Research on Safety Assessment Approach for UAS Operations over Uninhabited Areas

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1 Introduction

The development of effective airworthiness certification specification for UAS is an issue of paramount concerned by aviation authorities, manufacturers and operators. One of the basic requirements of the airworthiness is the basic regulatory requirements for the safe flight of UAS. Thus, safety assessment is the most important aspect of airworthiness approval of UAS. In order to integrate UAS to the national airspace system, it is of great significance to develop a quantitative method for the UAS safety assessment.

In view of the safety requirements of UAS operations over uninhabited areas, considering the requirements of safety in airworthiness certification, this paper analyzes the basis of safety assessment in manned aircraft airworthiness certification, which demonstrated the current safety assessment process and methodology for CPA were limited for UAS because of the giant difference between these two kinds of aircrafts.. Based on the principle that unmanned aircraft should follow an equivalent level of safety (ELOS) as the same class of piloted aircraft, a quantitative safety analysis process of civil UAS is established.

2 Research methods

If the safety airworthiness of UAS is researched separately, the time cost is unacceptable and not conducive to the early design. Therefore, learning from the existing mature CPA safety analysis method, considering the specialty of the UAV, research its safety. Here is a brief introduction, more details on these methods are discussed in Section 2.

2.1 UAV Safety Standard Research

Airworthiness refers to the ability of an aircraft to adapt to flight and is an inherent attribute of an aircraft. For civil aircraft, airworthiness requires the quality of the aircraft’s safe operation under the operating environment and operating restrictions for which the license is applied for [1]; while the airworthiness of military aircraft requires that it meets its tactical indicators At the same time to achieve safe flight [2]. Although the airworthiness of civil aircraft and military aircraft are not exactly the same, and their focus is also different, they both emphasize that airworthiness is embodied in the safety of aircraft. Airworthiness actually requires the designer and manufacturer of the aircraft to show to the airworthiness authority that the aircraft meets the "minimum safety level" requirements [3].

For manned aviation, the purpose of proposing the "minimum safety level" is to reduce the possibility of injury to the relevant personnel. This is stated in Annex 8 of the Convention on International Civil Aviation and the Chicago Convention. The main purpose of the drafting of civil aviation safety regulations is to ensure the safety of passengers and crew, and to reduce the risk of ground personnel as much as possible [4]

The safety goal of drones is not the same as that of manned aircraft. Because the safety risks of unmanned aerial systems mainly come from the life and property safety of ground personnel in the flight path area, this risk is much less harmful than accidents involving manned aircraft. The airworthiness safety requirements of drones mainly consider that the drones cannot cause damage to the lives and property of third-party personnel in the flight area when they fly in the fusion airspace, nor can they cause damage to the flight activities of other aircraft in the airspace. Cause unsafe impact.

Analyze the requirements of civil UAS safety in airworthiness certification specification. In view of the current lack of civil airworthiness certification standards for civil UAS in China, by comparative analysis of conventionally piloted aircraft airworthiness regulation (CCAR-23) and unmanned aircraft airworthiness standards recommendations (CS-LUAS), the preliminary airworthiness censorship certification and safety compliance standard for UAS operations over uninhabited areas is confirmed.

By comparing the airworthiness standard recommendation CS-LUAS of foreign civil aviation with the CCAR-23 part of my country's civil aviation airworthiness regulations, it can be found that the airworthiness standard of drones is mainly based on the standards of manned aviation. Delete the inapplicable regulations related to the personnel on board, revise or supplement the special provisions according to the design characteristics of the drone (such as ejection/rocket-assisted take-off, parachute/crash net recovery, data link and ground station, etc.) and finally form a reasonable Airworthiness standard for drones. For the establishment of airworthiness standards for my country's field information UAVs, we can learn from the experience and lessons in the CS-LUAS tailoring process to establish a complete and reasonable airworthiness standard for UAVs.

In addition, it can be seen from the tailoring process of Article 1309 that focuses on the safety requirements of UAV systems in the airworthiness regulations, although the tailored UAV airworthiness standards and the manned aircraft airworthiness standards have the same or the same contents or Similar, the meaning of the regulations are not exactly the same. Therefore, in the later exploration, it is necessary to study the risk reference system suitable for UAVs in combination with the characteristics of dangerous accidents of UAVs, and propose the target safety level suitable for UAVs.

In the following research, we will conduct research on UAV safety analysis and evaluation methods based on Article 1309(b), which is the most concentrated embodiment of UAV system safety in airworthiness regulations.

