Research Article

A Conflict Risk Analysis of MAV\UAV Flight in Shared Airspace

ChaoYu Xia ^{1,2}, **Chun-Rong Yang**^{1,2}, **Kang Xue** ¹, **HanBing Yan**^{1,2}, **JianHua Zhong**^{1,2}
and **Qiu Jun**^{1,2}

¹The 2nd Research Institute, Civil Aviation Administration of China, Chengdu 610041, China

²Chengdu Civil Aviation Air Traffic Control Science & Technology Co., Ltd., Chengdu 610041, China

Correspondence should be addressed to ChaoYu Xia; xcycuit@163.com and Kang Xue; xuekang_caac@yeah.net

Received 9 September 2021; Revised 2 October 2021; Accepted 8 October 2021; Published 3 November 2021

Academic Editor: Chen Pengyun

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The intelligent auxiliary decision-making (IADM) is emerging as a feasible solution for air traffic control (ATC) to reduce undesirable conflicts in shared airspace; meanwhile, unmanned aerial vehicles (UAVs) can be operated with enhanced efficiency and safety using IADM. This paper presents the conflict risk framework of the MAV\UAV flight that improves flight safety of MAVs and UAVs in shared airspace. This is accomplished by focusing on two steps: First, determine the minimum safety communication interval between the UAV and controller; second, build a conflict risk model to detect which decision mechanism will minimize risk. Our approach provides a standard model to start with to improve IADM and allow engineers to focus on the operational purpose of MAV/UAV. Results show that our work presented here is practical and straightforward, and it brings an evident engineering application prospect.

1. Introduction

Unmanned aerial vehicles (UAVs) are widely used in civilian industries, especially in remote sensing, and foreign object detection has attracted considerable attention [1, 2]. As a report goes, some UAVs can even fly at altitudes of tens of thousands of meters and has a range of more than 10,000 kilometers [3]. In recent, multimodal airport group operation is also gradually open to general aviation. However, UAVs can only rely on a notice to airmen (NO-TAM) for independent operation [4]. Specifically, UAVs operate primarily in an isolated airspace to prevent flight collisions; there is no doubt that this approach lowers the efficiency of airspace utilization.

The goal is obviously increasing traffic volumes in airspace, especially in the terminal area. Thus, sharing flight is a possible solution to the UAV industry. The shared airspace refers to a controlled airspace where all aircraft, including UAVs and manned aerial vehicles (MAVs), can apply for use. For the further better development, new ATC technologies have been studied, such as trajectory-based operation (TBO), situation awareness (SA), and intelligent auxiliary decision-making (IADM) [5–7]. However,

detecting future conflicts timely and accurately and providing effective relief strategies are the critical issues related to shared-airspace safety. In addition, UAVs violate minimum vertical and horizontal separation standards, and it can pose a serious threat to the safety of MAV transportation. So far, little work has focused on conflict detection in shared airspace. Most of the work targets on UAV obstacle avoidance only. Radmanesh et al. generated collision-free 3D trajectories for multiple UAVs operating in shared airspace based on a partial differential equation (PDE) and modeling the porosity values as a function of the risk of conflict [8]. Ho et al. used preflight conflict detection, and resolution (CDR) methods generate to conflict-free paths for a potentially large number of UAVs before actual takeoff [9]. Based on the established protect zone, the closest point of approach (CPA) strategy is employed by Shi et al. to detect potential conflicts [10]. Wang et al. proposed a three-layered collision avoidance system integrating conflict detection procedures [11]. Also, there are several existing trajectory planning approaches that have been introduced in the literature, such as [12]; the UAV optimal path in the Euclidean 3D space is determined through an optimization problem of maximizing the coalition head's total energy availability. These

results are widely used in low-altitude airspace. Unfortunately, these studies are independent, lacking of taking MAVs impact into consideration.

This article considers the conflict risk analytical framework of MAV\UAV flight in shared airspace as a main subject of the study. This work is aimed at exploring which decision mechanisms are conducted to minimize the probability of conflict risk. Two steps are required for a satisfied outcome: first, determining the minimum safety interval between UAV communication lag-time and controller response lag-time; second, based on the minimum security interval, build a conflict risk model intelligently detecting which decision mechanism has minimized the probability of conflict risk. The result points out the advantages and practicability of adjusting parameters such as steering angle, pitch angle, and flight speed, to quickly identify conflict risk. Moreover, our work can be applied to the design of the IADM decision system in engineering, which guarantees safe flight in shared airspace. Our research has a wide range of applications, such as risk assessment for UAS logistic delivery under UAS traffic management environment [13] and constrained urban airspace design for large-scale drone-based delivery traffic [14].

2. Preliminaries

The past few decades have witnessed a dramatic change in the UAV field for civil aviation. UAVs used for opening shared airspace becomes an inevitable trend [15]. However, air traffic control (ATC) in shared airspace is facing safety challenges and enhancing efficiency [16]. In the section, we analyze the minimum safety interval between UAVs and MAVs by communication lag-time, as well as a brief demonstration of the conflict relief scheme.

