A survey of safety separation management and collision avoidance approaches of civil UAS operating in integration national airspace system

民用无人机在国家空域系统内安全隔离管理与避障方法综述

Xiangmin GUAN [a,b] , Renli LYU [a,b,*] , Hongxia SHI [a,b] , Jun CHEN [c]
管祥民 [a,b]，吕仁利 [a,b,*]，石红侠 [a,b]，陈军 [c]
[a] Department of General Aviation, Civil Aviation Management Institute of China, Beijing 100102, China
[a] 中国民航管理干部学院通用航空系，北京 100102，中国
[b] General Aviation Institute of Zhejiang JianDe, Hangzhou 311600, China
[b] 浙江建德通用航空学院，杭州 311600，中国
[c] School of Engineering and Materials Science, Queen Mary University of London, London E1 4NS, United Kingdom
[c] 伦敦玛丽女王大学工程与材料科学学院，伦敦 E1 4NS，英国

KEYWORDS

关键词

Air transportation;
航空运输;
Collision avoidance;
避障;
Safety;
安全;
Separation control;
隔离控制;
Unmanned aircraft system
无人机系统

Abstract Recent years have witnessed a booming of the industry of civil Unmanned Aircraft System (UAS). As an emerging industry, the UAS industry has been attracting great attention from governments of all countries and the aviation industry. UAS are highly digitalized, informationized, and intelligent; therefore, their integration into the national airspace system has become an important trend in the development of civil aviation. However, the complexity of UAS operation poses great challenges to the traditional aviation regulatory system and technical means. How to prevent collisions between UASs and between UAS and manned aircraft to achieve safe and efficient operation in the integrated operating airspace has become a common challenge for industry and academia around the world. In recent years, the international community has carried out a great amount of work and experiments in the air traffic management of UAS and some of the key technologies. This paper attempts to make a review of the UAS separation management and key technologies in collision avoidance in the integrated airspace, mainly focusing on the current situation of UAS Traffic Management (UTM), safety separation standards, detection system, collision risk prediction, collision avoidance, safety risk assessment, etc., as well as an analysis of the bottlenecks that the current researches encountered and their development trends, so as to provide some insights and references for further research in this regard. Finally, this paper makes a further summary of some of the research highlights and challenges.

摘要近年来，民用无人机系统 (UAS) 产业蓬勃发展。作为一个新兴产业，UAS 产业已经吸引了各国政府和航空业的广泛关注。UAS 高度数字化、信息化和智能化，因此，将其融入国家空域系统已成为民用航空发展的重要趋势。然而，UAS 操作的复杂性对传统的航空监管体系和技术手段提出了巨大挑战。如何在融合运行的空域中防止 UAS 之间以及 UAS 与有人驾驶飞机之间的碰撞，以实现安全高效的运行，已成为全球业界和学术界共同面临的挑战。近年来，国际社会在 UAS 空中交通管理和部分关键技术方面进行了大量工作和实验。本文试图对融合空域中 UAS 分离管理及避障关键技术进行综述，主要关注 UAS 交通管理 (UTM)、安全间隔标准、检测系统、碰撞风险预测、避障、安全风险评估等方面的现状，以及分析当前研究遇到的瓶颈和其发展趋势，以期为这方面的进一步研究提供一些见解和参考。最后，本文进一步总结了一些研究亮点和挑战。

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* Corresponding author at: Department of General Aviation, Civil Aviation Management Institute of China, Beijing 100102, China.
* 通讯作者: 中国民航管理干部学院通用航空系，北京 100102，中国。
E-mail address: lvrenli@camic.cn (R. LYU).
电子邮件地址:lvrenli@camic.cn(R. LYU)。
Peer review under responsibility of Editorial Committee of CJA.
由《中国航空学会学报》编辑委员会负责同行评审。

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1. Introduction

1. 引言

In recent years, the civil Unmanned Aircraft System (UAS) industry enjoys a rapid development. Free from the limitations of on-board pilots, UASs have remarkable advantages in terms of the working environment, working hours, manufacturing, and application costs, and are thus more suitable for the implementation of hazardous and complex tasks and operations. With such advantages, UASs have been applied in depth in a wide range of fields such as aerial photography, plant protection, industry, environmental protection and emergency rescue, and are playing an increasingly important role in the national economy and national defense. As an emerging industry, it has been attracting great attention from governments of all countries and the whole aviation industry. [1,2] By the end of 2018, the number of officially registered UAS and licensed UAS companies in China reached 300000 and 6000 respectively, and nearly 1 million UAS flight hours were achieved in a year.

近年来，民用无人机系统 (UAS) 行业得到了快速发展。由于不受机上飞行员的限制，UAS 在作业环境、作业时间、制造和应用成本方面具有显著优势，因此更适合执行危险和复杂的任务和作业。凭借这些优势，UAS 已经在航空摄影、植物保护、工业、环境保护和紧急救援等领域得到深入应用，并在国民经济和国防中发挥着越来越重要的作用。作为一个新兴行业，它一直受到各国政府和整个航空业的极大关注。截至 2018 年底，中国官方注册的无人机数量和获得许可的无人机公司数量分别达到 30 万和 6000 家，一年内实现了近 100 万无人机飞行小时。

UAS means a system consisting of Unmanned Aerial Vehicle (UAV), ground control station, command and control data link, and any other component specified in the approved design model. There are different types of UAS with great different capabilities. Based on the operation risk, UAS can be divided into open class, specific class and certification class. The open class has very low operation risk, and operators can carry out flight activities according to the operation rules in altitude, speed, range and other aspects. The operation risk of certification class is as high as manned aircraft operation in air route network and the regulatory rules, and the requirements of certification class are almost exactly the same as manned aircraft. The operation of specific class has moderate risk, and the risk assessment method is introduced to evaluate whether the operation risk scope is within the acceptable range.

UAS 指的是由无人航空器 (UAV)、地面控制站、指挥与控制数据链以及在批准的设计模型中指定的任何其他组件组成的系统。存在不同类型的 UAS，它们具有 greatly different capabilities。根据操作风险，UAS 可以分为开放类、特定类和认证类。开放类具有非常低的操作风险，操作者可以根据高度、速度、范围等方面的操作规则进行飞行活动。认证类的操作风险与有人驾驶航空器在航线网络中的操作风险一样高，监管规则和认证类的要求几乎与有人驾驶航空器完全相同。特定类的操作具有中等风险，引入了风险评估方法来评估操作风险范围是否在可接受的范围内。

Besides, the UAS operation can also be classified into two types: isolation and integration. Isolation operation refers to a single mode operating environment with sparse UAS in isolated airspace without impact on operation of other manned aircraft. Integration operation not only refers to multi-type aircraft including UAS and manned aircraft operation in the connected airspace, but also refers to UAS joining in the air transportation system, such as feeder airport cargo by UAS now in China.

此外，UAS 操作还可以分为两种类型: 隔离操作和集成操作。隔离操作指的是在孤立空域中稀疏分布的 UAS 单一模式运行环境，不对其他有人航空器的运行产生影响。集成操作不仅指包括 UAS 和有人驾驶航空器在连接空域中的多类型航空器操作，还包括 UAS 加入空中交通系统，例如目前在中国，UAS 进行支线机场货物运输。

The integration of UAS into the National Airspace System (NAS) will become an important trend in the development of civil aviation. [3] Though now NAS is trying to adapt to the integration of UAS, in the future we may have a new era of fully unmanned aviation even for the air transportation system. However, now the complexity of UAS operation poses great challenges to the traditional aviation regulatory system and technical means especially for UAS in specific class and certification class as shown in Fig. 1. In order to make UAS fly better and farther, the international community has in recent years carried out a great amount of work and experiments in the regulatory standards, air traffic management and key technologies of UAS.

无人机系统 (UAS) 与国家空域系统 (NAS) 的融合将成为民用航空发展的重要趋势 [3] 。尽管现在 NAS 正在尝试适应 UAS 的融合，但未来我们可能迎来完全无人航空的新时代，甚至包括航空运输系统。然而，目前 UAS 操作的复杂性对传统的航空监管系统和技术手段提出了巨大挑战，特别是如图 1 所示的特定类别和认证类别的 UAS。为了使 UAS 飞得更好、更远，国际社会在近年来在监管标准、空中交通管理和 UAS 的关键技术方面进行了大量工作和实验。

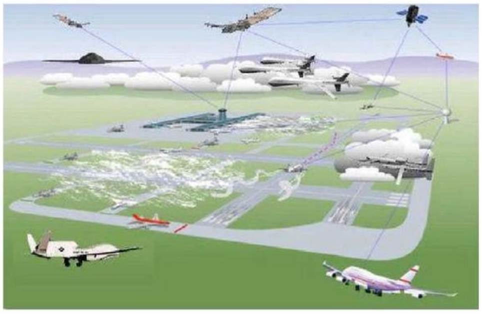

Fig. 1 Integration operation.
图 1 集成操作。

In terms of regulatory standards, International Civil Aviation Organization (ICAO), Joint Authorities for Rule-making of Unmanned Systems (JARUS), and some countries or regions like the United States, Europe, and China have made progress and achievements in such aspects as integration oversight, operation concepts, operation rules, procedural standards and personnel requirements. [4−6] However, due to the lack of mature operational experiences and sufficient data to support the development of regulatory standards, a mature regulatory legal system is yet to be established in a short period, and there is still a shortage of legal guidelines in the formulation of standards.

