_2 as shown in Fig. 7. The maximum and minimum γ angles can be calculated from $\Delta\gamma = \arcsin\left(\frac{L_{CA}}{L}\right)$ and Eq. (21) using the geometric relationships shown in Fig. 7.

$$\begin{cases} \gamma_{min} = \alpha - \Delta\gamma \\ \gamma_{max} = \alpha + \Delta\gamma \end{cases} \quad (21)$$

The relationship between relative distances can also be described by the triangle. The relative distance L between the aircraft and the intruder is known, and the nearest distance L_{CA} at which a maximum load turn to avoid collision can be calculated as mentioned above. One of the top angles of this triangle is known, and using the sine theorem, the remaining angle φ can be calculated by Eq. (22) and δ can be calculated by $\delta = \pi + \gamma - \alpha - \varphi$.

$$\varphi = \arcsin\left(\frac{L}{L_{CA}} \cdot \sin(\alpha - \gamma)\right) \quad (22)$$

The cosine theorem is then used to compute the distance x between the invading aircraft flying along its original trajectory without taking an avoidance manoeuvre and the occurrence of a collision, as shown in Eq. (23).

$$x = \sqrt{L^2 + L_{CA}^2 - 2LL_{CA}\cos(\delta)} \quad (23)$$

Knowing the relative velocity $\boldsymbol{v}_3$ and relative distance x of the aircraft and the intruder, it can be derived the predicted time t for a collision to occur if no avoidance manoeuvres are taken by $t = \frac{x}{\|\boldsymbol{v}_3\|}$.

C. Surveillance time

Referring to the Airborne Collision Avoidance System (ACAS) sXu's methods of integration with surveillance sources and considering the latency of Automatic Dependent Surveillance-Broadcast (ADS-B) system [33], surveillance time is refined into three types, ADS-B, remote identification, and airborne vision / lidar / radar sensor.

According to [34], [35], when using an ADS-B system, the aircraft receives information from a position source and processes it through the onboard avionics. There are two separate latency requirements for this purpose, including total latency and uncompensated latency. Total latency is defined as the time between the measurement to determine the aircraft's geometric position (latitude, longitude and geometric altitude) and the ADS-B transmitter broadcasting the aircraft's position. Under this rule, the total latency time cannot exceed 2.0 seconds. In this research, the total latency time is chosen as the time spent on the surveillance service, i.e., let μ_{sur} be 2 s and σ_{sur} be 0 s.

The surveillance time of some commercial drones and remote ID modules is summarised in [36]. As a conservative estimate, we chose the maximum 2 s delay for the remote ID method surveillance time, i.e., let μ_{sur} be 2 s and σ_{sur} be 0 s. As for the on-board sensors, due to their variety, surveillance time need to be defined according to the actual sensors used.

D. Separation service time

As mentioned above, we consider two types of separation services, including separation with human involvement and automatic separation. The one with human involvement may provide higher reliability nowadays, but cannot be realised as quickly as automated separation systems. In order to ensure safe separation, the paper chooses a separation service with human involvement (which takes longer) to estimate the time required for the separation service.

The experiment in [37] measured the reaction time of Air Traffic Control (ATC). The results suggested a normal distribution of that time. The average response time $\mu_{response}$ of controllers to an emergency situation is 4.6 s, with a standard deviation $\sigma_{response}$ of 4.1 s. After responding, the average time $\mu_{execute}$ taken to execute the separation service is 2.3 s, with a standard deviation $\sigma_{execute}$ of 2.7 s. The new normal distribution obtained by summing the above two normal distributions is the normal distribution of the time taken

to the separation service, where the expectation μ_{sep} of the separation service is 6.9 s and the standard deviation σ_{sep} of the separation services is 4.9 s.

E. Communication and responding time

In [33], it was assumed that communication between the separation service and the pilot requires a communication network that is not fully reliable and suffers from communication delays. However, the limitation of this assumption is that it ignores the situation where the aircraft performs collision avoidance automatically through the on-board obstacle avoidance system or through the pilot's observation and direct avoidance manoeuvres, resulting in an overly conservative assessment. In this study, the timeline is categorised into self-separation and airborne separation.

In [38], The end-to-end response time for an aircraft to complete a clearance, which may be referred to as Measured Response (MR), is defined in [38] as the difference in time from when the Air Traffic Control (ATC) issues a clearance instruction to the pilot to when the ATC indicates that the aircraft meets the clearance requirements. The components of MR include: MR1 Communication Lag: the time between the ATC completing the issuance of the command and the pilot starting to read it back verbally; MR 2- Execution Lag: the time between the ATC ending the issuance of the command and the pilot starting to execute it. In this research, the Traffic Alert and Immediate Turn times of MR1 and MR2 of [38] are taken as communication time and responding time.

For MR1, the expectation μ_{MR1} is 2.76 s and the standard deviation σ_{MR1} is 1.18 s. For MR2, the expectation μ_{MR2} is 1.7 s and the standard deviation σ_{MR2} is 0.93 s. Assuming that the communication and responding time also satisfies a normal distribution, the expectation μ_{com} of the communication service is 2.76 s and the standard deviation σ_{com} of the communication services is 1.18 s; the expectation μ_{pil} of the communication service is 1.7 s and the standard deviation σ_{pil} of the communication services is 0.93 s.

V. AIR AND GROUND RISK

According to Eq. (1), after the probability of UAM mid-air collision P_{MAC} is obtained, the subsequent probability of collided aircraft falling and hitting property $P_{IM|MAC}$ and the fatality probability $P_{FA|IM}$ need to be calculated, which has been investigated in our previous work [24]. This section will briefly review the air and ground risk assessment and link them with the mid-air collision modelled above.