2.1. Situation Awareness. In shared airspace, the UAVs must have a function of situation awareness. The situation awareness means that UAVs gain airspace information which can reflect the outside authentic scenery through sensors and complete the overall comprehension including the assessment and prediction of the situation. Specific methods are as follows, for cooperative objects, the UAVs can gain flight information of other aircrafts or vehicles by Traffic Conflict Avoidance System (TCAS), Automatic Dependent Surveillance-Broadcast (ADS-B), and responder [17, 18]. For noncooperative objects, the UAVs can judge risk through noncooperative sensors, such as inertial measurement unit (IMU), laser range finder (LRF), and stereoscopic camera [19]. Then, the analysis module extracts relevant airspace data, processes explicit and implicit information, and conducts situation representation. Finally, the decision module is generated on the basis of situation representation, outputting situational assessment, and situation prediction results. At the same time, the situation information is transmitted to the UAV ground control station and related control departments. This process usually contains complex data processing flow and information exchange, including the UAV prediction of flight at risk, collecting basic information such as distance, object's velocity, object's flight pro-

cedure, and priority avoidance judgment. By combining various sources of sensing information, situation awareness supports UAV flight safety in shared airspace. However, the UAV needs to complete the rapid and satisfactory situation awareness of surrounding flight space, and this also becomes the most significant challenge at the present stage [20]. They are using automated approaches, and intelligent data processing means significant improvement of speed and precision of situation awareness.

2.2. Communication Lag-Time. To note that, UAVs in our paper must be capable of two-way communication, such as utilizing microwave signals for satellite communications (as shown in Figure 1). The situation awareness data wirelessly transferred to UAVs must transit shipment by satellite. Compared with the speed of communication of MAVs, undoubtedly, the former produces a more prolonged time lag than the latter (MAVs are able to establish direct communication through a very high-frequency signal with the ground station). Similarly, the ATC instruction of the UAV controller also requires satellite data link to reach the front end of UAV's receiver, whereas this bidirectional communication process is only a part of the total lag-time.

Response lag-time is a time interval before human or machine is able to perform a response operation. Maneuver lag-time is defined as the time interval between aircraft (UAVs or MAVs) executing maneuvers and accomplishing the maneuver. As presented in the schematic illustration (Figure 2), other factors contain the ATC controller response lag-time, UAV controller response lag-time, UAV response lag-time, repeat instruction lag-time, and maneuver lag-time. On the contrary, the MAVs only include one-way link transmission lag-time, ATC controller response lag-time, pilot response lag-time, and maneuver lag-time (Figure 3). Additionally, the pilot operates the aircraft directly in case of emergency; there is only maneuver lag-time. Obviously, the lag-time of UAVs is much higher than MAVs in summary.

The communication between UAVs using a method based on literature [21] used smart agents; this requires a lot of training and does not seem feasible in a complex airspace. Self-rating techniques refer to each subject which provides a subjective measure of his/her lag-time based on a rating scale after task execution [22]. This paper makes full use of self-rating techniques to assess controller response lag-time. It means the machine lag-time and maneuver lag-time are acquired by a transducer. At the same time, a detailed summary of the total lag-time is made through vast amounts of data from *China's Southwest Air Traffic Control Bureau*. We collect and assess the average total lag-time generated by short instruction (instruction word length 32 bits) and long instruction (instruction word length 64 bits), please see Table 1 for further details. More importantly, only long instruction is considered in this paper because it can make the conflict risk assessment model have an additional safety margin.

2.3. Minimum Safety Interval. It was demonstrated in *EUROCONTROL Airspace management (ASM)* of studies

FIGURE 1: Shared airspace communication diagram.

FIGURE 2: UAV communication lag-time.

FIGURE 3: MAV communication lag-time.

that the altitude of MAV and UAV is not more than 360 km/h and 169 km/h, respectively, in low-level airspace (Flight altitude < 1000 m) [23]. According to visual flight

TABLE 1: Controller response lag-time by using self-rating techniques.

Types	Short instruction	Long instruction
UAV	2.18 s	5.49 s
MAV	0.81 s	1.01 s

safety interval, the airspeed of MAV and UAV is not more than 610 km/h and 224 km/h. Furthermore, in midlevel airspace (flight altitude 1000-4200 m) and in high-level airspace (flight altitude 4200-7800 m), the airspeed is not more than 720 km/h and 224 km/h. It is possible to calculate the safety margin of minimum safety interval between aircrafts by the average total lag-time and maximum airspeed; we define D

as a minimum safety margin.

$$D_j = t_{\text{long}} \cdot \left(V_{MAV,j} + V_{UAV,j} + \frac{Y_{MAV,j}}{2} + \frac{Y_{UAV,j}}{2} \right) + D_{wav}, \quad (1)$$

where t_{long} is a long instruction lag-time, $V_{MAV,j}$, $V_{UAV,j}$ are velocity of different aircraft in j th direction ($j \in [1, 2, 3]$), and $Y_{MAV,j}$, $Y_{UAV,j}$ fuselage in the direction of j th. Because of the randomness of flight, it is usually considered $D_1 = D_3$ as shown in Figure 4.

2.4. Conflict Relief Scheme. For the sake of avoiding the conflict risk, the current path planning by UAV controller decision-making is shown in Figure 5. To reduce or eliminate crashes caused by human decision-making errors, the need to additional development of intelligent auxiliary decision-making (IADM) for path planning must respond quickly to unexpected risks in shared airspace [24, 25]. The IADM usually relies on real-time situation awareness to achieve short-term forecast, evaluation, and instruction generation as well as independent analysis and decision-making function, optimal online multiplatform path plan, and control.

The UAV conflict relief process is shown schematically in Figure 6, and shared airspace needs to integrate multidimensional electronic intelligence, such as ATC service, fight data, and perceptual information. In the process of IADM, we fully follow the relevant policies and regulations of the current existing ATC and formulate the corresponding prioritization of avoiding. Generally speaking, the prioritization of UAVs is generally lower than MAVs (except for military UAVs). In the case of conflict, small UAVs should avoid large UAVs, and UAVs should avoid MAVs. Nevertheless, the existing path planning methods are often implemented for conflict relief in a specific application scenario, and it still requires lots of basic technology researches to achieve a reliable and stable path planning function in shared airspace.