在监管标准方面，国际民用航空组织 (ICAO)、无人机系统规则制定联合局 (JARUS) 以及美国、欧洲、中国等一些国家或地区在集成监管、操作概念、操作规则、程序标准和人员要求等方面取得了进展和成就 [4−6] 。然而，由于缺乏成熟的操作经验和足够的数据支持监管标准的发展，短期内还无法建立起成熟的监管法律体系，而且在标准制定中仍然缺少法律指导。

In the area of UAS Traffic Management (UTM), the United States, Europe, Japan, Singapore and China have all carried out researches on operational concepts and technologies and related system development, with the goal of achieving a safe and efficient integration of UAS flights into the national airspace with manned aircraft. [7−10] Due to the different performance of UAS, the variety of sensors and a lack of complete operating rules and separation standards, to achieve a transition from a single mode operating environment with sparse UAS to a complex and large-scale mixed environment with multi-type aircraft integrated in the airspace poses a serious challenge to the safe operation of integrated airspace. Maintaining safety separation and avoiding collision are the key technologies to ensure the safety of UAS operation, which is the core of the UAS management system. UAS onboard equipment is rudimentary and different in performance, and their operating environment is more complex and variable, so it is important to conduct a further study on the UAS safety separation and collision avoidance approaches and equipment based on different operating scenarios.

在无人机交通管理 (UTM) 领域，美国、欧洲、日本、新加坡和中国都开展了关于运行概念、技术和相关系统开发的研究，目标是实现无人机航班与有人驾驶飞机在国家空域的安全高效融合。[7−10] 由于无人机性能的不同、传感器的多样性和操作规则及分离标准的缺失，要从稀疏无人机的单一模式运行环境过渡到包含多型飞机混合在空域中的复杂大规模环境，对集成空域的安全运行提出了严重挑战。保持安全间隔和避免碰撞是确保无人机运行安全的关键技术，这也是无人机管理系统的核心。无人机机载设备功能简单，性能各异，其运行环境更加复杂多变，因此基于不同运行场景对无人机安全间隔和避碰方法和设备进行深入研究具有重要意义。

In general, how to ensure a safe separation between UASs and between UAS and manned aircraft and avoid collisions in order to achieve a safe and efficient operation in integrated airspace has become a common challenge for industry and academia around the world. [11,12]

通常，如何确保无人机之间以及无人机与有人驾驶飞机之间的安全间隔，避免碰撞，以实现集成空域中的安全高效运行，已成为全球业界和学术界的共同挑战。[11,12]

Safe separation management includes many highly coupled factors such as airspace capacity management, the performance of communication, navigation and surveillance, route planning, overtake rules, collision avoidance strategies, etc., and each one may lead to the dynamic change of the whole air traffic. It will be very challenging to establish the relationship between safe separation management method and collision risk now, since the whole airspace system is in the accommodation stage and all aspects of integration operation are still being explored. Although the overall research is still in the initial stage, there have emerged a large number of approaches or methods, which are valuable experiences or insights for the follow-up researches.

安全间隔管理包括许多高度关联的因素，如空域容量管理、通信、导航和监视性能、航线规划、超车规则、避碰策略等，每一个因素都可能引起整个航空交通的动态变化。目前建立安全间隔管理方法与碰撞风险之间的关系将非常具有挑战性，因为整个空域系统正处于适应阶段，所有方面的集成运行仍在探索中。尽管总体研究仍处于初步阶段，但已经出现了大量方法或手段，这些对于后续研究是有价值经验和见解。

Therefore, this paper attempts to make a comprehensive study on the key technologies of separation management and collision avoidance in terms of the integrated airspace operation by making a review of the current researches, especially in the scenarios with specific class and certification class UAS in air route and terminal area airspace. Unlike the air transportation system where the separation maintenance rules, equipment and technology are quite mature, the integration of UAS application scenarios brings redefinition of the safety separation criteria among different types of aircraft, different conflict detection and collision avoidance strategy, and new safety risk assessment method.

因此，本文试图通过回顾当前研究，特别是针对特定类别和认证类别无人机在航路和终端区空域的运行场景，对集成空域运行中的分离管理和避碰关键技术进行全面研究。与空中交通系统中分离维护规则、设备和技术相当成熟的情况不同，无人机应用场景的集成带来了不同类型飞机之间安全间隔标准、冲突检测和避碰策略的重新定义，以及新的安全风险评估方法。

Hence, as shown in Fig. 2, we firstly describe the international progress of the UAS operation regulatory standards and UTM and make the development stage of UAS integration operate clearly. Secondly, safety separation management and collision avoidance approaches are mainly reviewed from the UAS operation and Air Traffic Management (ATM) area on the aspects of UAS safety separation standards, collision risk prediction, collision avoidance, and safety risk assessment. Finally, an analysis is given on the bottlenecks of the current researches and their development challenges.

因此，如图 2 所示，我们首先描述了无人机运行监管标准和无人机交通管理系统 (UTM) 的国际进展，并明确了无人机集成运行的发展阶段。其次，本文主要从无人机运行和空中交通管理 (ATM) 领域，在无人机安全间隔标准、碰撞风险预测、避碰和安全风险评估方面回顾了分离管理和避碰方法。最后，对当前研究的瓶颈及其发展挑战进行了分析。

The rest of this paper is organized as follows: Section 2 presents the UAS traffic management system. Section 3 presents safety separation standards. Airspace situational awareness is given in Section 4. Section 5 presents the collision risk prediction method. Section 6 gives safety separation maintenance method. Section 7 summarizes the risk assessment method for UAV integrated operation. Section 8 presents conclusions with some remarks and future work.

本文其余部分安排如下: 第 2 节介绍无人机交通管理系统。第 3 节介绍安全间隔标准。第 4 节给出空域态势感知。第 5 节介绍碰撞风险预测方法。第 6 节给出安全间隔保持方法。第 7 节总结无人机集成操作的风险评估方法。第 8 节提出结论，并附上一些观点和未来工作。

2.UAS traffic management system

2. 无人机交通管理系统

2.1.UAS operation regulatory policies and standards

2.1. 无人机运行监管政策和标准

In order to give a clearer description of the current situation and trends of related technological development, this paper first summarizes the progress of UAS operational regulations development at home and abroad. At present, countries and organizations around the world have carried out a great amount of researches and issued many documents on the legal norms and regulations for the integrated operation of UAS.

为了更清晰地描述当前相关技术发展的状况和趋势，本文首先总结了国内外无人机运行规则制定进展。目前，世界各国和组织已经开展了大量研究，并发布了关于无人机集成运行的法律规范和规定的许多文件。

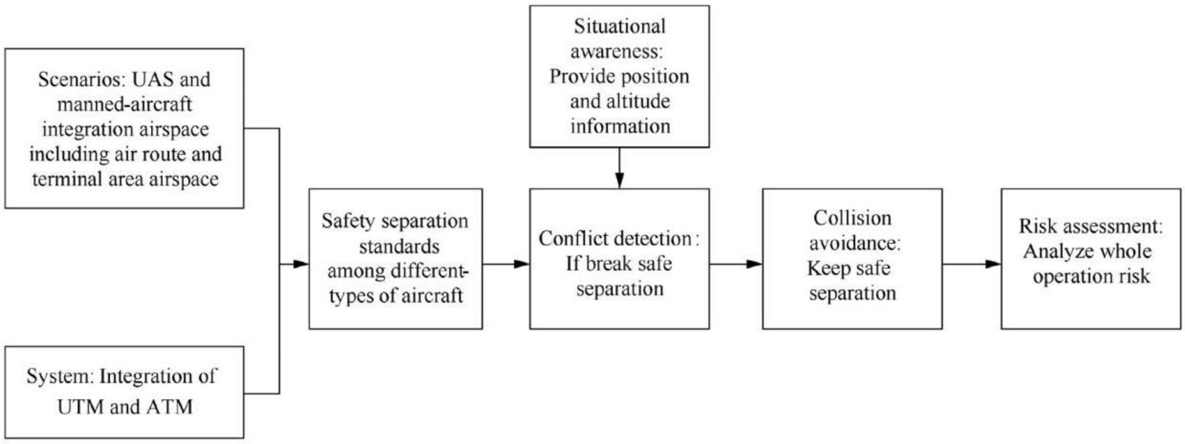

Fig. 2 General framework of sub-sections.
图 2 分节通用框架。

The most common practice in the world today is to classify UAS operations first by the level of operational risks, rather than by the unmanned aircraft themselves. Subsequently, national and regional regulators further classify UAS based on a specific management purpose, such as registration, pilot management, etc. For example, the European Aviation Safety Agency proposed a regulatory framework based on operational risks mainly consisting of such categories as open classes (low risks), specific classes (medium risks), and certification classes (high risks), and put forward a clear regulatory program and technology structure for each category. [13]