In order to assess the risk of the flight plan to the ground, it is necessary to analyse the process by which the aircraft fails and falls to the ground. The probability of collided aircraft falling to the ground and hitting property on the ground $P_{IM|MAC}$ is calculated from Eq. (24). In the equation, C_{linear} is linear coefficient, $\rho_{veh/people}$ is the density of vehicles or pedestrians in the affected area, and A_{impact} represents the ground collision risk area.

$$P_{IM|MAC} = C_{linear} \cdot \rho_{veh/people} \cdot A_{impact} \quad (24)$$

The fatality rate $P_{FA|IM}$ can be described by Eq. (25). Where α is the impact energy that might cause 50% fatality with $c_{shelter}=0.5$, and β is the impact energy threshold required to cause fatality as $c_{shelter}$ approaching zero [39]. In this paper, we set α to 10^6 J and β to 100 J following our previous studies.

$$P_{FA|IM} = \frac{1}{1 + \sqrt{\frac{\alpha}{\beta}} \left(\frac{\beta}{E_k} \right)^{\frac{1}{4c_{shelter}}}} \quad (25)$$

The UAM associated risks imposed to traditional manned aircraft are crucial to the integration of manned and unmanned operations. For civil manned aircraft, the cruising altitude is usually from 6000 to 12600 meters. The operating altitude of UAM aircraft is typically much lower than this altitude. Therefore, we only consider the traditional manned aircraft during their take-off and landing phase.

For the subsequent risk to other air traffic participants after a mid-air collision, the impact probability $P_{IM|MAC}$ is linearly correlated with the number of collisions $N_{aircraft}$ between manned aircraft and UAM per flight hour, which can be calculated by Eq. (26). The fatality rate can also be estimated by Eq. (25).

$$P_{IM|MAC} = C_{linear} \cdot N_{aircraft} \quad (26)$$

The number of collisions $N_{aircraft}$ between manned aircraft and unmanned per flight hour can be calculated by Eq. (27). In the equation, $\rho_{aircraft}$ represents the density of manned aircraft at the overlap of the vertical projection of the risk area on the ground and the projection of the airport area on the ground. $A_{affected}$ represents the overlap area of the vertical projection of the UAM risk area and the airport area on the ground.

$$N_{aircraft} = \rho_{aircraft} \cdot A_{affected} \quad (27)$$

VI. MONTE-CARLO SIMULATION

In the risk assessment model proposed in this research (recall Eq. (1)), three components are considered, namely the probability of a collision in the mid-air, the aircraft falling after a collision and causing damage to property on the ground or in the air. $P_{IM|MAC}$ and $P_{FA|IM}$ have been presented in previous studies [6] and [24], which will not be discussed in this paper. In this section, the discussion will rather focus on the probability of a collision occurring in the mid-air.

A. Simulation setup

For strategic mitigation failure $P_{TC|SC}$, this research refers to the gas model [40], which is a widely studied method. Roland, et al. assessed the risk of air collisions between drones and other aircraft using the gas model combined with air traffic density data from an FAA surveillance source [41]. Using simulation experiments, Christopher and Blake demonstrated that random gas molecule collisions are a fairly representative model in most cases [42]. In addition, we consider collision avoidance failure risk $P_{providence}$ as the case where the aircraft

is too late to avoid the intruder even when using the maximum load turn.

Therefore, the risk components of the strategic mitigation failure risk and collision avoidance failure risk have been evaluated and discussed, but the tactical mitigation failure $P_{CA|TC}$ have not been validated by simulation, which is the core of the discussion in this section. In order to verify the accuracy of the tactical mitigation failure model proposed in this research, Monte Carlo approach is used to simulate different encounter scenarios to calculate the number of collisions occurring in the simulation, and compare the results against the calculation using the proposed model.

The sensor error of the simulation process corresponds to the ring envelope region of width $L_{uncertainty}$ of the aircraft risk envelope. It will be verified in the simulations if this ring envelope model is able to well describe the conflict process caused by sensor errors.

B. Aircraft parameters

In the Monte Carlo simulation, a typical air taxi EHang 216 eVTOL model is chosen as the mission UAM aircraft. Detailed information about air taxi EHang 216 can be found in [43]. The intruding aircraft performing aerial photography task in the mission airspace is a common self-assembled drone with a Pixhawk flight control system, with Ardupilot flight control firmware flashed. The specific parameters of both aircraft are shown in Table I.

TABLE I
SIMULATION AIRCRAFT PARAMETERS

Aircraft parameters	EHang 216	Aerial photography drone
Length (m)	3.86	0.52
Height (m)	1.76	0.35
Propellers	16	4
Weight (kg)	453.59	3.44
Flight control system	/	Pixhawk (Ardupilot)
Maximum speed (m/s)	36.11	26.11
Cruise speed (m/s)	15	8
Maximum altitude (m)	3000	500
Range (km)	35	7
Flight time (min)	21	25

C. Data input

As mentioned above, the flight data in the Monte Carlo simulation is generated through the SITL simulation in the Ardupilot flight Control firmware. In the SITL simulation environment, the virtual drone is guided through a number of mission flights. By sending flight plans to the virtual Pixhawk flight controller, the virtual drone in SITL simulator will perform the mission flights and save the flight data in the simulation log. After a number of simulated mission flights, 10000 sets of each of the necessary flight data are saved to form a pre-defined database.