3. Conflict Risk Assessment

3.1. Scenario Hypothesis. IADM is the principal means to ensure a safe flight in shared airspace with the assistance of intelligently maintaining distance, controlling steer angle, pitch angle, and flight speed. It helps the controller resolve conflict. In this section, considers cross-route flight conflict zone in shared airspace (as shown in Figure 7). We establish a conflict risk model to study what decisions IADM can make to minimize the probability of conflict risk. The model can be divided into two stages. In the first stage, the MAV flights along the OE direction until O -point, and the UAV steers to angle θ at O -point to avoid conflict, which is shown in Figure 7(a). In the second stage, suppose no conflict occurs, the MAV flights along the OC direction, and the UAV flights along the OB direction as shown in Figure 7(b). Besides, let us make the following assumptions:

FIGURE 4: Three-dimensional space minimum safety interval.

FIGURE 5: Situation awareness and conflict relief plan.

- (i) At the initial time, both aircrafts are flying along the route AE direction
- (ii) At time t_0 , the UAV is aware of the risk and conducts path planning (turning θ angle); the route changed to OB
- (iii) At time t_0 , the altitude difference between the MAV and UAV is H , and $|OA| = d$
- (iv) At time t , there is an inevitable conflict if $d_{EF} < D_w$ ($d_E'^{F'} < D_w$) & $d_H < D_y$ (& represents AND gate operator)
- (v) The average velocity of MAV and UAV satisfies:

$$\begin{cases} u_{hi} = u_i \cos \theta_3, \\ u_{vi} = u_i \sin \theta_3, \end{cases} \quad (2)$$

where θ_3 is the pitch angle (13~20 degrees in general); u_{hi} is horizontal speed of the i th aircraft; u_{vi} is vertical speed of the i th aircraft, $i \in [MAV, UAV]$

- (vi) Measurement airspeed V_{hi} , V_{vi} obeys the Gaussian distribution with $V_{hi} \sim N[(u_{hi} - k_i \sigma_{hi}), \sigma_{hi}^2]$, $V_{vi} \sim N[(u_{vi} - k_i \sigma_{vi}), \sigma_{vi}^2]$, where k_i is a speed deviation factor
- (vii) ω_{hi}^N , ω_{vi}^N denotes required navigation performance (RNP); the errors follow a normal distribution $N[0, 0.5102a]$, which means that the aircraft performs PNP-a flight procedure, $a \in [1, 4, 12.6, 20]$
- (viii) ω_{hi}^C , ω_{vi}^C denotes required communication performance (RCP); the errors follow a normal distribution $N[0, 0.5102aV_{v|hi}]$, where $\setminus$ represents OR gate operator
- (ix) ω_{hi}^S , ω_{vi}^S denotes required surveillance performance (RSP); the errors follow a normal distribution $N[$

FIGURE 6: Conflict relief scheme process.

FIGURE 7: Conflict risk model.

$0, 0.5102bV_{vhi}]$, where b represents the reaction time. The altitude is less than 4200 m; b is approximately equal to 2.2 s. Otherwise, b is approximately equal to 2.5 s

3.2. Formula Derivation. Based on an analysis of the geometric relationship of tracks, we can quickly get the following equation.

$$\begin{cases} \theta = \theta_1 + \theta_2, \\ \frac{|OE|}{\sin \theta_2} = \frac{|OF|}{\sin \theta_1}, \end{cases} \quad (3)$$

or

$$\begin{cases} \pi = \theta'_1 + \theta'_2 + \theta, \\ \frac{|OE'|}{\sin \theta'_2} = \frac{|OF'|}{\sin \theta'_1}, \end{cases} \quad (4)$$

where $|OE| = |OA| - |AE| = d - V_{hMAV}t$, $|OF| = V_{hUAV}t$, $|OE'| = |AE'| - |OA| = V_{hMAV}t - d$, and $|OF'| = V_{hUAV}t$. t and t' denote time difference compared with the initial time. Next, we should calculate whether there are conflicts in horizontal and vertical directions, respectively. In the first stage, we can define $d_1(t)$ and $d_2(t)$ as follows:

$$\begin{aligned} d_1(t) &= [d - (\omega_{hMAV}^N + \omega_{hMAV}^C + \omega_{hMAV}^S + V_{hMAV}t)] \cos \theta_1 \\ &\quad + (\omega_{hUAV}^N + \omega_{hUAV}^C + \omega_{hUAV}^S + V_{hUAV}t) \cos \theta_2, \\ d_2(t) &= [\omega_{vMAV}^N + \omega_{vMAV}^C + \omega_{vMAV}^S + V_{vMAV}t] \\ &\quad - [\omega_{vUAV}^N + \omega_{vUAV}^C + \omega_{vUAV}^S + V_{vUAV}t] + H. \end{aligned} \quad (5)$$