当今世界上最常见的做法是首先根据操作风险等级对无人机系统 (UAS) 操作进行分类，而不是根据无人机本身。随后，国家和地区的监管机构根据特定的管理目的，如注册、飞行员管理等，进一步对 UAS 进行分类。例如，欧洲航空安全局提出了一个基于操作风险的监管框架，主要包括开放类别 (低风险)、特定类别 (中等风险) 和认证类别 (高风险)，并为每个类别提出了明确的监管计划和技術架构。[13]

On this basis, each country has gradually constructed a regulatory system which takes operations as the core. Depending on the level of the operational risks, the corresponding management methods will vary. For example, for class C operations, which have a high operational risk, the general practice is to adopt exactly the same regulatory approach as that for manned aircraft. Category B operations are the most resilient, and most countries adopt an approach of risk assessment, i.e. assessing the relevant elements of a particular operation in accordance with the risk assessment methodology, standards and procedures; if the risks of this particular operation are assessed to be acceptable, it will be approved by the regulatory authority or the qualified entity (an organization authorized by the regulatory authority).

在此基础上，各国逐步构建了以操作为核心的管理体系。根据操作风险等级，相应的管理方法会有所不同。例如，对于风险较高的 C 类操作，通常采用与有人驾驶飞机完全相同的监管方法。B 类操作最具韧性，大多数国家采用风险评估方法，即根据风险评估方法、标准和程序评估特定操作的相关要素；如果评估认定该特定操作的风险可接受，则将由监管机构或经授权的实体 (由监管机构授权的组织) 批准。

However, despite the efforts made by many countries, regions and international organizations to establish a standardized system in the shortest possible time, it is still quite slow in the progress. There are two reasons for that: first, there is no mature regulatory legal system in place at the national and international levels which could serve as a guideline for the development of standards; second, operational practices are not mature enough to collect sufficient data to support the development of standards, including accidents and incidents investigation and reporting data.

然而，尽管许多国家、地区和国际组织努力在尽可能短的时间内建立标准化系统，进展仍然相当缓慢。这有两个原因: 首先，国家和国际层面没有成熟的监管法律体系作为标准发展的指导；其次，操作实践还不够成熟，无法收集足够的支持标准发展的数据，包括事故和事件调查与报告数据。

2.2.UTM system

2.2. 无人机交通管理系统 (UTM)

Recently, driven by the United States, Europe and some other countries, ICAO and JARUS are both committed to developing UTM framework and operational guiding materials, aiming at improving the safety, security, efficiency, effectiveness, scalability, and privacy of UAS.

最近，在美国、欧洲和其他一些国家的推动下，国际民航组织 (ICA) 和联合无人驾驶航空系统规则组织 (JARUS) 都致力于开发无人机交通管理系统 (UTM) 框架和操作指导材料，旨在提高无人机系统的安全性、保安性、效率、有效性、可扩展性和隐私性。

Complete UTM should be able to achieve the following functions as shown in Fig. 3: UAS and pilots registration, geo-fencing and flying airspace dynamic/static mapping optimization, capacity and traffic flow management, weather information display, flight plan management and tracking, identification and dynamic monitoring of cooperative targets, collision risk detection and collision avoidance of cooperative targets, early warning of near-terrain detection and cross-border flight, various forms of information dissemination services, big data storage, backup, statistics and analysis, and so on. [4,5,7] Currently the most influential UTM solutions in the world are: the 'UAS Integration in the National Airspace System (NAS) Project' (UAS-NAS) mainly intended for the mid-to-high altitude operations, and UAS Traffic Management (UTM) for light and small drones operating at low altitude, both of which are developed by the USA; the U-space System that is being developed the Joint Undertaking (JU) of the Single European Sky ATM Research (SESAR) to be capable of supporting a safe, efficient and large-scale operation of UAS at low-altitude airspace; the program of Urban Traffic Management of UAS by Singapore; the UAS operation management project proposed by China as shown in Fig. 4.

完整的 UTM 系统应能够实现如图 3 所示以下功能: 无人机和飞行员注册、地理围栏和飞行空域动态/静态映射优化、容量和流量管理、天气信息显示、飞行计划管理和跟踪、合作目标的识别和动态监控、合作目标的碰撞风险检测和避让、接近地形探测和跨境飞行的预警、各种形式的信息分发服务、大数据存储、备份、统计和分析等。[4,5,7] 目前世界上最具影响力的 UTM 解决方案有: 主要由美国开发的“无人机集成国家空域系统 (NAS) 项目”(UAS-NAS)，主要针对中高空的运行；以及针对低空运行的轻小型无人机的无人机交通管理 (UTM)；正在由单一欧洲天空空中交通管理研究 (SESAR) 的联合企业 (JU) 开发的 U-space 系统，能够支持低空空域中无人机安全、高效的大规模运行；新加坡的无人机城市交通管理系统；以及如图 4 所示的中国提出的无人机运行管理项目。

The efforts made by the above countries and regions on the development and testing of UTM systems helped form a primary framework for the integrated operation of UAS and manned aircraft, and provided scientific basis for the development and application of relevant policies and key technologies.

以上国家和地区在 UTM 系统的开发和测试上所做的努力，帮助形成了无人机和有人机综合运行的基础框架，并为相关政策和关键技术的开发与应用提供了科学依据。

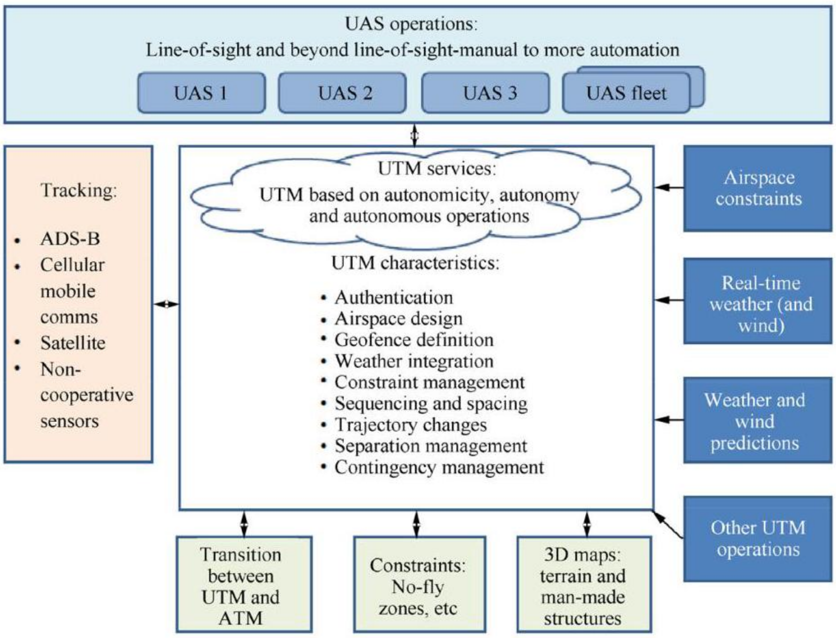

Fig. 3 UTM system framework.
图 3 UTM 系统框架。

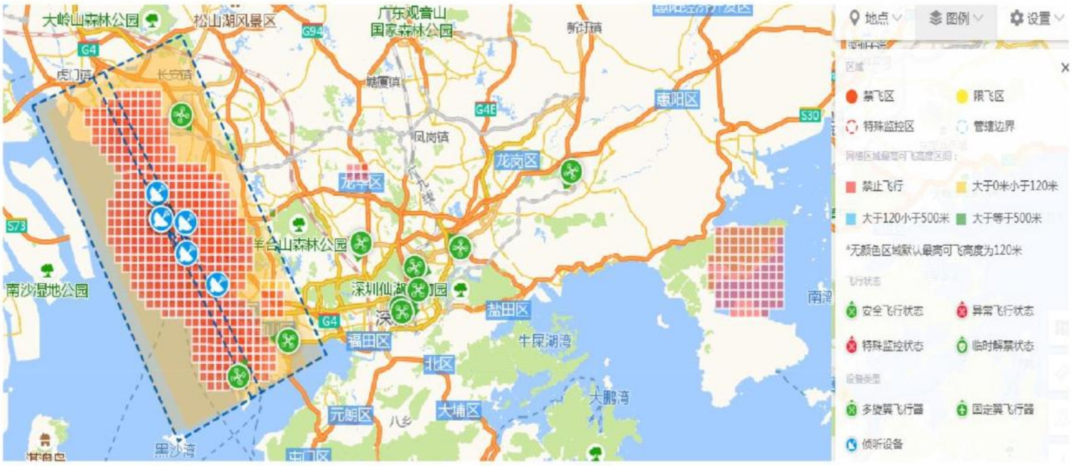

Fig. 4 UAS operation management project of China.
图 4 中国无人机运行管理项目。

Besides, it is necessary for UTM to integrate with traditional ATM to realize situational awareness sharing and process interoperability. The convergence of UTM and ATM requires three stages including accommodation, integration and evolvement. In the first stage, UAS is adapted to integrate into the national airspace system via persistent regulation and optimization. And then in the second stage, all types of aircraft will operate harmoniously and efficiently at current ATM system. Finally, in the future, the whole air transportation system will become fully unmanned aviation. Hence, a lot of work needs to be done in terms of operation concept, key technologies, standards, regulations and policies.