In the SITL simulation, in order to be more close to the actual mission flight situation, sensor errors, including GPS positioning error, compass heading error, barometer altitude

error, and attitude calculation error caused by vibration, are incorporated. Environmental factors are also taken into account, that is, wind and turbulence of random direction and scale are added. The lateral positioning error due to GPS position drift and airspeed sensor output data in the presence of external noise interference collected during a full SITL simulation mission flight are shown in Fig. 8.

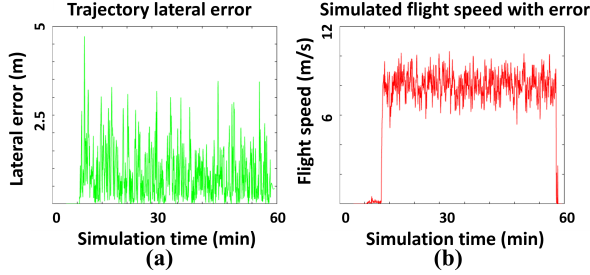


Fig. 8. Lateral positioning error and velocity during mission flight.

In this simulation mission flight, the offset error between the expectation heading angle and the actual heading angle collected by the virtual compass is shown in Fig. 9 (a). The offset of the angle of roll angle of the drone angle collected by the IMU module of the virtual flight control system is shown in Fig. 9 (b).

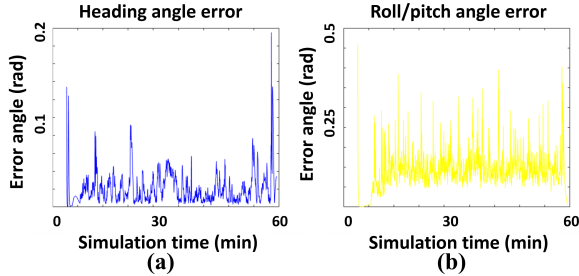


Fig. 9. Pitch, roll angle and heading angle error during mission flight.

The obstacle detection, pilot response, and aircraft manoeuvring delay are also considered in addition to the inclusion of uncertainties in aircraft position velocity due to external environmental factors and the aircraft's own sensor errors. 10000 simulations are performed for each simulation scenario, and the distribution of time delays that occurred during the simulation for various reasons is shown in Fig. 10. It is assumed that the simulation begins with an aircraft encounter with an intruder, but due to sensor and pilot reaction delays, the avoidance manoeuvre is executed only after a delayed time chosen according to sampled data according to the distribution shown in Fig. 10.

D. Navigation error

According to [44], [45], the overall positioning error of the aircraft can be divided into the following parts: navigation system error, flight technical error, and path definition error.

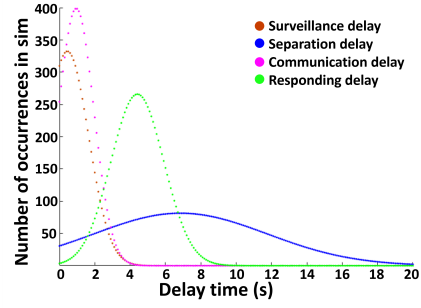


Fig. 10. Distribution of various delay times and occurrence rates between an aircraft encounters an intruder and performs avoidance manoeuvres.

Navigation system error represents the difference between the current position of the aircraft estimated by the aircraft navigation system (for example, GNSS system) and the actual position of the aircraft. Flight technical error represents the position deviation generated by the pilot or the airborne flight control computer when following the flight plan. Path definition error represents the error in the definition of the path during the flight plan development process. The flight plan development errors are beyond the scope of this research.

For navigation system errors in the horizontal and lateral direction, this research considers the accuracy of GNSS systems and treats their accuracy limits as navigation system errors. According to the GNSS manual proposed by ICAO [46], the maximum horizontal/lateral errors allowed by GNSS systems is 40 m. For flight technical error, ICAO [44] mentioned that it should be less than 45 m (at or below 1500 m) or 73 m (above 1500 m). Combining the above two errors, the navigation error L_{nav} is defined as 85 m (at or below 1500 m) and 113 m (above 1500 m).

E. Wind impact

Wind is also an important influence factor on aircraft position. Rapid changes in wind speed and direction over short distances can have a significant impact on an aircraft, this is known as wind shear. In the horizontal/lateral direction, when light aircraft face wind speed changes above 15 m/s (and civil aircraft above 23 m/s), it is considered as wind shear. For the vertical direction, the change of wind speed at 2.5 m/s can be regarded as wind shear. Hongsheng, et al. assessed the effects of different intensities of turbulence on the position of the aircraft in the horizontal or lateral case. In the case of severe turbulence, the upper limit of deviation of the aircraft position is 4.5 m (14.6 ft) [47].

F. Simulated scenarios

For the simulation scenario is shown in Fig. 11, EHang 216 is the mission UAM aircraft. The flight altitude is 100 m and flight speed is 15 m/s, with the mission UAM heading as the reference direction. The intruder is an aerial photography drone with a flight altitude of 100 m and a theoretical flight speed of 8 m/s. Intruding drones with azimuths α of $\pm 15^\circ$ and $\pm 30^\circ$. The azimuth β of the intruding drones velocities

v_2 are $+/-90^\circ$ and $+/-120^\circ$. Different intruding distances L are also initiated, ranging from 500 m to 200 m at 25 m intervals.

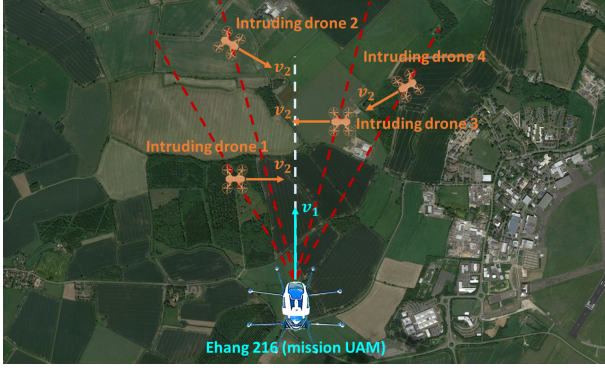


Fig. 11. Simulated scenario setup with 4 invading drone azimuths, 4 invading drone speed directions and varying intruding distances.