With $d_1(t)$ representing $|EF|$, $d_2(t)$ is the altitude differ-

ence between the UAV and MAV. We can obtain a simple deduction as follows:

$$d_1(t) \sim N[u_1, \sigma_1^2]; d_2(t) \sim N[u_2, \sigma_2^2],$$

$$u_1 = d \cos \theta_1 - (u_{hMAV} - k_{MAV}\sigma_{hMAV})t \cos \theta_1 + \cos \theta_2(u_{hUAV} - k_{UAV}\sigma_{hUAV})t,$$

$$\begin{aligned} \sigma_1^2 &= \cos^2 \theta_1 \cdot (0.5102a_{MAV} + 0.5102a_{MAV}V_{hMAV} \\ &\quad + 0.5102bV_{hMAV} + \sigma_{hMAV}^2 \cdot t^2) \\ &\quad + \cos^2 \theta_2 \cdot (0.5102a_{UAV} + 0.5102a_{UAV}V_{hUAV} \\ &\quad + 0.5102bV_{hUAV} + \sigma_{hUAV}^2 \cdot t^2), \end{aligned}$$

$$u_2 = (u_{vMAV} - k_{MAV}\sigma_{vMAV} - u_{vUAV} + k_{UAV}\sigma_{vUAV})t + H,$$

$$\begin{aligned} \sigma_2^2 &= 0.5102(a_{MAV}(1 + V_{vMAV}) + bV_{vMAV} + a_{UAV}(1 + V_{vUAV}) \\ &\quad + bV_{vUAV}) + t^2(\sigma_{vMAV}^2 + \sigma_{vUAV}^2). \end{aligned} \quad (6)$$

In order not to steal the attention of the main proof, the proof has been included in the appendix. Furthermore, according to the relation of geometry in the second stage, we can obtain $|EF| = |OF| \cos \theta'_2 + |OE| \cos \theta'_1$ and reach the following equivalence that

$$d_1(t)' \sim N[u_1', \sigma_1'^2]; d_2(t)' \sim N[u_2', \sigma_2'^2],$$

$$\begin{aligned} u_1' &= (u_{hMAV} - k_{MAV}\sigma_{hMAV})t' \cos \theta_1' \\ &\quad + \cos \theta_2'(u_{hUAV} - k_{UAV}\sigma_{hUAV})t' - d \cos \theta_1', \end{aligned}$$

TABLE 2: Experiment parameters.

Airspace	PSP	PNP	MAV horizontal airspeed variance (m^2)	UAV horizontal airspeed variance (m^2)	MAV vertical airspeed variance (m^2)	UAV vertical airspeed variance (m^2)	MAV airspeed deviation factor	UAV airspeed deviation factor	Maximum airspeed of MAV (km/h)	Maximum airspeed of UAV (km/h)	Horizontal safety margin D_H (m)	Vertical safety margin D_V (m)
Low- level	2.2	1	4.7	3	1.71	1	0.675	1	360	169	1.1204×10^3	353.78
Midlevel	2.2	1	4.7	3	1.71	1	0.675	1	610	224	1.5846×10^3	567.78
High- level	2.5	4.1	6.12	4.1	2.31	1.33	0.675	1	720	224	1.7521×10^3	569.84

FIGURE 8: Conflict risk assessment of horizontal flight in low-level airspace (flight altitude < 1000 m) versus steer angle $d \in [1.5, 2.9 \text{ Km}]$, $H = 0$, $\theta_{3 \text{ MAV}} = \theta_{3 \text{ UAV}} = 0$, $V_{\text{MAV}} = 360 \text{ Km/h}$, and $V_{\text{UAV}} = 169 \text{ Km/h}$. Results are averaged over 1000 simulations. (a) $\theta = \pi/9$; (b) $\theta = \pi/6$; (c) $\theta = \pi/3$; (d) $\theta = \pi/2$; (e) $\theta = 2\pi/3$; (f) $\theta = 8\pi/9$.

$$\begin{aligned}
 \sigma_1^{2'} &= \cos^2 \theta_1' \cdot (0.5102 a_{\text{MAV}} + 0.5102 a_{\text{MAV}} V_{h \text{ MAV}} \\
 &\quad + 0.5102 b V_{h \text{ MAV}} + \sigma_{h \text{ MAV}}^2 \cdot i^2) \\
 &\quad + \cos^2 \theta_2' \cdot (0.5102 a_{\text{UAV}} + 0.5102 a_{\text{UAV}} V_{h \text{ UAV}} \\
 &\quad + 0.5102 b V_{h \text{ UAV}} + \sigma_{h \text{ UAV}}^2 \cdot i^2), \\
 u_2' &= (u_{v \text{ MAV}} - k_{\text{MAV}} \sigma_{v \text{ MAV}} - u_{v \text{ UAV}} + k_{\text{UAV}} \sigma_{v \text{ UAV}}) \dot{t} + H, \\
 \sigma_2^{2'} &= 0.5102 (a_{\text{MAV}} (1 + V_{v \text{ MAV}}) + b V_{v \text{ MAV}} \\
 &\quad + a_{\text{UAV}} (1 + V_{v \text{ UAV}}) + b V_{v \text{ UAV}}) \\
 &\quad + i^2 (\sigma_{v \text{ MAV}}^2 + \sigma_{v \text{ UAV}}^2). \quad (7)
 \end{aligned}$$

The proof process is similar and should be no longer repeated here.

Furthermore, let $f_{d_1}(x)$ and $f_{d_2}(x)$ be the probability density function (PDF) of the horizontal and vertical distance between aircraft the MAV and UAV:

$$\begin{aligned}
 f_{d_1}(x) &= \frac{1}{\sqrt{2\pi}\sigma_1} e^{-(x-u_1)^2/2\sigma_1^2}, \\
 f_{d_2}(x) &= \frac{1}{\sqrt{2\pi}\sigma_2} e^{-(x-u_2)^2/2\sigma_2^2}. \quad (8)
 \end{aligned}$$

Horizontal conflict and vertical conflict can be regarded

as two independent events. We assume that $P_h(t)$, $P_v(t)$ are the conflict probabilities in horizontal and vertical directions, respectively.

$$P_{h,v}(t) = P_h(t) \cdot P_v(t). \quad (9)$$

Simultaneity, D_j is closely related to conflict risk analysis. For instance, if the interval between two aircrafts is reduced to a certain value, the conflict may be unavoidable.