2.3 Problems in the safety analysis of civilian UAVs

Although the current NATO, JARUS and other organizations have modified Article 1309(b) of the manned aviation airworthiness regulations, they have stated the severity and acceptable safety level of drone risk events. However, the current UAV safety analysis still faces the following problems[5]:

(1) How to establish the safety target level of drones, that is, how to measure such terms as "extremely impossible";

(2) The clause does not propose a risk reference system for drones, that is, which types of events should be considered "catastrophic";

(3) How to establish a UAV safety analysis system and safety analysis method.

In order to solve the above three problems, we must first pay attention to the equipment safety requirements of manned aviation.

At present, the safety supervision of manned aviation is mainly achieved through the formulation of regulations and regulations. These aviation regulations mainly refer to the subsystems of the aircraft system and the standards that must be followed in all stages of design, production and operation. The implementation of these standards guarantees the reliability of aircraft system components and makes the entire system meet the set safety level [6].

The concept of "safety level" not only involves the formulation of airworthiness standards, but also attracts the attention of the entire society. The safety of aircraft is closely related to the reliability of aircraft systems and on-board equipment. According to the definition of reliability, when a system is composed of n parallel units (redundancy), the reliability measure can be expressed by the following formula:

$$\begin{cases} R(t)+F(t)=1 \\ F(t)=\prod_{n=1}^{n} P_n(t) \end{cases} \qquad (1)$$

In the formula, $R(t)$ represents the probability that the system completes the specified function within the specified conditions and time range; $F(t)$ represents the failure probability of the system, which has a complementary relationship with the reliability; $P_n(t)$ represents the failure probability of each parallel unit.

It is known from the above formula that when the failure probability of each unit is constant, 100% reliability can be obtained only when n tends to infinity. Moreover, a high-redundancy system will be bulky, expensive, and complicated, which will cause the system to have low-reliability redundancy. Therefore, the acceptable safety level needs to be defined based on the acceptable accident rate of the aircraft over a period of time. It cannot be defined as an abstract subjective desire, but should be based on objective feasibility.

The relevant safety assessment rules are contained in the XX.1309 clauses of different aircraft airworthiness standards, while the relevant consulting materials are kept in ACJ, AC, AMC and GM respectively. Such safety goals are usually expressed as a risk reference system, which classifies events based on their severity and assigns the highest probability of occurrence to each type of event. Table 1 describes the risk reference system proposed in "EASA CS 25 Standard AMC Chapter 1309". Among them, failures including injury or death are classified as dangerous situations. The regulation requires that the probability of dangerous accidents is extremely small (less than 10^{-7} times/flight hours). If it is assumed that a large commercial aircraft may have 100 potential failure conditions leading to a dangerous situation, then for each subsystem, the acceptable probability of dangerous failure is less than 10^{-9} flight hours. This is the "basic concept of the greatest probability of catastrophic effects without redundant systems" for large transport aircraft.

Of course, the risk reference system in Table 1 does not apply to all aircraft, because there are differences in aircraft of different sizes. It has been found that applying certification standards for transport aircraft to smaller aircraft will result in unrealistic requirements for increased equipment reliability. According to the statistics of my country's civil aviation accidents for ten consecutive years, among the main causes of accidents, crew causes accounted for 66%, while equipment problems accounted for only 11%[7]. This shows that the overall impact of high requirements on equipment reliability on aviation safety is not obvious.

Different target safety requirements are adopted for different types of aircraft. In this regard, the United States is at the forefront of the world. In 1999, the Federal Aviation Administration issued AC 23.1309-1C, which included the certification of the Army Equipment Command aircraft in accordance with the FAR Part 2 regulations. This document defines 4 types of aircraft. In the event of a failure, each type of aircraft has different acceptable probabilities.

The analysis of the above-mentioned methods for establishing the safety level of manned aviation shows that the standard for evaluating the safety of aircraft systems and equipment is not simply as high as possible, but requires that the loss of life and property caused by aviation accidents to personnel is appropriate. Level, and this level is related to the overall operation of the aircraft over a period of time. Secondly, for different types of aircraft, the safety standards are different. When formulating a risk reference system for drones, these two points need to be focused on.

2.3 UAS Collision Analysis Research

At present, a consensus among the civil aviation authorities and related agencies of various countries is that UAVs should have the same level of safety (ELOS) as manned aircraft of the same level. The safety of aircraft is the same as the safety of other means of delivery, in essence it is to protect the lives of personnel. The difference between manned aviation and unmanned aerial vehicles is that the former mainly protects the people on board, while the latter mainly considers the impact of drones on third-party personnel after an accident. So from the perspective of protecting the life and safety of personnel, ELOS can be measured in this way-the degree of injury to third-party personnel caused by drone accidents should be the same as the probability and severity of injury to personnel caused by manned aviation accidents.