In the simulation scenario described above, Monte Carlo simulations are performed with 4 initial intruding drone azimuths α , 4 initial intruding drone velocity directions β and 13 sets of initial intruding distances L . For each combination of intruding distance and angle, 10000 mid-air collision simulations are carried out, assuming the UAM aircraft capable of avoiding collisions with its maximum load. As a result, the number of collisions that occur after failed avoidance can be counted under each combination.

G. Result analysis

To verify the validity of Monte Carlo simulations, it is necessary to ensure that the probability of a collision occurring is counted over a large number of simulations. If the collision probabilities converge gradually with the number of simulations, it is demonstrated that probabilistic prediction is feasible. As shown in Fig. 12, 1000 simulations are carried out for each of the above 4 simulation scenarios at different intruding distances L , where the probability of collision is plotted along the simulation iteration.

As can be seen in Fig. 12, the mid-air collision probability converges to a fixed value in all the 4 simulation scenarios as the number of simulation iterations increases. The precision of the mid-air collision risk assessment model proposed in this research can be verified by comparing the difference between this fixed value against the probabilities $P_{CA|TC}$ generated by using the model following all the steps defined above.

Fig. 13 shows a comparison between the probability of the mid-air collision from Monte Carlo simulation and the probabilities $P_{CA|TC}$ calculated using the model, for different intruding distances under 4 simulation scenarios. The results demonstrate that the collision probability is directly related to the distance and relative speed of the aircraft and the intruder. The higher the relative speed, the greater the probability of an mid-air collision at the same distance.

Comparing the results calculated by the risk assessment model and by the Monte Carlo simulation, it can be seen that

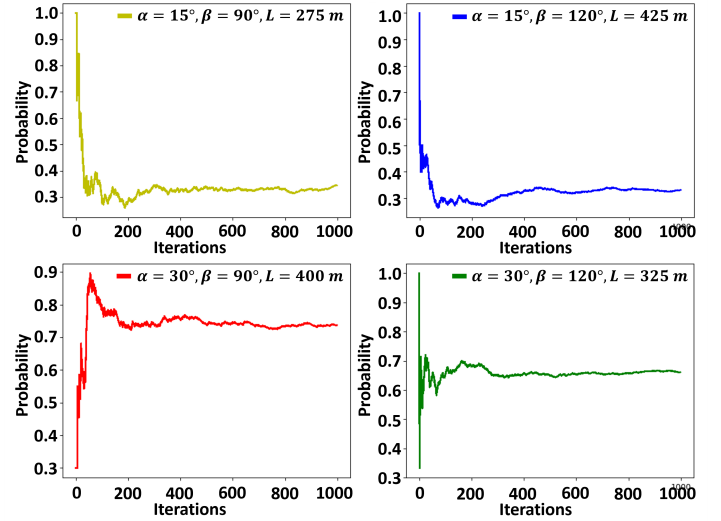


Fig. 12. Relationship between the probability of mid-air collision and the iteration of simulations for different scenarios.

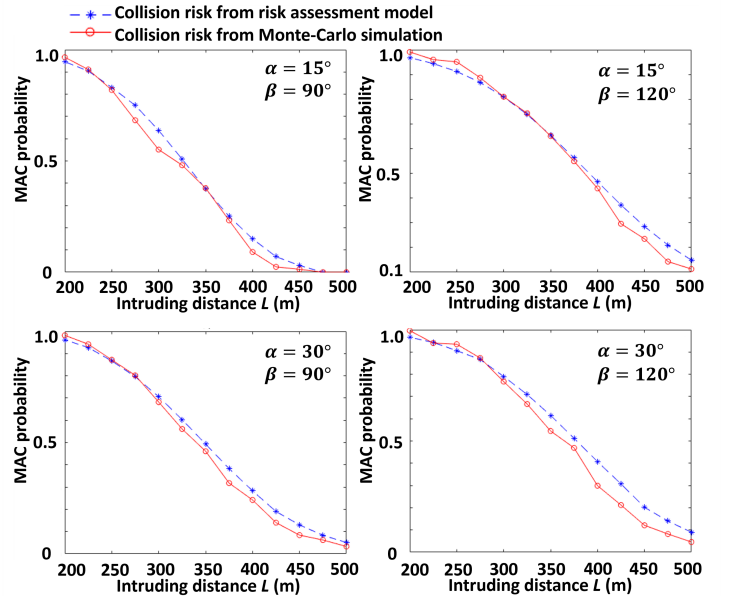


Fig. 13. Comparison between results generated by simulation and by proposed model, in terms of the probability of mid-air collision changing along the intruding distance L in 4 simulation scenarios.

for an aircraft speed of 15 m/s and an intruder with speed of 8 m/s, the model's results match with the simulation's, in particular for the 4 simulated environments at intruding distances L of 200 m to 400 m. Their results are slightly different at intruding distances L of 400 m to 500 m. The following reasons may contribute to this outcome:

First, as seen in Eq. (3), the aircraft risk envelope is a circular region consisting of the maximum length of the aircraft plus the uncertainty. Whenever an intruder enters the region, a collision is considered to have occurred. This design consideration is to simplify the calculation process and to

ensure the safety of the aircraft by providing a fast risk assessment of the current situation when the aircraft encounters an intruder in the air. However, in the simulation, the position uncertainty of the aircraft in the velocity direction is different from the position uncertainty in the vertical velocity direction, which is smaller than the velocity and position uncertainty. The position uncertainty distribution of the actual aircraft may be elliptical, leading to errors in the model prediction results.