$$P_h(t) = P(|d_1| \leq D_1) = \int_{-D_1}^{D_1} \frac{1}{\sqrt{2\pi}\sigma_1} e^{-(x-u_1)^2/2\sigma_1^2} dx, \quad (10)$$

$$P_v(t) = P(|d_2| \leq D_2) = \int_{-D_2}^{D_2} \frac{1}{\sqrt{2\pi}\sigma_2} e^{-(x-u_2)^2/2\sigma_2^2} dx. \quad (11)$$

Integrating Equations (10) and (11), we can obtain $P_{h,v}(t)$ from Equation (9). Next, the complexity of the algorithm is analyzed, letting the number of executions $T(n)$ be a function of the problem scale n . Represent the change of $T(n)$ with n and determine the order of magnitude of $T(n)$. Secondly, the growth rate of algorithm execution time is $f(n)$, $T(n) = O(f(n))$. The algorithm complexity calculation rule replaces all additive constants in run time with constant 1; meanwhile, keep the highest order items. Time complexity according to sequential

FIGURE 9: Conflict risk assessment of horizontal flight in low-level airspace (flight altitude < 1000 m) versus $\theta \in [\pi/9, 8\pi/9]$, $H = 0$, $\theta_{3\text{MAV}} = \theta_{3\text{UAV}} = 0$, $V_{\text{MAV}} = 360 \text{ Km/h}$, and $V_{\text{UAV}} = 169 \text{ Km/h}$. Results are averaged over 1000 simulations. (a) $d = 10^3$; (b) $d = 1.5 \times 10^3$; (c) $d = 2 \times 10^3$; (d) $d = 2.5 \times 10^3$; (e) $d = 3 \times 10^3$; (f) $d = 3.5 \times 10^3$.

structure, $f(n) = 4$. It has no highest order term at all, so the time complexity of this algorithm is $O(1)$.

4. Experiments

In this section, we describe our experiments. All scenarios are implemented in MATLAB and run on an I5-4200U @ 1.60 GHz Intel Core with 8 GB RAM. Statistical measures are used to study the simulated results; each result is averaged over 1000 simulations. For our experiments, unbolted curves in the illustration indicate conflict probability < $10^{(-7)}$. We need to place more emphasis on parameters that minimize conflict probability in various scenarios. It provides a theoretical basis for IDAM to avoid risks.

4.1. Simulation Parameters. Assume that the MAV is Boeing 747-400; the scale is about $70.6 \text{ m} \times 60.4 \text{ m} \times 19.4 \text{ m}$. The UAV-“Shen Diao” scale is about $42 \text{ m} \times 29.6 \text{ m} \times 4.5 \text{ m}$. Suppose there is a long instruction lag-time; the minimum safety margin is obtained by Equation (1). The so-called RNP- a flight procedure referring to 95% of total flight time must not deviate from a mile on either side of the route centerline. In low-level and mid-level airspace, they fly in compliance with the PNP-1 procedure; the response time of monitoring equipment is 2.2 s in RSP.

Meanwhile, in high-level airspace, flying follows the PNP-4.1 procedure; the response time of monitoring equipment is 2.5 s. The aircraft speed is measured by the speed sensor and then transmitted by ADS-B; the measurement speed variance is also affected by airspace altitude as shown from data in Table 2 for more detail parameters. In the next, four works are examined to assess conflict risk based on different situations and the flight environment.

4.2. Conflict Risk Assessment of Horizontal Flight in Low-Level Airspace. The relationship between initial distance d and conflict risk in low-level airspace (flight altitude < 1000 m) is presented below. For private parameters, $H = 0$, $\theta_{3\text{MAV}} = \theta_{3\text{UAV}} = 0$, $V_{\text{MAV}} = 360 \text{ Km/h}$, $V_{\text{UAV}} = 169 \text{ Km/h}$. The value range of $d \in [1.5 \text{ Km}, 2.9 \text{ Km}]$; different steer angles θ were used as reference experiments. 1000 Monte Carlo runs are performed, and the result is averaged over all runs. As shown in Figure 8, we can easily get that conflict onset is delayed with increasing d . Meanwhile, it is interesting to see that conflict risk decreases as d increases in certain θ steer angle. This trend is because the aircraft maneuver is too late to respond in long instruction lag-time when d is small enough. Another reason is that a narrow steer angle also increases the chance of conflict risk. To further explore the relationship between steer angle θ and conflict risk in the low-level airspace, we pick a broader value for d , $d \in [1 \text{ Km}, 3.5 \text{ Km}]$. To illustrate the preceding

FIGURE 10: Conflict risk assessment of horizontal flight in low-level airspace (flight altitude $< 1000\text{ m}$) versus $V_{\text{MAV}} \in [210\text{ Km/h}, 360\text{ Km/h}]$, $H = 0$, $\theta_{3\text{MAV}} = \theta_{3\text{UAV}} = 0$, and $V_{\text{UAV}} = 169\text{ Km/h}$. Results are averaged over 1000 simulations. (a) $d = 2 \times 10^3$, $\theta = \pi/6$; (b) $d = 2 \times 10^3$, $\theta = \pi/3$; (c) $d = 2 \times 10^3$, $\theta = \pi/2$; (d) $d = 2.5 \times 10^3$, $\theta = \pi/6$; (e) $d = 2.5 \times 10^3$, $\theta = \pi/3$; (f) $d = 2.5 \times 10^3$, $\theta = \pi/2$; (g) $d = 3 \times 10^3$, $\theta = \pi/6$; (h) $d = 3 \times 10^3$, $\theta = \pi/3$; (i) $d = 3 \times 10^3$, $\theta = \pi/2$.

analysis with experimental results as shown in Figure 9, the steer angle $\theta = 3\pi/9$ is more sensitive to changes in d , and conflict risk is minimized in this experiment. On the contrary, the steer angle $\theta = 8\pi/9$ is not sensitive to the change in d . Since the speed of MAVs does not differ significantly from UAVs in low-level airspace, the second conflict risk may occur at a specific d . Secondary conflict risk should also be considered in IDAM design.