此外，对于无人机交通管理系统 (UTM) 来说，与传统的空中交通管理系统 (ATM) 集成以实现态势感知共享和处理互操作性是必要的。UTM 与 ATM 的融合需要经历三个阶段，包括适应、集成和演变。在第一阶段，无人机系统 (UAS) 通过持续的规范和优化适应并融入国家空域系统。然后在第二阶段，所有类型的飞机将在当前的 ATM 系统中和谐高效地运行。最终，在未来，整个航空运输系统将变成完全无人驾驶航空。因此，在运营理念、关键技术、标准、法规和政策方面还有很多工作要做。

3.UAS safety separation standards

3. 无人机系统安全间隔标准

Due to the different operational and performance requirements of the integration operation airspace, the separation standard of UAS is far less than that the current air traffic control requires, so the existing safety separation standard and threshold quantification methods of civil aviation do not apply to the UAS Sense and Avoidance (SAA) system and are unable to meet the needs of operations in different scenarios. [14,15] Therefore, the definition and measurement of the safety separation of the UAS are a new and much-needed field of research. [11] If the safety separation standard is defined too small, the operational risk will increase, whereas a too large separation standard will affect the efficiency of airspace use. Therefore, how to appropriately define the safety separation standard of UAS to ensure both safety and efficiency of the airspace is the focus of researches in recent years.

由于集成运行空域的不同运营性能要求，无人机的间隔标准远低于当前空中交通管制的要求，因此现有的民用航空安全间隔标准和阈值量化方法不适用于无人机感知与避让 (SAA) 系统，无法满足不同场景下运营的需要。因此，无人机安全间隔的定义和测量是一个崭新且急需研究的领域。如果安全间隔标准定义得太小，运营风险将会增加，而标准过大则会影响空域使用的效率。因此，如何恰当地定义无人机安全间隔标准以确保空域的安全和效率是近年来研究的焦点。

The 228 document (SC-228) issued by Radio Technical Commission for Aeronautics (RTCA) sets minimum requirements for the operation of UAS, and technical requirements for the detection and avoidance, but does not establish a safe separation standard for operations. [15] USA researchers pioneered the efforts in defining the safety separation standard of large UAS integrated into the civil aviation controlled airspace. The concept of well-clear being considered a spacing standard has been widely accepted. The relationship between the separation maintenance safety domain and the collision safety domain is clearly illustrated in Fig. 5. [16] The separation threshold and collision avoidance threshold are the key points where the UAS begins to maneuver to maintain a good separation safety domain or collision safety domain. UAS are considered intruders after crossing the Self-Separation Threshold (SST), when the threatened UAS begins to maneuver slowly to maintain a Well Clear (WC). Similarly, an intruder crossing the Collision Avoidance Threshold (CAT) is considered a threat, and the threatened UAS begins to perform emergency evasive maneuvers to prevent the intruder from entering its own collision safety domain.

由航空无线电技术委员会 (RTCA) 发布的 SC-228 文件规定了无人航空系统 (UAS) 操作的最小要求以及检测与避让的技术要求，但未为操作设定安全间隔标准。[15] 美国研究人员在定义大型 UAS 集成到民用航空管制空域的安全间隔标准方面开创了先河。将“足够间隔”视为间隔标准的概念已被广泛接受。在第 5 图中清楚地说明了保持间隔安全域与碰撞安全域之间的关系。[16] 间隔阈值和避碰阈值是 UAS 开始机动以保持良好间隔安全域或碰撞安全域的关键点。当受威胁的 UAS 开始缓慢机动以保持“足够间隔”(WC) 时，越过自我间隔阈值 (SST) 的 UAS 被视为入侵者。同样，越过避碰阈值 (CAT) 的入侵者被视为威胁，受威胁的 UAS 开始执行紧急规避机动，以防止入侵者进入其自身的碰撞安全域。

There are three typical separation threshold definitions: distance-based, time-based, and time-and-distance combination. [9] The distance-based approach is to set boundaries, with the drone as the center, in the horizontal and vertical directions, i.e. forming a cylindrical safety area, if which is entered by an intruder, it is judged to be a loss of safety separation. But this approach does not take into account the speed of the intruding aircraft, and thus not applicable in the context of the integrated operation. The time-based approach takes into account the relative speed of the UAS and the intruder by measuring the time to reach the Closest Point of Approach (CPA). If this time is less than the time threshold, it is judged to be a loss of safety separation, but this approach is difficult to visualize. The approach of combining time and distance combines the advantages of the previous two and has become the trend of defining the safety separation of UAS.

有三种典型的分离阈值定义: 基于距离的、基于时间的以及时间和距离组合的。[9] 基于距离的方法是以无人机为中心，在水平和垂直方向上设置边界，即形成一个圆柱形的安全区域，如果有入侵者进入该区域，则判定为失去安全间隔。但这种方法没有考虑到入侵飞机的速度，因此在集成操作的背景下不适用。基于时间的方法通过测量到达最近接近点 (CPA) 的时间来考虑无人机与入侵者的相对速度。如果这个时间小于时间阈值，则判定为失去安全间隔，但这种方法难以形象化。时间和距离组合的方法结合了前两种方法的优势，已成为定义无人机安全间隔的趋势。

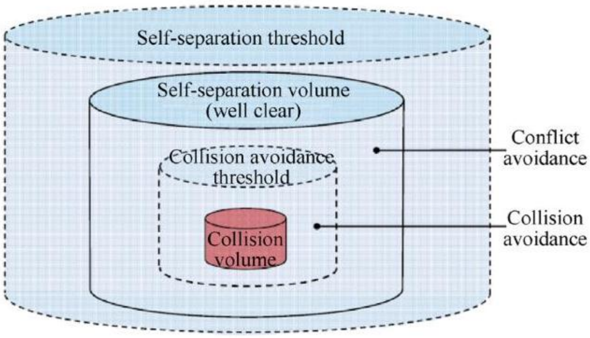

Fig. 5 Separation maintenance safety domain and collision safety domain. [16]

图 5 分离维护安全域和碰撞安全域。[16]

Weinert et al. adopted an air collision risk-based approach for low-altitude operation scenarios, first defining the range of the ”well clear” and risk threshold, then simulating and adjusting the initial value through the Monte Carlo method, evaluating the adaptability of the operation and the sensitivity of the hypothesis, and finally getting the well clear’s quantitative definition, that is 2000ft ($1\text{ft} = 0.3048$ m) horizontal separation, and 250ft vertical separation. [17] However, this was only a distance-based approach, and the speed of the intruder was not distinguished.

Weinert 等人针对低空操作场景采用了一种基于空中碰撞风险的方法，首先定义了“保持清晰”的范围和风险阈值，然后通过蒙特卡洛方法模拟和调整初始值，评估操作的适应性和假设的敏感性，最终得到“保持清晰”的定量定义，即 2000ft ($1\text{ft} = 0.3048$ m) 水平间隔，和 250ft 垂直间隔。[17] 然而，这仅仅是一种基于距离的方法，并没有区分入侵者的速度。

The study on the definition of UAS safety separation threshold for mid-to-high altitude operations was first conducted by the UAS Sense and Avoid Research Panel (SARP). Muñoz et al. [18] developed a mathematical basis for the concept of Well Clear, taking the intruder as the origin to construct an Euclid three-dimensional coordinate system, through which the minimum horizontal and vertical separation was quantitatively defined by taking into account the relative motion of the intruder and the UAS based on a combination of time and distance, and then the separation in time is defined according to the closest proximity point. This study has been validated in their DAIDALUS system, resulting in the RTCA standard file DO-365: 35 s, 4000ft in horizontal separation, 450ft for vertical separation threshold, and 700ft for the advisory warning vertical separation threshold. [8]

对中高空无人机 (UAS) 安全间隔阈值定义的研究首次由无人机感知与避障研究小组 (SARP) 进行。Muñoz 等人 [18] 为“安全间隔”概念建立了数学基础，以入侵者作为原点构建了三维欧几里得坐标系，通

过该坐标系，结合时间和距离，考虑入侵者与 UAS 的相对运动，定量定义了最小水平与垂直间隔，并根据最近接近点定义了时间间隔。这一研究在他们的 DAIDALUS 系统中得到了验证，并导致了 RTCA 标准文件 DO-365 的制定: 35 s, 4000ft 用于水平间隔，450ft 用于垂直间隔阈值，700ft 用于咨询警告垂直间隔阈值。[8]