Next, in addition to the conservative estimate of location uncertainty, the model does not take into account the cumulative effect of uncertainty. From the simulations of the 4 scenarios, it can be seen that the simulated collisions are generally lower than those model predicted when the intrusion distance is greater than 400 m. The reason for this may be that, when the distance is far, errors such as velocity and direction of the aircraft will accumulate during the approach, and this deviation may cause the intruder to avoid the collision risk zone.

Last, once the intruder enters the area within which the aircraft cannot avoid even with the maximum load turning, the model treats the probability of collision in this case as providential. For conservative reasons, the model assumes that a collision must occur in this case. However, in simulation, it is possible for such a situation where aircraft can still avoid the intruder. This could be another reason why the model prediction is higher than the simulation outcome.

In this section, the results of theoretical calculations for mid-air collision risk assessment are compared and validated by Monte Carlo simulations. Compared with previous simulations, the novelty includes: (1) The simulation setup in this research is based on the UAM deployment verification scenario of the AMU-LED project, built on the previous collection and processing of a vast amount of real-world datasets, which brings the benefits of real engineering applications into this research; (2) The simulation focuses on the collision process of a pair of UAM approaching to each other, considering the flight performance of a variety of UAM vehicles, with a variety of approach azimuths and velocities in a two-dimensional plane; and (3) By introducing external environmental information, aircraft dynamics model and sensor error database, simulating the actual airspace traffic situation, and calculating the probability of collision, the generated corresponding probability curves are compared with the theoretical calculation results in order to prove the accuracy of the model estimation.

VII. ILLUSTRATIVE EXAMPLES

The AMU-LED project is expected to demonstrate the safe integration of different types of manned and unmanned aircraft in urban airspace to realise increasingly sustainable smart cities. This section will explain how the proposed collision risk assessment model can be applied, using illustrative examples encompassing a real-world case study performed in the AMU-LED project.

A. Real-world scenario description

In order to more accurately simulate realistic mission situations, we use Ardupilot Native Physics Simulator integrating

the aircraft's dynamics model, including the aircraft's collision dimensions, three axial moments of inertia, individual engine pull, gravity, lift, drag, maximum load, range, lift limit, and maximum/cruise speed. The wind parameters are implemented through the Firmware SITL wind simulator. Factors including wind direction, wind force, turbulence and height variations are taken into account. The scenarios used in the simulation are derived from the co-simulation experimental scenario in the AMU-LED project. In this section, the mid-air collision risk assessment framework presented will be validated entirety.

The scenario of the case study is shown in Fig. 14, where the mission UAM (Ehang 216), which requires in-air collision risk assessment, enters the mission airspace from the bottom of the diagram. Other UAM participants' information in this scenario is shown in Table II. The flight directions of these aircraft are shown with the arrows. The coloured translucent areas in the diagram depict the different functional areas on the ground, which are taken into account for ground and air risk assessment.



Fig. 14. A typical real-world scenario for mid-air collision risk assessment.

The different coloured functional areas represent the level of risk of damage to property on the ground in the event of a collision over the area. The colours range from green to red, representing low to high risk. Similarly, the rainbow strips represent risks associated with ground roads, from which it can be seen that the collision risk is higher above the middle of the road than at the edge of the road.

The red circle represents the temporary flight restricted area in the mission area and the blue sectors in the bottom right corner represents a part of airspace divisions of Cranfield University Airport. The mid-air collisions within these areas may pose a risk to the manned aircraft in the air.

TABLE II
INFORMATION ABOUT THE MISSION UAM

UAM model	Performance	Use case	Speed
Amazon	Standard	Delivery	Low
Cranfield eVTOL	High	Transportation	High
Cranfield twin mapper	Standard	Delivery	Medium
DJI mavic pro	Standard	Photography	Low
Ehang 216	High	Transportation	High
Technalia UMILES 2	High	Transportation	Very low

The parameters of the considered aircraft are shown in Table III. In this scenario, the aircraft are cruising at an altitude of 50 meters.

B. P_{MAC} estimation

In the simulation, we will extract the flight information of the simulated aircraft in the airspace in real time, including position, speed and heading. Then, we calculate $P_{TC|SC}$, $P_{CA|TC}$, and eventually obtain P_{MAC} . The results are shown in the first column of Table IV. The results, as expected, show that the probability of mid-air collision P_{MAC} becomes significantly higher when a pair of aircraft are in close proximity and at high relative speeds, resulting in a higher risk of mid-air collision R .

1) $P_{TC|SC}$ component: Based on the number of aircraft in the airspace in real time and the dimension of the airspace, the aircraft density $\rho_{aircraft}$ in the airspace is estimated. Based on the dimensional parameters of the aircraft, A_{SC} is obtained. Then, the flight time $t_{mission}$ in the mission airspace is obtained from the mission information of the aircraft to be evaluated. After obtaining the above parameters, $P_{TC|SC}$ is obtained using Eq. (7).

2) $P_{CA|TC}$ component: After comparing the model calculation and Monte Carlo simulation result curves in section VI, it is found that the model calculation results are in consistency with the simulation results. Therefore, the calculation method of this validated model will be used to derive $P_{CA|TC}$ of the scenario.