Furthermore, the research goal is to find the relation between MAV velocity and conflict risk in low-level airspace. In Figure 10(a), only one conflict will occur at $V_{\text{MAV}} = 360\text{ Km/h}$, and three may occur at $V_{\text{MAV}} = 300\text{ Km/h}$. Significant low velocity will increase the probability of the risk occurrence. In fact, this is not surprising; when

the velocity satisfies a particular condition, intersection occurs multiple times with their minimum safety margin. Meanwhile, the relationship between speed magnitude and conflict probability is not clear. Speed is in the direct ratio to the conflict risk probability in Figure 10(a), but speed is inverse ratio with conflict risk probability in Figure 10(h), and this seems to be closely related to the initial distance d ; the steer angle θ .

4.3. Conflict Risk Assessment of Constant Airspeed Climb in Midlevel Airspace. The relationship between initial distance d and conflict risk of constant airspeed climb in midlevel airspace (flight altitude 1000-4200 m) is shown below. It

FIGURE 11: Conflict risk assessment of constant airspeed climb (MAV and UAV climbing at the same θ_3) in midlevel airspace (flight altitude 1000-4200 m) versus $d \in [2, 3.6 \text{ Km}]$, $H = 0$, $V_{\text{MAV}} = 610 \text{ Km/h}$, and $V_{\text{UAV}} = 224 \text{ Km/h}$, let $\theta_{3\text{MAV}} = \theta_{3\text{UAV}} = \theta_3$. Results are averaged over 1000 simulations. (a) $\theta = \pi/6$, $\theta_3 = 13\pi/180$; (b) $\theta = \pi/3$, $\theta_3 = 13\pi/180$; (c) $\theta = \pi/2$, $\theta_3 = 13\pi/180$; (d) $\theta = \pi/6$, $\theta_3 = 15\pi/180$; (e) $\theta = \pi/3$, $\theta_3 = 15\pi/180$; (f) $\theta = \pi/2$, $\theta_3 = 15\pi/180$; (g) $\theta = \pi/6$, $\theta_3 = 20\pi/180$; (h) $\theta = \pi/3$, $\theta_3 = 20\pi/180$; (i) $\theta = \pi/2$, $\theta_3 = 20\pi/180$.

might have been expected, with the steer angle increasing; the conflict risk drops first and then rises, and the result can be deduced from Figure 11. In addition, conflict risk is inversely proportional to d because the more significant d causes wider the horizontal profile spacing between the UAV and MAV.

The experiment further explores the relationship between pitch angle and conflict risk of constant airspeed climb in midlevel airspace. It is verified that conflict risk is inversely proportional to pitch angle and presents the data in Figure 12. These findings are understandable because the more prominent the pitch angle results in the wider the vertical profile spacing between the UAV and MAV. Furthermore, the minimum percentage of conflict risk in $\theta_3 = 20\pi/180$ is the values of d and θ . We can interpret a higher larger pitch angle for the aircraft at a higher vertical velocity. In addition, the

MAV vertical speed is greater than the UAVs; the two aircrafts could get far away from each other in a vertical direction.

4.4. Conflict Risk Assessment of MAV Constant Airspeed Climb and UAV Horizontal Flight in Midlevel Airspace. Next, our work is devoted to assessing conflict risk with MAV constant airspeed climb and UAV horizontal flight in midlevel airspace. In order to further verify the conflict risk versus initial altitude difference between the MAV and UAV, we also change parameters of d and $\theta_{3\text{MAV}}$ to obtain extensive results. As shown in Figure 13, it should be pointed out that $H = 1000 \text{ m}$ get the highest conflict risk. Another interesting finding is that conflict risk with H increasing initially is followed by a decrease. Too low or high H will avoid conflict at the interaction point. And it has to also be

FIGURE 12: Conflict risk assessment of constant airspeed climb (MAV and UAV climbing at the same θ_3) in midlevel airspace (flight altitude 1000-4200 m) versus $H = 0$, $V_{MAV} = 610$ Km/h, and $V_{UAV} = 224$ Km/h, let $\theta_{3,MAV} = \theta_{3,UAV} = \theta_3 \in [13\pi/180, 20\pi/180]$. Results are averaged over 1000 simulations. (a) $d = 3 \times 10^3$, $\theta = \pi/6$; (b) $d = 3 \times 10^3$, $\theta = \pi/3$; (c) $d = 3 \times 10^3$, $\theta = \pi/2$; (d) $d = 3.5 \times 10^3$, $\theta = \pi/6$; (e) $d = 3.5 \times 10^3$, $\theta = \pi/3$; (f) $d = 3.5 \times 10^3$, $\theta = \pi/2$.