Mullins et al. proposed the dynamic separation threshold for the UAS on-board detection avoidance system. They took into account the performance of the intruding aircraft, replaced the distance-based threshold with a time-based threshold, and adopted corner geometry to achieve a solution with less computation. [16]

Mullins 等人提出了无人机机上检测避障系统的动态间隔阈值。他们考虑了入侵飞机的性能，用基于时间的阈值取代了基于距离的阈值，并采用角落几何学以实现计算量更小的解决方案。[16]

Johnson et al. analyzed the existing definition of well-clear separation between UAS and man-made aircraft in class E airspace, and the impact of warning standards on the airspace and the characteristics of encountering. [19] They set up a simulated environment with simulation tools based on UAS models, flight profiles, and historical radar data, and analyzed the risks and impact of the three well-clear separation definitions made by Federal Aviation Administration Radio Technical Commission for Aeronautics and Traffic Collision Avoidance System II respectively on the integrated hybrid operation of UAS and manned aircraft in the airspace. They also evaluated the impact of the warning logic on drone operators' maintenance of adequate space between aircraft. The results of the analysis provided guidance for the requirements of SAA sensors and the design of SAA traffic display.

Johnson 等人分析了现有关于无人机与人造飞机在 E 类空域中“安全间隔”的定义，以及警告标准对空域和遭遇特性的影响。[19] 他们基于无人机模型、飞行剖面和历史雷达数据，使用仿真工具建立了一个模拟环境，并分析了美国联邦航空管理局无线电信技术委员会和交通防撞系统 II 分别提出的三个“安全间隔”定义对无人机和有人机在空域中混合运行的影响。他们还评估了警告逻辑对无人机操作员保持飞机间足够空间的影响。分析结果为 SAA 传感器的需求和 SAA 交通显示的设计提供了指导。

4. Airspace situational awareness

4. 空域态势感知

Operation of UAS in the integrated airspace should first have the capability of airspace situational awareness, which helps render reasonable avoidance solutions for UAS based on the surrounding aircraft in order to ensure the operational safety.

无人机系统在集成空域中的运行应首先具备空域态势感知能力，这有助于基于周围航空器的情况为无人机提供合理的避让解决方案，以确保运行安全。

The detection system of the UAS is mainly divided into two kinds: collaborative and non-collaborative as shown in Table 1.2

无人机系统的检测系统主要分为两种: 协作式和非协作式，如表 1.2 所示。

The collaborative detection system means that the UASs are equipped with the same kind of sensors and the communications between UASs are established, which mainly includes ACAS-X U system upgraded specifically for the UAS from the TCAS system, and ADS-B. FAA developed ACAS X system for large aircraft as the next-generation airborne collision avoidance system. At the same time, the ACAS-X U system has been specifically developed for the UAS operating in an integrated airspace. [21,22]

协作式检测系统意味着无人机装备有同类型的传感器，并且无人机之间建立了通信，这主要包括专门为无人机从 TCAS 系统升级而来的 ACAS-X U 系统，以及 ADS-B。FAA 为大型飞机开发了 ACAS X 系统，作为下一代空中防撞系统。同时，ACAS-X U 系统已经专门为在集成空域中运行的无人机开发。[21,22]

The UAS with non-collaborative detection systems does not directly establish communications between each other. They detect intruders mainly through the use of optoelectron-ics, radar, infrared, acoustics, vision and other sensors and multi-source data fusion methods. Their advantage is that they can autonomously sense the aircraft within the detection range (without establishing communications) and other targets, but their performance is affected by the UAS flight attitude and the surrounding environment, and blind detection spots may occur. Besides, some detection systems designed on the basis of multi-sensor fusion are proposed. [23]

配备非协作式检测系统的无人机之间不直接建立通信。它们主要通过使用光电、雷达、红外、声学、视觉等传感器和多源数据融合方法来探测入侵者。它们的优点是可以自主感知探测范围内的航空器和其他目标 (无需建立通信)，但它们的性能会受到无人机飞行姿态和周围环境的影响，并可能出现盲检区域。此外，还提出了基于多传感器融合设计的某些检测系统。[23]

Table 1 Comparison of different types of detection. [20]

表 1 不同类型检测方法的比较。[20]

System	Detection type	Detection range (km)	Detection information	Comparison
ADS-B	Collaborative	240	Location altitude. speed	Having both the capabilities of surveillance and communication
TCAS/ACAS-X U	Collaborative	160	Distance, altitude	Heavy in weight, difficult to be equipped onto the UAS
Optoelectronics (EO system)	Non-collaborative	20	Relative bearing, elevation	Susceptible to weather, lacking in guidance range
Synthetic Aperture Radar (SAR)	Non-collaborative	35	Distance, relative bearing	Low accuracy
LIDAR	Non-collaborative	3	distance	Small view
Infrared (IR system)	Non-collaborative	4.4	Relative bearing. elevation	Not applicable to IMC
Acoustic system	Non-collaborative	10	Relative bearing, elevation	Time delays
Visionary system	Non-collaborative	1.9	Position, speed	Small range, affected by the performance of camera

系统	检测类型	检测范围 (公里)	检测信息	比较
ADS-B	协作	240	位置高度、速度	具备监控和通信的双重能力
TCAS/ACAS-X U	协作	160	距离，高度	重量大，难以安装在无人机系统 (UAS) 上
光电系统 (EO 系统)	非协作的	20	相对方位角，高度	易受天气影响，制导范围不足
合成孔径雷达 (SAR)	非协作的	35	距离，相对方位角	精度低
激光雷达 (LIDAR)	非协作的	3	距离	小视角
红外系统 (IR 系统)	非协作的	4.4	相对方位。高度	不适用于 IMC
声学系统	非协作的	10	相对方位角，高度	时间延迟
洞察系统 (Visionary 系统)	非协作的	1.9	位置，速度	小范围，受摄像头性能影响

We can see that it is not conducive for non-collaborative detection system to aware overall airspace, so the collaborative detection system is more feasible for complex and large-scale multi-type aircraft operation in the integration airspace.

我们可以看到，非协作式检测系统不利于感知整体空域，因此，对于复杂且大规模的多类型航空器在集成空域中的运行，协作式检测系统更为可行。

5. Collision risk prediction method

5. 碰撞风险预测方法

Collision risk prediction is to determine whether an unmanned aircraft will violate safety separation with the other one and cause conflict according to their flight plans and predicted trajectories in the case of UAS fully mastering the airspace situation information.

碰撞风险预测是指根据无人机完全掌握空域情况信息的情况下，依据它们的飞行计划和预测轨迹，确定无人机是否会与其他无人机违反安全间隔并引发冲突。

Reich firstly proposed the Reich aircraft collision risk model, [24] in which each aircraft is assumed to be a cuboid with the same size. The collision probability between two aircraft can be expressed as the collision risk between two cuboids, and it is equivalent to the collision risk probability between a particle and a cuboid. A number of researchers have done similar work based on Reich's model. Combining various uncertainties which may affect flight safety, they changed the Reich's collision zone into an oval or other shaped protected area defined by the minimum safety separation standard. On this basis, domestic and foreign scholars have proposed many conflict detection methods, [25] which can be roughly divided into two categories: deterministic and probabilistic as shown in Table 2.

Reich 首先提出了 Reich 飞机碰撞风险模型，[24] 在该模型中，假设每架飞机都是一个大小相同的立方体。两架飞机之间的碰撞概率可以表示为两个立方体之间的碰撞风险，这等同于一个粒子与立方体之间的碰撞风险概率。许多研究者基于 Reich 的模型进行了类似的工作。结合可能影响飞行安全的各种不确定性，他们将 Reich 的碰撞区域变为椭圆形或其他由最小安全间隔标准定义的保护区域。在此基础上，国内外学者提出了许多冲突检测方法，[25] 可以大致分为确定性方法和概率性方法，如表 2 所示。

5.1. Deterministic conflict detection method

5.1. 确定性冲突检测方法

In deterministic conflict detection method, ideal trajectory is adopted to describe the movement of aircraft. It is assumed that the aircraft moves along the ideal trajectory composed of a series of route points in the flight plan, and the flight speed between the route points is also given. [26−29] Then, conflict detection is transformed into determining whether the minimum distance between the ideal tracks of aircraft is less than the safety separation within the predicted time range.