C. $P_{IM|MAC}$, $P_{FA|IM}$ and R estimation

Having assessed the probability of the mid-air collision, it is necessary to consider the impact of the collision on the surrounding environment after it occurs. $P_{IM|MAC}$ is calculated taking into account the weather information, ground pedestrian density, ground traffic flow, airport and TFR information at the time of the mission. Combining the aircraft's kinetic energy and sheltering coefficients, $P_{FA|IM}$ can be produced. The calculation process for these two parts is described in detail in our previous research [6] and [24]. The results for $P_{IM|MAC}$ and $P_{FA|IM}$ are shown in the second and third columns of Table IV.

It can be noticed that, when the collision occurs over a densely populated urban area, the probability of impact on ground property $P_{IM|MAC}$ becomes greater, and the probability of damage to human on the ground $P_{FA|IM}$ is relatively greater when the aircraft has a higher self-weight thus higher kinetic energy.

The above intermediate conditional probabilities are multiplied to derive the pair aircraft's mid-air collision risk R . The calculation results of mid-air collision risk R are as shown in the fourth column of Table IV. In general, by assessing the mid-air collision risk of aircraft in the scenario, those that may pose a remarkable threat can be quickly identified in time, such that the corresponding collision avoidance measures can be taken in advance.

D. Extended application

The mid-air collision risk assessment model proposed in this study is capable of assessing the collision risk of a pair of known approaching aircraft in mission airspace. In addition, this approach can be extended to assess the distribution of the risk of collisions caused by intruders present in the area around a UAM, when only the movement parameters of that UAM are known.

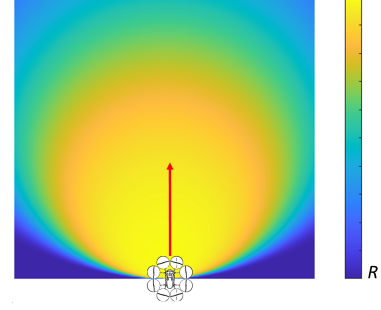


Fig. 15. Airspace collision risk distribution map around the UAM using the extended collision risk assessment method with known UAM information.

As shown in Fig. 15, we use mission UAM Ehang 216 as an example, and its aircraft parameters and flight information are extracted. The distribution of collision risk corresponding to different locations around the mission UAM is obtained without knowing specific information about the intruder. As shown by the coloured bar on the right in the diagram, the risk of mid-air collision is coloured from blue to yellow from low to high.

VIII. CONCLUSIONS AND FURTHER WORK

This study presented a method for assessing the risk of mid-air collisions as a result of UAM operations. It considered three components: the probability that a collision occurs in the air, the probability that a fall occurs after a collision, and the probability of damage to property on the ground or in the air after the fall. To obtain the probability of mid-air collision, three main barriers were modelled. The probability of strategic mitigation failure was assessed using the gas model. For the probability of tactical mitigation failure, a concept of encounter timeline was used. The maximum load turn of the aircraft was taken into account for deriving the probability of collision avoidance mitigation failure. Monte Carlo simulations were performed to validate the risk assessment model, followed by demonstrating a co-simulation scenario based on the AMU-LED project.

There are some limitations in this research. 3D motion, including climb/descent or vertical collision avoidance, is not considered in this research. This research targets UAM in the cruise phase and in the future will integrate a 3D collision avoidance warning service for special situations. Similar to ACAS X, compared to the 3D solution of ACAS II, which will use the Nucleus module to select a horizontal or vertical manoeuvre for avoidance [48]. The benefit of this processing is that it saves computational resources and allows the service

TABLE III
RELEVANT PARAMETERS FOR PARTICIPANTS

Aircraft	Model	Weight (kg)	Azimuth (°)	Distance (m)	Heading (°)	Speed (m/s)
Mission UAM	Ehang 216	453.59	/	/	0	17
Air taxi 1	Technalia UMILES 2	650	47	750	-100	6
eVTOL 1	Cranfield twin mapper	12	74	1350	79	15
eVTOL 2	Cranfield twin mapper	12	3	1130	180	15
eVTOL 3	Cranfield eVTOL	11.5	-27	650	160	18
Drone 1	Amazon drone	15	-58	880	90	10
Drone 2	DJI mavic pro	0.75	-98	560	50	8

TABLE IV
RESULTS OF THE RISK ASSESSMENT FOR A SCENARIO

Aircraft	P_{MAC} (collision / h)	$P_{IM MAC}$ (impact / collision)	$P_{FA IM}$ (fatality / impact)	R (fatality / h)
Air taxi 1	4.775×10^{-4}	0.1503	0.3608	2.588×10^{-5}
eVTOL 1	0	/	/	0
eVTOL 2	3.896×10^{-3}	0.2348	0.08772	8.024×10^{-5}
eVTOL 3	0.4447	0.3381	0.6983	0.01049
Drone 1	2.185×10^{-5}	0.6956	0.04434	6.740×10^{-8}
Drone 2	1.171×10^{-4}	0.1781	0.02873	5.988×10^{-7}

to adapt more efficiently to different traffic scenarios, reducing unnecessary altitude changes.

For fast-time computation, some simplifications are made, for example, the model uses a circular region to model aircraft position uncertainty. A collision is considered certain when an intruding aircraft enters the area within the minimum turning radius. In addition, the probability of a collision when an intruder comes within the maximum load avoidance range is worthy of investigation. Finally, this research focuses on the situation of a pair of aircraft. When there are multiple intruders in the airspace, the risk is superimposed on the risk of each pair of approach situations. The interaction between multiple aircraft and whether new collision risks arise after avoidance manoeuvres are problems that require further research.