FIGURE 13: Conflict risk assessment of MAV constant airspeed climb and UAV horizontal flight in midlevel airspace (flight altitude 1000-4200 m) versus $H \in [100, 1900]$, $\theta_{3,UAV} = 0$, $V_{MAV} = 610$ Km/h, and $V_{UAV} = 224$ Km/h. Results are averaged over 1000 simulations. Unbolded curves in the illustration indicate conflict probability $< 10^{(-7)}$. (a) $d = 2 \times 10^3$, $\theta_{3,MAV} = 20\pi/180$, $\theta = \pi/3$; (b) $d = 2.5 \times 10^3$, $\theta_{3,MAV} = 20\pi/180$, $\theta = \pi/3$; (c) $d = 3 \times 10^3$, $\theta_{3,MAV} = 20\pi/180$, $\theta = \pi/3$; (d) $d = 3.5 \times 10^3$, $\theta_{3,MAV} = 20\pi/180$, $\theta = \pi/3$; (e) $d = 3 \times 10^3$, $\theta_{3,MAV} = 13\pi/180$, $\theta = \pi/3$; (f) $d = 3 \times 10^3$, $\theta_{3,MAV} = 15\pi/180$, $\theta = \pi/3$; (g) $d = 3 \times 10^3$, $\theta_{3,MAV} = 20\pi/180$, $\theta = \pi/6$; (h) $d = 3 \times 10^3$, $\theta_{3,MAV} = 20\pi/180$, $\theta = \pi/2$.

FIGURE 14: Conflict risk assessment of MAV constant airspeed decline and UAV constant airspeed climb in high-level airspace (flight altitude 4200-7800 m) versus $\theta \in [\pi/9, 8\pi/9]$, $V_{MAV} = 720$ Km/h, and $V_{UAV} = 224$ Km/h. Results are averaged over 1000 simulations. Unbolded curves in the illustration indicate conflict probability $< 10^{-7}$. (a) $H = 2000$, $d = 3 \times 10^3$, $\theta_{3MAV} = -20\pi/180$, $\theta_{3UAV} = 20\pi/180$; (b) $H = 2000$, $d = 4 \times 10^3$, $\theta_{3MAV} = -20\pi/180$, $\theta_{3UAV} = 20\pi/180$; (c) $H = 2000$, $d = 5 \times 10^3$, $\theta_{3MAV} = -20\pi/180$, $\theta_{3UAV} = 20\pi/180$; (d) $H = 2000$, $d = 5.5 \times 10^3$, $\theta_{3MAV} = -20\pi/180$, $\theta_{3UAV} = 20\pi/180$; (e) $H = 800$, $d = 5 \times 10^3$, $\theta_{3MAV} = -20\pi/180$, $\theta_{3UAV} = 20\pi/180$; (f) $H = 1500$, $d = 5 \times 10^3$, $\theta_{3MAV} = -20\pi/180$, $\theta_{3UAV} = 20\pi/180$; (g) $H = 3000$, $d = 5 \times 10^3$, $\theta_{3MAV} = -20\pi/180$, $\theta_{3UAV} = 20\pi/180$; (h) $H = 4000$, $d = 5 \times 10^3$, $\theta_{3MAV} = -20\pi/180$, $\theta_{3UAV} = 20\pi/180$; (i) $H = 4500$, $d = 5 \times 10^3$, $\theta_{3MAV} = -20\pi/180$, $\theta_{3UAV} = 20\pi/180$; (j) $H = 2000$, $d = 5 \times 10^3$, $\theta_{3MAV} = -13\pi/180$, $\theta_{3UAV} = 13\pi/180$; (k) $H = 2000$, $d = 5 \times 10^3$, $\theta_{3MAV} = -15\pi/180$, $\theta_{3UAV} = 15\pi/180$; (l) $H = 2000$, $d = 5 \times 10^3$, $\theta_{3MAV} = -17\pi/180$, $\theta_{3UAV} = 17\pi/180$.

mentioned that conflict risk rises rapidly with d or θ_{3MAV} increasing, by comparison with curve trend. The major reason is increasing d causes a backward shift in interaction time.

4.5. Conflict Risk Assessment of MAV Constant Airspeed Decline and UAV Constant Airspeed Climb in High-Level Airspace. At last, we come in sight of MAV constant airspeed decline and UAV constant airspeed climb in high-level airspace. Due to much faster speed of MAV and UAV, adjusting d and θ to decrease conflict risk is ineffective. However, the change value of H and θ_{3MAV} has a significant impact on conflict risk. It can be concluded from Figures 14(f)–14(l). More specifically, conflict risk is more sensitive to H and θ_{3MAV} in high-speed movement.

Above all, we reach the outcomes of the conflict risk prediction for the IADM system to make a decision, but we can also conclude that parameter adjustment scheme should be adopted in different level airspace. In low- and midlevel air-

space, keeping as much interval d as possible between MAVs and UAVs is required to ensure efficient flow and maintain throughput. Adjustments should be made on the first θ in the event of a conflict. On the other hand, in high-level airspace, keep as much vertical H as possible between MAVs and UAVs. And when the conflict occurs, adjust θ_3 whenever possible.

5. Conclusion

In summary, we develop a conflict risk analytical framework of MAV/UAV flight in shared airspace. In general, the primary findings provide fundamental information about designing IADM decisions in engineering which help ensure a safe flight. Compared to other methods, our method ensure a safe flight in shared airspace with the assistance of intelligently maintaining distance, controlling steer angle, pitch angle, and flight speed. Meanwhile, our approach is

based on communication navigation monitoring performance; it has strong universality and can make scientific decisions quickly. On the other hand, we also have explored the communication lag-time and controller response lag-time in shared airspace. We collect and assess the UAV average total lag-time generated by long instruction (instruction word length 64 bits) as high as 5.49s; this is the main reason for the failure of online multiplatform path planning and control. As also recommended above, future research should focus on solving the issue of UAV's situational awareness to obtain accurate airspace information. In addition, our model is idealized, and it is essential that future research can be conducted to seek out more constraints, such as metroplex environment, weather factors, and wake flow.