在确定性冲突检测方法中，采用理想轨迹来描述飞机的运动。假设飞机沿着由飞行计划中的一系列航路点组成的理想轨迹移动，并且给出了航路点之间的飞行速度。[26−29] 然后，冲突检测转化为确定在预测时间范围内，飞机理想轨迹之间的最小距离是否小于安全间隔。

Table 2 Collision risk prediction method.
表 2 碰撞风险预测方法。

Method	Conflict detection method	Conflict detection dimension	Conflict detection scenario
Deterministic approach Probability method	Build complete mathematical description and pairwise strategy Based on space-time grids with global strategy Segment the airspace with all ideal tracks using the dichotomy Hybrid Integer Nonlinear Optimization model Monte Carlo method Kinematics model Stochastic differential equation based on the kinematics model Brownian motion Markov chains	2D Horizontal 2D vertical 3D	Between UASs Between UAS and manned aircraft Between manned aircraft and manned aircraft

方法	冲突检测方法	冲突检测维度	冲突检测场景
确定性方法概率方法	构建完整的数学描述和成对策略基于时空网格的全局策略使用二分法将空域与所有理想轨迹分段采用混合整数非线性优化模型蒙特卡洛方法动力学模型基于动力学模型的随机微分方程布朗运动马尔可夫链	2D 水平 2D 垂直 3D	无人机系统之间 (UASs) 无人机系统与有人驾驶飞机之间有人驾驶飞机之间

Dowek and Muñoz [30] provided a complete mathematical description of deterministic conflict detection method, that is, the ideal track of aircraft was taken as the center point, and the spherical or cylindrical protection zone of aircraft around the center point was expressed as the safety separation. They also proposed a conflict detection method based on the ”pairwise strategy”. However, when dealing with the conflict detection of multi-aircraft, the method proved to be highly complex in terms of computations, because with this method, the conflict detection had to be done in pairs.

Dowek 和 Muñoz [30] 提供了确定性冲突检测方法的完整数学描述，即以飞机的理想轨迹作为中心点，将围绕中心点的飞机球形或圆柱形保护区表示为安全间隔。他们还提出了基于“成对策略”的冲突检测方法。然而，在处理多架飞机的冲突检测时，此方法在计算上被证明具有高度复杂性，因为使用此方法，冲突检测必须成对进行。

Jardin proposed a conflict detection method based on ”global strategy”, which could improve the computational efficiency. [31] In this method, the airspace was divided into space-time grids, and conflict happens if any grid was occupied by more than two aircraft. The spatial data structure model was further used to describe the ideal track, and then the calculation of three-dimensional distance of aircraft could be simplified to judge the overlap of aircraft arrival time, which greatly reduced the computational complexity. [32−34]

Jardin 提出了基于“全局策略”的冲突检测方法，该方法可以提高计算效率。[31] 在这种方法中，空域被划分为时空网格，如果有任何网格被两架以上的飞机占用，则发生冲突。进一步使用空间数据结构模型来描述理想轨迹，然后可以将飞机的三维距离计算简化为判断飞机到达时间的重叠，从而大大降低了计算复杂度。[32−34]

The dichotomy was adopted to segment the airspace with all ideal tracks, and the iteration terminates until each airspace segment contained only one ideal track. The computational complexity of this method was less affected by the number of conflicting aircraft. In the simulation testing scenario of 10,000 aircraft in German airspace, it only took 14 min to complete all the conflict detection, and the average conflict detection for each aircraft only took 0.08 s , close to real-time detection. [35]

采用二分法将包含所有理想轨迹的空域进行分割，直到每个空域段仅包含一条理想轨迹时迭代终止。这种方法的计算复杂度受冲突飞机数量影响较小。在德国空域 10,000 架飞机的模拟测试场景中，它仅用了 14 min 完成所有冲突检测，每架飞机的平均冲突检测时间仅为 0.08 s ，接近实时检测。[35]

Alonso-Ayuso et al. presented a hybrid integer nonlinear optimization model for conflict detection. [36] Han and Bang studied the UAS conflict detection algorithm based on the conventional proportional guidance law, and then they extended the guidance law to tackle the 3D maneuver problem. [37] Jilkov et al. adopted multiple models to improve the prediction accuracy from the perspective of track prediction, thereby improving the estimation accuracy of the conflict probability. [38]

Alonso-Ayuso 等人提出了一个用于冲突检测的混合整数非线性优化模型。[36] Han 和 Bang 研究了基于传统比例导引律的无人机系统 (UAS) 冲突检测算法，然后他们将导引律扩展以解决 3D 操纵问题。[37] Jilkov 等人采用了多种模型来提高轨迹预测的预测准确性，从而提高了冲突概率的估计准确性。[38]

5.2. Probabilistic conflict detection method

5.2. 概率冲突检测方法

Probabilistic conflict detection introduces uncertainty in the representation of actual track, including direct superposition of random disturbance on ideal track, and aircraft kinematics or dynamics model described by stochastic differential equation. As one of the advocates of this method, Yang and Kuchar proposed an aircraft track prediction model in the case of free flight, in which different probability densities are used to depict aircraft dynamic parameters, and the Monte Carlo method was adopted to solve the conflict probability. [39] Paielli and Erzberger used kinematics model to express the aircraft ideal track, and employed Gaussian distribution to describe the random disturbance, which was assumed to be independent both in time and space. [40] Liu and Hwang introduced a stochastic differential equation to describe the track uncertainty based on the kinematics model. [41] Besides, Brownian motion was used to portray random disturbances in three-dimensional space, and they were assumed to be spatial correlated. [42] Jilkov et al. improved the estimation accuracy of conflict probability via enhancing the track prediction ability. [38]

概率冲突检测在表示实际轨迹时引入了不确定性，包括在理想轨迹上直接叠加随机干扰，以及由随机微分方程描述的飞机动力学或运动学模型。作为这种方法的支持者之一，Yang 和 Kuchar 在自由飞行的条件下提出了一个飞机轨迹预测模型，在该模型中使用了不同的概率密度来描述飞机的动态参数，并采用蒙特卡洛方法求解冲突概率。[39] Paielli 和 Erzberger 使用运动学模型来表达飞机的理想轨迹，并采用高斯分布来描述随机干扰，假设其在时间和空间上都是独立的。[40] Liu 和 Hwang 引入了一个随机微分方程，基于运动学模型描述轨迹不确定性。[41] 此外，布朗运动被用来描述三维空间中的随机干扰，并假设它们在空间上是相关的。[42] Jilkov 等人通过提高轨迹预测能力来改进冲突概率的估计准确性。[38]

Based on the actual track model, the probabilistic conflict detection method is turned into a conflict probability calculation problem. Conflict is assumed to happen if the conflict probability of the actual tracks is greater than the warning threshold. The existing conflict probability calculation methods include approximate analysis method, grid calculation method and Monte Carlo method. A grid computing method was proposed by Hu and Prandini to calculate the conflict probability through discretization of the random process of aircraft motion in time and space, and then Markov chains were employed to approximate the stochastic differential equation. [42] However, the computational complexity of this method is high and can easily lead to ”dimensional disaster”, especially with the increase of the number of aircraft and the airspace range. According to the aircraft track model and conflict scenario, the Monte Carlo method was adopted to generate actual track samples, [43] and to estimate the conflict probability. This method can effectively deal with the complex aircraft track model and avoid ”dimensional disaster”. However, in order to obtain high probability estimation accuracy, the Monte Carlo method requires a large number of actual track samples, which would lead to poor efficiency.

基于实际轨迹模型，概率冲突检测方法转化为冲突概率计算问题。如果实际轨迹的冲突概率超过预警阈值，则假定冲突会发生。现有的冲突概率计算方法包括近似分析方法、网格计算方法和蒙特卡洛方法。Hu 和 Prandini 提出了一种网格计算方法，通过在时间和空间上对飞机运动随机过程进行离散化来计算冲突概率，然后使用马尔可夫链来近似随机微分方程。[42] 然而，此方法的计算复杂度较高，容易导致“维度灾难”，特别是在飞机数量和空域范围增加时。根据飞机轨迹模型和冲突场景，采用蒙特卡洛方法生成实际轨迹样本，[43] 并估计冲突概率。这种方法可以有效处理复杂的飞机轨迹模型并避免“维度灾难”。但是，为了获得高概率估计精度，蒙特卡洛方法需要大量的实际轨迹样本，这会导致效率低下。

A collision probability evaluation method was proposed based on conditional probability. The whole path was divided into a number of discrete path points and the collision probability of the whole path was evaluated by estimating the conditional probability of the current path points without collision. However, this method was mainly suitable for collision in two-dimensional plane. [44]

基于条件概率提出了一种碰撞概率评估方法。整个路径被划分为多个离散路径点，通过估计当前路径点无碰撞的条件概率来评估整个路径的碰撞概率。然而，这种方法主要适用于二维平面内的碰撞。[44]

Besides, polynomial chaos was introduced to estimate collision probability which expressed the solution of stochastic differential equation by polynomial chaotic expansion approximation, and then calculated the collision probability by Monte Carlo simulation. [45]

此外，多项式混沌被引入来估计碰撞概率，它通过多项式混沌展开近似表达随机微分方程的解，然后通过蒙特卡洛模拟计算碰撞概率。[45]

6. Safety separation maintenance

6. 安全间隔保持

Safety separation maintenance is to relieve the aircraft of the conflict that will occur in the local airspace in a short time, on the basis of the flight conflict detection, so as to ensure a safe separation between aircraft. This method is the main means to prevent conflict and collision of UAS in short term. The air traffic flow management in fact is a strategy method to guarantee safe interval; however there are few studies on the control and resource distribution management about civil aviation aircraft and UAS. A distributed implementation method based on integer programming was proposed to solve the problem of large-scale air traffic flow management with the UAS integration into air transportation system. [46] In terms of the methods of tactical resolutions, it can be divided into centralized resolution and distributed autonomous resolution as shown in Table 3. From the perspective of maneuver strategy, it has six basic strategies including acceleration, deceleration, left turn, right turn, climb, and descent, and the combination strategy.