For wind uncertainty, the effect of turbulent kinetic energy on flight stability is not explored in detail. Only approximate flight deflections under specific wind conditions are anticipated in this research based on historical flight data. Further flight risk assessment studies are necessary to consider the threat of turbulent kinetic energy on aircraft destabilization and to limit the cruising speed of the aircraft based on the turbulence condition in mission airspace.

REFERENCES

- [1] Ellis L Thompson, Abenezer G Taye, Wei Guo, Peng Wei, Marcos Quinones, Ibrahim Ahmed, Gautam Biswas, Jesse Quattrociocchi, Steven Carr, Ufuk Topcu, et al. A survey of evtol aircraft and aam operation hazards. In *AIAA AVIATION 2022 Forum*, page 3539, 2022.
- [2] Ersin Ancel, Francisco M Capristan, John V Foster, and Ryan C Condotta. Real-time risk assessment framework for unmanned aircraft system (uas) traffic management (utm). In *17th aiaa aviation technology, integration, and operations conference*, page 3273, 2017.
- [3] S Bertrand, N Raballand, F Viguiet, and F Muller. Ground risk assessment for long-range inspection missions of railways by uavs. In *2017 International Conference on Unmanned Aircraft Systems (ICUAS)*, pages 1343–1351. IEEE, 2017.
- [4] Sylvain Bertrand, Nicolas Raballand, and Flavien Viguiet. Evaluating ground risk for road networks induced by uav operations. In *2018 International Conference on Unmanned Aircraft Systems (ICUAS)*, pages 168–176. IEEE, 2018.
- [5] Bizhao Pang, Xinting Hu, Wei Dai, and Kin Huat Low. Third party risk modelling and assessment for safe uav path planning in metropolitan environments. *arXiv preprint arXiv:2107.01834*, 2021.
- [6] Yu Su and Yan Xu. Risk-based flight planning and management for urban air mobility. In *AIAA AVIATION 2022 Forum*, page 3619, 2022.
- [7] Robert E Machol. Thirty years of modeling midair collisions. *Interfaces*, 25(5):151–172, 1995.
- [8] A ICAO. unified framework for collision risk modelling in support of the manual on airspace planning methodology with further applications, circ 319-an/181 ed. *International Civil Aviation Organization, Montreal, Canada*, 2008.
- [9] Jacky Civil Harry Daly. The longitudinal reich collision risk model. In *Separation and Airspace Safety Panel (SASP) meeting of the working group of the whole*, 2012.
- [10] Valtteri Kallinen and Aaron McFadyen. Collision risk modeling and analysis for lateral separation to support unmanned traffic management. *Risk analysis*, 42(4):854–881, 2022.
- [11] Aaron McFadyen and Terrence Martin. Understanding vertical collision risk and navigation performance for unmanned aircraft. In *2018 IEEE/AIAA 37th Digital Avionics Systems Conference (DASC)*, pages 1–10. IEEE, 2018.
- [12] GTA May. A method for predicting the number of near mid-air collisions in a defined airspace. *The Journal of Navigation*, 24(2):204–218, 1971.
- [13] Jialong Zhang, Jianguo Yan, Pu Zhang, and Xiangjie Kong. Collision avoidance in fixed-wing uav formation flight based on a consensus control algorithm. *IEEE access*, 6:43672–43682, 2018.
- [14] Richard Melnyk, Daniel Schrage, Vitali Volovoi, and Hernando Jimenez. Sense and avoid requirements for unmanned aircraft systems using a target level of safety approach. *Risk Analysis*, 34(10):1894–1906, 2014.
- [15] Anders la Cour-Harbo. Quantifying risk of ground impact fatalities for small unmanned aircraft. *Journal of Intelligent & Robotic Systems*, 93(1):367–384, 2019.
- [16] Suraj Bijjhalli, Alessandro Gardi, Nichakorn Pongsakornsathien, Roberto Sabatini, and Trevor Kistan. A unified airspace risk management framework for uas operations. *Drones*, 6(7):184, 2022.
- [17] Hans-Joachim K Ruff-Stahl, Steven Esser, Dirk Farsch, Thomas Graner, Robert Klein, Christian Schneidt, and Stefan Schoenborn. Not-so-risky business? assessing the risk of integrating large rpvs into the current air traffic system. *International Journal of Aviation, Aeronautics, and Aerospace*, 3(1):7, 2016.
- [18] James T Luxhøj. A socio-technical model for analyzing safety risk of

unmanned aircraft systems (uas): An application to precision agriculture. *Procedia Manufacturing*, 3:928–935, 2015.