Appendix

Formula Derivation Proof

Proof. To prove Eq. assumption conditions in Section 3.1; on the one hand, we denote to

$$d_1(t) = [d - (\omega_{hMAV}^N + \omega_{hMAV}^C + \omega_{hMAV}^S + V_{hMAV}t)] \cos \theta_1 \\ + (\omega_{hUAV}^N + \omega_{hUAV}^C + \omega_{hUAV}^S + V_{hUAV}t) \cos \theta_2,$$

$$d_1(t) = \{d \cos \theta_1 - \cos \theta_1 [N[0, 0.5102a_{MAV}] \\ + N[0, 0.5102a_{MAV}V_{hMAV}] + N[0, 0.5102bV_{hMAV}] \\ + N[(u_{hMAV} - k_{MAV}\sigma_{hMAV})t, \sigma_{hMAV}^2 \cdot t^2]]\} \\ + \cos \theta_2 \{N[0, 0.5102a_{UAV}] + N[0, 0.5102a_{UAV}V_{hUAV}] \\ + N[0, 0.5102bV_{hUAV}] + N[(u_{hUAV} - k_{UAV}\sigma_{hUAV})t, \sigma_{hUAV}^2 \cdot t^2]\} \\ = \{d \cos \theta_1 - \cos \theta_1 \cdot N[(u_{hMAV} - k_{hMAV}\sigma_{hMAV})t, 0.5102a_{MAV} \\ + 0.5102a_{MAV}V_{hMAV} + 0.5102bV_{hMAV} + \sigma_{hMAV}^2 \cdot t^2]\} \\ + \cos \theta_2 \cdot N[(u_{hUAV} - k_{UAV}\sigma_{hUAV})t, 0.5102a_{UAV} \\ + 0.5102a_{UAV}V_{hUAV} + 0.5102bV_{hUAV} + \sigma_{hUAV}^2 \cdot t^2] \\ = \{d \cos \theta_1 + N[-(u_{hMAV} - k_{hMAV}\sigma_{hMAV})t \cos \theta_1, \cos^2 \theta_1 \cdot \\ \cdot (0.5102a_{MAV} + 0.5102a_{MAV}V_{hMAV} + 0.5102bV_{hMAV} \\ + \sigma_{hMAV}^2 \cdot t^2)]\} + N[\cos \theta_2(u_{hUAV} - k_{UAV}\sigma_{hUAV})t, \cos^2 \theta_2 \cdot \\ \cdot (0.5102a_{UAV} + 0.5102a_{UAV}V_{hUAV} + 0.5102bV_{hUAV} \\ + \sigma_{hUAV}^2 \cdot t^2)] \sim N[d \cos \theta_1 - (u_{hMAV} - k_{MAV}\sigma_{hMAV})t \cos \theta_1 \\ + \cos \theta_2(u_{hUAV} - k_{UAV}\sigma_{hUAV})t, \cos^2 \theta_1 \cdot \\ \cdot (0.5102a_{MAV} + 0.5102a_{MAV}V_{hMAV} + 0.5102bV_{hMAV} \\ + \sigma_{hMAV}^2 \cdot t^2) + \cos^2 \theta_2 \cdot (0.5102a_{UAV} + 0.5102a_{UAV}V_{hUAV} \\ + 0.5102bV_{hUAV} + \sigma_{hUAV}^2 \cdot t^2)]. \quad (A.1)$$

On the other hand, we have

$$d_2(t) = H + [\omega_{vMAV}^N + \omega_{vMAV}^C + \omega_{vMAV}^S + V_{vMAV}t] \\ - [\omega_{vUAV}^N + \omega_{vUAV}^C + \omega_{vUAV}^S + V_{vUAV}t],$$

$$d_2(t) = \{H + N[0, 0.5102a_{MAV}] + N[0, 0.5102a_{MAV}V_{vMAV}] \\ + N[0, 0.5102bV_{vMAV}] \\ + N[(u_{vMAV} - k_{vMAV}\sigma_{vMAV})t, \sigma_{vMAV}^2 \cdot t^2]\} \\ - \{N[0, 0.5102a_{UAV}] + N[0, 0.5102a_{UAV}V_{vUAV}] \\ + N[0, 0.5102bV_{vUAV}] \\ + N[(u_{vUAV} - k_{vUAV}\sigma_{vUAV})t, \sigma_{vUAV}^2 \cdot t^2]\} \\ = H + N[(u_{vMAV} - k_{vMAV}\sigma_{vMAV})t, \\ \cdot (0.5102a_{MAV} + 0.5102a_{MAV}V_{vMAV} \\ + 0.5102bV_{vMAV} + \sigma_{vMAV}^2 \cdot t^2)] \\ - N[(u_{vUAV} - k_{vUAV}\sigma_{vUAV})t, (0.5102a_{UAV} \\ + 0.5102a_{UAV}V_{vUAV} + 0.5102bV_{vUAV} + \sigma_{vUAV}^2 \cdot t^2)] \\ \sim N[(u_{vMAV} - k_{MAV}\sigma_{vMAV} - u_{vUAV} + k_{UAV}\sigma_{vUAV})t \\ + H, (0.5102a_{MAV} + 0.5102a_{MAV}V_{vMAV} \\ + 0.5102bV_{vMAV} + \sigma_{vMAV}^2 \cdot t^2 + 0.5102a_{UAV} \\ + 0.5102a_{UAV}V_{vUAV} + 0.5102bV_{vUAV} + \sigma_{vUAV}^2 \cdot t^2)]. \quad (A.2)$$

□

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

Special thanks go to the 2nd Research Institute, Civil Aviation Administration of China. Furthermore, this work was supported by the Science and Technology Bureau of Sichuan Province, grant no. 2020YFG0414 and Department of Chengdu Science and Technology, grant no. 2019-YF05-02105-GX.

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