安全间隔保持是为了缓解飞机在短时间内将在本地空域发生的冲突，基于飞行冲突检测，以确保飞机之间的安全间隔。这种方法是防止无人机系统短期内冲突和碰撞的主要手段。实际上，空中交通流量管理是一种保证安全间隔的策略方法；然而，关于民用航空飞机和无人机控制及资源分配管理的研究较少。提出了一种基于整数规划的分布式实现方法，用以解决大规模空中交通流量管理问题，并将无人机集成到空中交通系统中。[46] 在战术解决方法方面，可以分为集中式解决和分布式自主解决，如表 3 所示。从

机动策略的角度来看，它包括加速、减速、左转、右转、爬升和下降六种基本策略，以及组合策略。

6.1. Centralized conflict resolution method

6.1. 集中式冲突解决方法

In the airspace where the ground control unit is responsible for the safety separation, the ground control unit analyzes the operational situation of aircraft in the airspace, detects possible conflicts, calculates the conflict resolution strategy, and sends the instructions to the aircraft involved in the conflict for execution. The centralized conflict resolution method takes aircraft involved in conflicts as a whole and tends to obtain the overall optimal resolution strategy. [47−49]

在地面控制单位负责安全间隔的空域中，地面控制单位分析空域中飞机的运行情况，检测可能的冲突，计算冲突解决策略，并将指令发送给涉及冲突的飞机以执行。集中式冲突解决方法将涉及冲突的飞机视为一个整体，倾向于获得整体最优的解决策略。[47−49]

Table 3 Comparison of conflict resolution methods and strategies.

表 3 冲突解决方法和策略的比较。

Tactical resolutions	Method	Explanation
Traffic flow management	A distributed implementation method based on integer programming	Strategy method
Conflict resolution methods	Numerical optimization method	High computational complexity
	Rule-based method	High efficiency, poor flexibility, no need for information exchange
	Artificial potential field method	High efficiency, difficult to restrain the physical performance of UAS
	Game theory method	Applicable to short- term, non-cooperative target conflict
	Geometric method	High efficiency, not suitable for multi-UAS situation
	Multi-agent method	Suitable for multiple and cooperative UAS conflict
Conflict resolution strategies	Adjusting speed	Acceleration, deceleration
	Adjusting turn Adjusting altitude	left, right climb, descent

战术解决方案	方法	说明
交通流管理	基于整数规划的分布式实现方法	策略方法
冲突解决方法	数值优化方法	高计算复杂度
	基于规则的方法	高效率，灵活性差，无需信息交换
	人工势场方法	高效率，难以抑制无人航空系统 (UAS) 的物理性能
	博弈论方法	适用于短期、非合作目标冲突
	几何方法	高效率，不适用于多无人机系统 (UAS) 情况
	多代理方法	适用于多无人机系统 (UAS) 合作冲突
冲突解决策略	调整速度	加速，减速
	调整转向，调整高度	左转，右转，爬升，下降

At present, centralized conflict resolution methods generally employ numerical optimization methods including linear programming, optimal control, genetic algorithm, colony algorithm, etc. The method based on numerical optimization is often concerned with obtaining the most economical conflict prevention route, and therefore aims to work out the optimal conflict avoidance strategy, based on optimal control and intelligent calculation by establishing the corresponding target function and constraint conditions. Durand et al. viewed conflict avoidance as a constraint optimization problem with minimum time delay, and adopted genetic algorithm and stochastic optimization techniques to generate avoidance maneuvers. [50] Frazzoli et al. approached collision avoidance as a convex optimization problem, and made use of random search to calculate the feasible local optimal conflict-free strategy. [51] Pallottino et al. portrayed conflict avoidance as a mixed integer linear programming problem. [52] Sislak et al. proposed a non-cooperative conflict avoidance method when the aircraft could not communicate with each other, and adopted the A* algorithm to plan a trajectory that did not intersect with the dynamic prohibited flight area, so as to avoid potential conflicts.

目前，集中式冲突解决方法通常采用数值优化方法，包括线性规划、最优控制、遗传算法、群算法等。基于数值优化的方法通常关注于获得最经济的冲突预防路径，因此旨在通过建立相应的目标函数和约束条件，基于最优控制和智能计算来制定最优的冲突避免策略。Durand 等人将冲突避免视为一个以最小时间延迟为约束的优化问题，并采用遗传算法和随机优化技术生成避障机动。[50] Frazzoli 等人将避碰问题视为一个凸优化问题，并利用随机搜索计算可行的局部最优无冲突策略。[51] Pallottino 等人将冲突避免描述为一个混合整数线性规划问题。[52] Sislak 等人提出了一种非合作的冲突避免方法，当飞机之间无法通信时采用，并采用 A* 算法规划不与动态禁飞区相交的轨迹，以避免潜在的冲突。

The advantage of traditional numerical and intelligent optimization methods is to achieve overall optimization. However, due to the complex environment of integration airspace, the different performance of aircraft and the high computational complexity, the numerical and intelligent optimization method have limitations in terms of the feasibility and scalability, and it is difficult for them to solve the problem of rapid iteration of the optimization scheme with time and environmental changes.

传统数值和智能优化方法的优点在于实现整体优化。然而，由于集成空域的复杂环境、飞机性能的差异以及高计算复杂性，数值和智能优化方法在可行性和可扩展性方面存在局限性，并且它们难以解决随时间和环境变化而快速迭代的优化方案问题。

6.2. Distributed conflict resolution method

6.2. 分布式冲突解决方法

The distributed safety separation maintenance method focuses on the efficiency and safety of individual aircraft, with the advantages of rapid response and short calculation time. However, it does not consider the stability of the entire airspace. [54] Generally, the distributed conflict resolution method mainly includes rule-based method, artificial potential field method, geometric method, game theory, multi-agent negotiation, etc. [55]

分布式安全间隔保持方法关注于单架飞机的效率和安全性，具有快速响应和短计算时间的优点。但是，它没有考虑整个空域的稳定性。[54] 通常，分布式冲突解决方法主要包括基于规则的方法、人工势场法、几何法、博弈论、多代理谈判等。[55]

The rule-based approach is mainly to optimize the set of anti-collision rules based on air traffic and operating rules during the system design stage, and enforce the same rules for all aircraft in the integrated airspace. A research based on this method is made by Zhang et al. who designed a conflict detection and resolution method based on rules for large UAS equipped with ADS-B and TCAS in the integrated airspace, and conducted safety assessment on the operation of UAS. [56] The rule-based approach has the main advantages of simplicity and easy accessibility, requiring little or even no information exchange between aircraft. The disadvantage of the rule-based approach is its inability to consider the future intention and needs of the aircraft. [57]

基于规则的策略主要是优化在系统设计阶段的空中交通和运行规则中的一组防撞规则，并在集成空域中为所有飞机强制执行相同的规则。张等人基于此方法进行了研究，为大型无人机设计了基于规则的冲突检测和解决方法，这些无人机配备了 ADS-B 和 TCAS 并在集成空域中运行，并对无人机的运行进行了安全评估。[56] 基于规则的策略的主要优点是简单性和易于访问性，需要飞机之间很少甚至不进行信息交换。基于规则的策略的缺点在于它无法考虑飞机未来的意图和需求。[57]

The method based on the artificial potential field mainly regards each UAS as a charged particle, and calculates the field distribution based on the situational information of each UAS, such as the position of other aircraft, weather conditions and the uncertainty. [58] Collision avoidance of UAS is realized by the repulsive forces between fields. The advantage of this method is simple implementation, but due to the strong coupling of field forces, it is difficult to deal with complex situations. Besides, the method cannot take full consideration of the physical performance constraints of the aircraft, and may cause unfeasible solution. Duong and Zeghal studied the distributed conflict resolution based on the artificial potential field method. The whole process of conflict resolution can be achieved by establishing repulsive fields between aircraft and gravitational fields between aircraft and destination. [59]

基于人工势场的方法主要将每个无人机视为一个带电粒子，并基于每个无人机的情境信息 (如其他飞机的位置、天气条件和不确定性) 计算场分布。[58] 通过场之间的排斥力实现无人机的避撞。这种方法的优点是实施简单，但由于场力之间的强耦合，处理复杂情况较为困难。此外，该方法无法充分考虑飞机的物理性能约束，并可能导致不可行的解决方案。Duong 和 Zeghal 研究了基于人工势场的分布式冲突解决方法。通过在飞机之间建立排斥场以及飞机与目的地之间的引力场，可以实现冲突解决的全过程。[59]

The geometric method mainly considers the specific environment of UAS conflict, and seeks the best collision avoidance strategy via geometric characteristics analysis. The most common practice at present is to consider the conflict between two unmanned aircraft. In the case of multiple unmanned aircraft conflicts, the iterative method is generally used to solve the conflict between two unmanned aircraft, but it cannot guarantee the safety. Bilimoria proposed an optimal collision avoidance algorithm based on geometry in which the change of velocity is minimized with the minimum deviation from nominal trajectory. [60] Considering that UAS had different collision avoidance efficiency due to their different maneuverability, Park et al. [61] proposed a vector sharing method to make UAS with a slow speed take more responsibility and accomplish more maneuvers in the same time. Hence, all UASs could bring their respective advantages into full play to maximumly ensure the flight safety.