- [19] William H Joyce Jr and Carl A Luxhøj. Modeling multiple uas performing agricultural spraying: object-oriented bayesian network approach. In *IIE Annual Conference. Proceedings*, pages 410–415. Institute of Industrial and Systems Engineers (IISE), 2017.
- [20] Anders la Cour-Harbo and Henrik Schjøler. Probability of low-altitude midair collision between general aviation and unmanned aircraft. *Risk Analysis*, 39(11):2499–2513, 2019.
- [21] M Matteo, P Stefano, and G Giorgio. Air risk maps for unmanned aircraft in urban environments. In *Proceedings of the 2022 International Conference on Unmanned Aircraft Systems (ICUAS), Dubrovnik, Croatia*, pages 21–24, 2022.
- [22] James Reason. *Human error*. Cambridge university press, 1990.
- [23] Jun Tang. Conflict detection and resolution for civil aviation: A literature survey. *IEEE Aerospace and Electronic Systems Magazine*, 34(10):20–35, 2019.
- [24] Yu Su, Yan Xu, and Gokhan Inalhan. A comprehensive flight plan risk assessment and optimization method considering air and ground risk of uam. In *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*, pages 1–10. IEEE, 2022.
- [25] James Reason. Human error: models and management. *Bmj*, 320(7237):768–770, 2000.
- [26] Pablo Rangel and Luis Rodolfo Garcia Carrillo. Safety bubble control for coordination of multiple unmanned aircraft systems. *IFAC-PapersOnLine*, 51(12):50–55, 2018.
- [27] Thomas Dubot and Antoine Joulia. Towards u-space conflict management services based on 4d protection bubbles. In *AIAA AVIATION 2021 FORUM*, page 2347, 2021.
- [28] Suraj Bijjahalli, Alessandro Gardi, Nichakorn Pongsakornsathien, and Roberto Sabatini. A unified collision risk model for unmanned aircraft systems. In *2021 IEEE/AIAA 40th Digital Avionics Systems Conference (DASC)*, pages 1–10. IEEE, 2021.
- [29] Giancarmine Fasano, Domenico Accado, Antonio Moccia, and David Moroney. Sense and avoid for unmanned aircraft systems. *IEEE Aerospace and Electronic Systems Magazine*, 31(11):82–110, 2016.
- [30] Dennis Coulter. Uas integration into the national airspace system: modeling the sense and avoid challenge. In *AIAA Infotech@ Aerospace Conference and AIAA Unmanned... Unlimited Conference*, page 1926, 2009.
- [31] Guillaume JJ Ducard and Mike Allenspach. Review of designs and flight control techniques of hybrid and convertible vtol uavs. *Aerospace Science and Technology*, 118:107035, 2021.
- [32] Tielin Ma, Xiangsheng Wang, Jingcheng Fu, Shuai Hao, and Pu Xue. Three-dimensional flight envelope for v/stol aircraft with multiple flight modes. *Aerospace*, 9(11):691, 2022.
- [33] Juan A Vila Carbó, Juan V Balbastre Tejedor, Pablo Morcillo Pallarés, and Pedro Yuste Pérez. Risk-based method for determining separation minima in unmanned aircraft systems. *Journal of Air Transportation*, 31(2):57–67, 2023.
- [34] TC Smith. Automatic dependent surveillance broadcast (ads-b) out performance requirements to support air traffic control (atc) service final rules. *FAA, Federal Aviation Admin., Washington, DC, USA, Tech. Rep., FAA, Rule*, 14, 2010.
- [35] Michael M Madden. A component-level model of automatic dependent surveillance-broadcast (ads-b). In *2018 Modeling and Simulation Technologies Conference*, page 4061, 2018.
- [36] Kais Belwafi, Ruba Alkadi, Sultan A Alameri, Hussam Al Hamadi, and Abdulhadi Shoufan. Unmanned aerial vehicles’ remote identification: A tutorial and survey. *IEEE Access*, 10:87577–87601, 2022.
- [37] Benjamin S Levy, Pradip Som, and Richard Greenhaw. Analysis of flight technical error on straight, final approach segments. In *Proceedings of the 59th Annual Meeting of The Institute of Navigation and CIGTF 22nd Guidance Test Symposium (2003)*, pages 456–467, 2003.
- [38] Robert J Shively, Kim-Phuong L Vu, and Timothy J Buker. Unmanned aircraft system response to air traffic control clearances: Measured response. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 57, pages 31–35. SAGE Publications Sage CA: Los Angeles, CA, 2013.
- [39] Konstantinos Dalamagkidis, Kimon P Valavanis, and Les A Piegl. Evaluating the risk of unmanned aircraft ground impacts. In *2008 16th mediterranean conference on control and automation*, pages 709–716. IEEE, 2008.
- [40] Shinsuke Endoh. *Aircraft collision models*. PhD thesis, Massachusetts Institute of Technology, 1982.
- [41] Roland E Weibel and R John Hansman. Safety considerations for operation of unmanned aerial vehicles in the national airspace system. Technical report, MIT, 2006.
- [42] Christopher Lum and Blake Waggoner. A risk based paradigm and model for unmanned aerial systems in the national airspace. In *Infotech@ Aerospace 2011*, page 1424. Infotech, 2011.
- [43] Ehang eh216-s (production model). <https://evtol.news/ehang-216/>.
- [44] ICAO Doc. 9613 performance-based navigation (pbn) manual. *International Civil Aviation Organisation: Montréal, QC, Canada*, 2008.
- [45] Jaewoo Jung, Sarah N D’Souza, Marcus A Johnson, Abraham K Ishihara, Hemil C Modi, Ben Nikaido, and Hashmatullah Hasseeb. Applying required navigation performance concept for traffic management of small unmanned aircraft systems. In *ICAS 2016 Congress of the International Council of the Aeronautics Sciences*, 2016.
- [46] Peter JG Teunissen and Oliver Montenbruck. *Springer handbook of global navigation satellite systems*, volume 10. Springer, 2017.
- [47] ZHAO Hongsheng, XU Xiaohao, Jun Zhang, ZHU Yanbo, YANG Chuansen, and HONG Sheng. Lateral flight technical error estimation model for performance based navigation. *Chinese Journal of Aeronautics*, 24(3):329–336, 2011.
- [48] Guido Manfredi and Yannick Jestin. An introduction to acas xu and the challenges ahead. In *2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC)*, pages 1–9. IEEE, 2016.

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2025-02

Institute of Electrical and Electronics Engineers (IEEE)

<https://doi.org/10.1109/tiv.2024.3426915>

Su Y, Xu Y. (2025) A risk assessment method for mid-air collisions in urban air mobility operations. IEEE Transactions on Intelligent Vehicles, Volume 10, Issue 2, February 2025, pp. 1327-1341