The severity of injuries caused by aviation accidents includes minor injuries, serious injuries, fatal injuries, and so on. It is unrealistic to realize that the probability of every type of injury caused by manned aircraft and drone accidents is the same. A method often used in safety engineering is to define the safety constraints of special accidents by predicting the worst possible outcome. For drone operations, the worst result of most accidents is one or more casualties, so ELOS can be measured by the most serious result caused by drone risk.

When studying the failure modes of UAVs and their effects, we must first make statistics and analysis on the types of UAV accidents. According to the safety concerns, we define the UAV ground impact accident as the ground impact incident that caused the UAV after the UAV started to slide out to the landing and taxi to the designated position to close [66]. mainly includes:

(1) The aircraft was damaged during taxiing. During the take-off phase of the aircraft, due to operator error or fuselage failure, the UAV did not taxi according to the set trajectory, causing the UAV to crash, including running out of the runway, rolling over due to a tire burst and other malfunctions.

(2) The drone crashes due to the loss of control during the flight. Due to the failure of the flight management system and the loss of the data link, the aircraft loses control during the flight.

(3) The drone was damaged during landing. When the drone is landing, the landing gear cannot be lowered, the landing gear is broken, or the tire is blown, which causes the drone to touch down on the outside of the runway, deviate from the runway, or roll over and crash during landing.

Among these three types of incidents, the crash of the drone caused by the loss of control of the drone during the flight is the main cause of the ground impact. Next, we will use this type of incident as the top incident to establish the safety analysis of the drone out of control event. .

Based on the ELOS principle, the main risks of UAVs are analyzed, and the UAV crash fatality rate evaluation method based on impact kinetic energy is used to establish the safety evaluation model for the two key events of UAV ground impact and air collision.

According to the ELOS, this paper analyses the main risks of UAS, and establishes a safety evaluation model of UAS ground impact and air collision, which is based on the assessment of crash mortality of impact kinetic energy.

UAS ground collision expected mortality model is expressed as Eq.(1):

$$f_F = \lambda_{buffer} \bullet \sum_i (N_{i,\exp} \bullet P(\mathit{fatality} \mid \mathit{exposure}) \bullet f_G \qquad (1)$$

Among them: f_F is the expected probability of death of ground personnel caused by UAS ground impact accident; $N_{\exp}$ is the number of people exposed to accidents； $P(\mathit{fatality} \mid \exp osure)$ is the probability that a person will be fatally injured in an accident; f_F is the frequency of ground impact accidents；Subscript i indicates the number of groups of people exposed to different environments.

UAS air collision expected mortality model is expressed as Eq.(2):

$$f_F = N_{\exp} \bullet P(\mathit{fatality} \mid \mathit{collision}) \bullet f_{MAC} \qquad (2)$$

Among them: f_{MAC} is the frequency of the UAS air collision accident; $P(\mathit{fatality} \mid \mathit{collision})$ is the probability of death in an air accident for the affected person, f_{MAC} is the frequency of an UAV air impact accident.

2.4 Quantitative risk assessment of drones based on flight routes

One of the main applications of information-supported UAVs is remote survey missions for linear infrastructure (such as oil, electricity or railways). For railway surveys, drones can be equipped with sensors to obtain ground information through remote sensing, combined with three-dimensional spatial data processing, modeling, and application analysis technology methods, which can detect railroad tracks, as well as lithological combinations and structures around the track. The direction and width of the surface occurrence and unloaded load belt are identified [8]. Compared with traditional manual surveying methods, one of the main advantages of UAVs is that they can measure and monitor infrastructure without affecting train operation, which reduces the maintenance cost of railways. The typical use of drones in railway surveys is to use one or several fixed-wing drones equipped with a set of payloads (cameras, lidars, etc.) to perform long-distance and low-altitude detection missions on specific railway sections.

The use of drones to perform such survey tasks requires flight permits from the relevant authorities, and such flight permits can only be authorized when the drone meets a given target safety level. For our country, the railway runs through the wild and nearby residential areas, and it also needs to be connected to the railway station in the city. For complex mission routes in this way, risk assessment can determine the degree of risk of the UAV's current mission, plan flight missions and assist relevant authorities in the process of route flight authorization. According to the accident type of the drone, a wide range of ground impact risks and aerial impact risks should be covered in the risk assessment. In this chapter, we focus on ground risk assessment, and pay more attention to the risk of casualties (fatal injuries) in residential areas.

For the convenience of modeling, it is now assumed that the failure event occurred at a certain point during the flight, and the subsequent failure trajectory will affect the third party relative to this failure point. The probability distribution of the ground impact point is simulated based on the uncertain factors during the descent of the UAV. For example, when the wing structure is damaged, the drag coefficient is inaccurate. In addition, it was also affected by wind during the fall. According to the mission characteristics of this type of UAV, we assume that loss of control during flight will lead to the following two types of uncontrolled trajectories.

This paper proposes a quantitative risk assessment method based on flight path for long-range inspection missions of infrastructure by UAS. In order to quantitatively assess the risk during the long-range mission, two kinds of aircraft trajectories after the loss control of UAS, ballistic descending and uncontrolled gliding, were modeled. By taking into account the uncertainty of the parameters for an aircraft that may have lost an engine or a wing and influence of wind, a probability distribution of UAS travelled distance was simulated. By using the GIS, the distribution of geographic population in flight areas of the UAS was also simulated to assess the probability of casualties caused by UAS ground impact.

3 Results and discussion

Analytical calculations show that the frequency of out-of-control events in the UAS is 2.393×10^{-5}/h. In the crash simulation process, we assume that the UAS takes off from Shanghai Station and inspects the railway information from Shanghai Station to Shanghai North Suburb Station along the railway line for a total length of 18 kilometers. It is assumed that the UAS will be leveled at the cruising speed throughout the flight. The flight selects 120 sampling points throughout the flight and assumes that the UAS may have a runaway event at each sampling point.

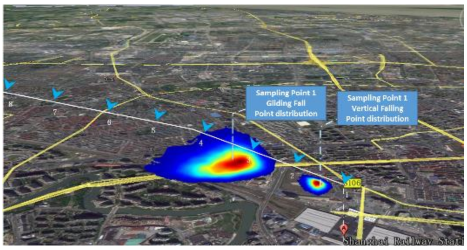

Fig. 1 Simulation diagram of UAS flight path probability drop point simulation

Figure 1 shows a simulation of UAS flight path probability drop point. The smaller one is vertical fall. In this way, the center of the drop point is about 250 meters away from the uncontrolled point of the drone. The distribution of the drop point is small and has an elliptical pattern. The center of the drop point of the gliding fall is about 1000 meters away from the uncontrolled point of the drone. The distribution of the drop point is large, and it is affected by the wind in the west direction.

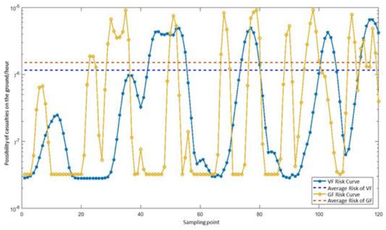

Fig. 2 The possibility of UAS threatening ground personnel on the flight path

Figure 2 shows the probability distribution of death threats to ground personnel by drones near all sampling points during flight. It can be seen from the figure that when the aircraft out of control event occurs, the fault track is more threatening to the ground personnel than the ballistic descending mode when the gliding is lowered. This is because the UAS has a longer flight distance and a larger area of influence.

The analysis shows that the fatality rate per flight hour is 1.335×10^{-6} when the UAS is on mission. According to ELOS, the probability is not higher than 1×10^{-7}. The results show that when the frequency of out-of-control events of the known UAS is $2.393\times10^{-}$

^{5}/h, the UAS cannot meet the safety requirements of ELOS when performing railway inspection tasks in Shanghai.

4 Simulation results of the impact of risk mitigation measures on safety

In order to improve the safety of the system, we consider the impact on the safety of UAVs after adding risk mitigation measures (parachute system).

A common risk mitigation measure for civilian UAVs is the parachute program, which can reduce the impact kinetic energy of the UAV to a large extent after falling, thereby reducing the damage caused by the UAV to the ground personnel. Here we use Israel's ParaZero's SafeAir drone safe landing solution as an example for simulation. The device is suitable for civilian drones of 2 kg to 300 kg, and the user can customize the falling speed between 3-6m/s.

Here we assume that the landing speed of the UAV is 5m/s. According to the formula (3), we can calculate the crash fatality rate of the UAV after the parachute device is adopted $P(fatality|\exp osure)$. Table 1shows the comparison of the impact fatality rate when the UAV hits the ground at the terminal speed and when the parachute recovery device hits the ground. It can be seen that the parachute device can effectively reduce the fatality rate of drones in collisions.

$$A_{\exp} = (W_{\text{aircraft}} + 2W_{person}) \times \left[L_{aircraft} + \frac{H_{person}}{\tan(\alpha_{glide})} + 2W_{person} \right] \quad (3)$$

Fig. 3 Schematic diagram of SafeAir drone safe landing solution personnel on the flight path

Table 1 The influence of parachute recovery device on UAV crash fatality rate

Number of masks P_s	3	4	6
Drone crash fatality rate when not carrying a parachute device	0.366	0.189	0.080
Impact fatality rate of drones when carrying a parachute device	0.0782	0.0465	0.0274

The parachute descent process is actually a gliding descent process affected by wind. We assume that the drone can open the umbrella normally in an emergency. Suppose the delay event of opening the parachute is seconds, and the initial height of the UAV is meters. Assuming that once the parachute is opened, the horizontal speed immediately drops to zero. Although this is not the case in real life, the distance traveled during the parachute opening process and the parachute deceleration phase is negligible compared to the area affected by the entire parachute descent process. Then the time to descend to the horizontal along the parachute ：

$$t_{drop} = \frac{y}{v_{drop}} = y\sqrt{\frac{A_p C_{d,\rho}}{2mg}} \quad (4)$$

In the formula, m is the mass of the drone, g is the acceleration of gravity, A_p is the open area of the parachute, and $C_{d,\rho}$ is the drag coefficient of the parachute.

The ground-affected area of a parachute descending is mainly related to the direction of flight, the offset of the parachute opening process, and the influence of the wind. The trajectory of the landing process is similar to the uncontrolled gliding mode except for the offset of the parachute opening process.

The above model is used to simulate the threat to ground personnel when the UAV carrying the parachute device surveys along the road. The number of shelter systems here is P_s=3, and the rest of the parameters are the same as those of gliding and landing. In addition, the reliability of the parachute device itself also needs to be considered. Here we set the reliability of the parachute device as $P_{Parachute}=0.95$ Then the probability of death to a third party caused by a drone P_i out-of-control event at each sampling point

$$P_{\mathrm{i,impact}} = P_{\mathrm{loc}} \bullet P_{Parachute} \bullet A_{\mathrm{exp}} \bullet P(fatality \,|\, \mathrm{exposure}) \bullet \sum_{i=1}^{\mathrm{m}} \sum_{\mathrm{j}=1}^{\mathrm{n}} \rho_{\mathrm{exp},ij} \bullet P_{area,ij} \tag{5}$$

The simulation result is shown in Figure 4. According to calculations, when carrying a parachute device, the average threat/flight hour of the UAV $P_{total\_impact}=0.915\times10^{-7}$ to ground personnel during the flight is lower than the requirement of ELOS 1.0×10^{-7}. It can be seen that the parachute device greatly improves the safety of the UAV flight path.

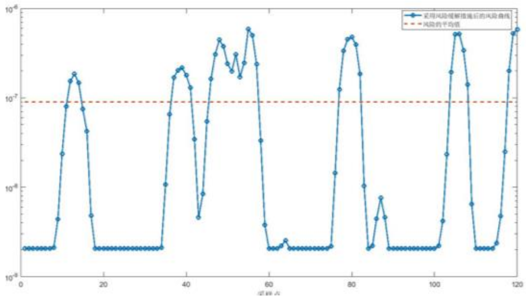

Fig. 5 The possibility that drones carrying parachute devices threaten ground personnel on the flight path

5 Conclusions

According to the safety assessment requirements of the UAS operations over uninhabited areas, this paper analyzes the safety requirements in the airworthiness certification, and proposes the principles and methods for the development of the UAS safety standards based on the ELOS principle. Therefore, the safety analysis process of civil UAV system is established, and the quantitative safety evaluation method of UAS is proposed. Aiming at the risk assessment of information-supported UAVs when performing infrastructure inspection tasks, a UAV safety assessment method based on the characteristics of UAV flight scenes and flight routes is proposed. In order to quantitatively assess the risk during the UAV mission, the two main crash modes of the UAV after it loses control-vertical fall and gliding fall were modeled, taking into account the uncertainty of the drag coefficient and other parameters after the damage of the aircraft body After the impact of the wind, the probability of the drone's falling point distribution was simulated; the geographic population distribution information of the drone's flight area was obtained with GIS tools, and the probability of casualties on the ground during the drone's flight was carried out. Computer simulation. The results show that the UAV cannot meet the safety requirements when performing railway exploration missions in urban areas. In addition, the impact of risk mitigation measures such as parachutes on the safety of UAVs during flight is also studied. The simulation results show that after adding parachute devices, the UAV can meet the safety requirements during flight. The method needs to be further improved and perfected in the future, including the use of drones to conduct flight experiments in actual areas, drop experiments on drones, simulated human impact experiments, and so on. With the improvement of the model, the model can be used to help aviation authorities assess the safety risks of certain types of drones operating in certain areas, and as an effective assessment tool when drone operators apply for airspace in a certain area.

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