几何方法主要考虑无人机系统 (UAS) 冲突的具体环境，并通过几何特性分析寻求最佳的避碰策略。目前最常见的做法是考虑两架无人机之间的冲突。在多架无人机冲突的情况下，通常使用迭代方法来解决两架无人机之间的冲突，但这种方法无法保证安全。Bilimoria 提出了一种基于几何的最优避碰算法，该算法通过最小偏离名义轨迹来最小化速度的变化。[60] 考虑到不同机动性的 UAS 具有不同的避碰效率，Park 等人 [61] 提出了一种向量共享方法，使得速度较慢的 UAS 在相同时间内承担更多的责任并完成更多的机动动作。因此，所有 UAS 都能充分发挥各自的优势，最大程度地确保飞行安全。

The application of game theory in the field of air traffic is gradually emerging and has achieved inspiring results. Tomlin et al. [62] used non-cooperative game theory to solve flight conflicts. In the two-aircraft conflict scenario, based on the two-person zero-sum non-cooperative differential game theory framework, the accessibility analysis of mixed system was employed to obtain the "unsafe" subset of state space. Based on the satisfactory game theory, Ref. 63 established the relationship between aircraft by using conditional probability method to express the influence of the current aircraft's resolution decisions on other aircraft. Being a decentralized and cooperative method, it can effectively solve the conflict problem among a large scale of aircraft.

在航空交通领域，博弈论的应用逐渐兴起并取得了令人鼓舞的成果。Tomlin 等人 [62] 使用非合作博弈论来解决飞行冲突。在双机冲突场景中，基于两人零和非合作微分博弈理论框架，采用混合系统的可访问性分析来获得状态空间中的“不安全”子集。基于满意博弈论，参考文献 63 使用条件概率方法建立飞机之间的关系，以表达当前飞机的解决决策对其他飞机的影响。作为一种去中心化和合作的方法，它可以有效地解决大规模飞机的冲突问题。

In the multi-agent-based approach, each UAS is considered as an agent, which can communicate with each other and negotiate collision avoidance strategies by using efficiency functions. [64] Archibald et al. studied an agent method based on principle negotiation in which different agents in air traffic management can obtain their own interests via time slots negotiation. [65] Each agent optimizes its own behavior by evaluating the benefits of each decision, and designs cooperative search solution to improve the overall benefits. Cai and Shen [66] established a high-precision multi-agent framework which could be used for large-scale UAS control. The negotiated collision avoidance approach helps to reduce maneuver costs and avoid inappropriate maneuvers which may exacerbate conflict. However, in the event of a data link failure or data exchange interference, the negotiation may be interrupted. A robust and efficient algorithm based on decomposition of a large multi-agent Markov decision process was proposed to generate recommendations for each UAS. [67]

在基于多代理的方法中，每个无人机系统 (UAS) 被视为一个代理，它们可以相互通信并通过效率函数协商避碰策略。[64] Archibald 等人研究了一种基于原则协商的代理方法，在该方法中，空中交通管理中的不同代理可以通过时间槽协商来获得各自的利益。[65] 每个代理通过评估每个决策的好处来优化自己的行为，并设计合作搜索解决方案以提高整体利益。Cai 和 Shen [66] 建立了一个高精度的多代理框架，可用于大规模无人机控制。协商避碰方法有助于减少机动成本，并避免可能导致冲突加剧的不当机动。然而，在数据链路故障或数据交换干扰的情况下，协商可能会中断。提出了一种基于分解大规模多代理马尔可夫决策过程的鲁棒高效算法，为每个无人机生成建议。[67]

The trajectory projection method is suitable for the control avoidance strategy based on the airborne vision sensor, which is required to estimate the current state of the intruder and predict the intruder's trajectory. If the position of the UAS enters the dangerous area, a new heading angle command will be generated immediately to make the UAS leave the dangerous area, and then the UAS will fly back to the original trajectory along the original heading. The method is simple, direct and easy to implement. [68]

轨迹预测方法适用于基于机载视觉传感器的控制避碰策略，这需要估计入侵者的当前状态并预测入侵者的轨迹。如果无人机的位置进入危险区域，将立即生成一个新的航向角命令，使无人机离开危险区域，然后无人机将沿着原始航向飞回原始轨迹。该方法简单、直接且易于实施。[68]

7. Risk assessment method for UAV integrated operation

7. 无人机集成运行风险评估方法

Risk assessment mainly refers to the quantitative estimation of the impact of the consequences caused by a potential or actual accident by using scientific calculation methods and models. It is an important step to determine whether UAS can be safely integrated into the national airspace system.

风险评估主要是指使用科学计算方法和模型对潜在或实际事故造成的后果影响进行定量估计。这是确定无人机能否安全融入国家空域系统的重要步骤。

The risks are mainly divided into mid-air collision risks and ground collision risks. Mid-air collision risks refer to the probability of collision between UAS and other aircraft, while ground collision risks mainly refer to the probability of UAS hitting the ground.

风险主要分为空中碰撞风险和地面碰撞风险。空中碰撞风险指的是无人机系统 (UAS) 与其他航空器发生碰撞的概率，而地面碰撞风险主要指的是无人机系统 (UAS) 撞击地面的概率。

For the assessment of mid-air conflict risks of UAS in the integrated airspace, Zhang et al. established a cylindrical collision risk model based on conflict zones, and studied the conflict risk between manned aircraft and UAS. [56] The risk analysis results showed that the large UAS equipped with ADS-B, TCAS and airborne sensing systems did interfere with the operation of other aircraft in the integrated airspace. Especially as the number of aircraft increases, the automatic avoidance system of UAS would need more time to avoid collision and trigger the safety alarm, but the safety level was still acceptable.

针对无人机在融合空域中的空中冲突风险评估，张等人建立了一个基于冲突区的圆柱形碰撞风险模型，并研究了有人机与无人机之间的冲突风险。[56] 风险分析结果表明，配备有 ADS-B、TCAS 和机载感知系统的大型无人机在融合空域中确实会干扰其他航空器的运行。特别是随着航空器数量的增加，无人机的自动避障系统需要更多的时间来避免碰撞并触发安全警报，但安全水平仍然是可接受的。

Liu et al. proposed an aircraft collision model based on the density of flights in different areas of China's airspace, and constructed the relative collision area between UAS and manned aircraft and their flight speeds, mainly studying the fatality risk caused by the collision in the air. [69] For ground collision risks, Liu et al. also assessed the fatality threat from that risk. With consideration of system reliability required to meet a target level of safety for different UASs, a ground impact assessment model was proposed and both fixed-wing and rotary-wing UAS were taken into account under a real scenario. Considering the land and population data of the experimental scenario and the UAS characteristics, casualty area of impacting debris could be obtained as well as the probability of fatal injuries on the ground.

刘等人提出了一种基于中国不同空域航班密度的航空器碰撞模型，并构建了无人机与有人机及其飞行速度之间的相对碰撞区域，主要研究空中碰撞造成的致命风险。[69] 对于地面碰撞风险，刘等人也评估了该风险的致命威胁。考虑到系统可靠性以满足不同无人机所需的目标安全级别，提出了一种地面撞击评估模型，并在实际场景下考虑了固定翼和旋翼无人机。考虑到实验场景的土地和人口数据以及无人机的特性，可以获得撞击碎片造成的伤亡区域以及地面致命伤害的概率。

Waggoner conducted mining and analysis on the historical collision data of manned aircraft, and established the mid-air collision risk and ground collision risk models of UAS. [70] Lum et al. evaluated the risk of ground collision for UAS operating in densely populated areas. [71]

瓦格纳对有人机的历史碰撞数据进行了挖掘和分析，并建立了无人机的空中碰撞风险和地面碰撞风险模型。[70] Lum 等人评估了在人口密集区域运行的无人机地面碰撞风险。[71]

In addition, Gonçalves et al. provided a Petri net-based modeling method for UAS safety assessment process, aiming to describe the frequency of UAS in high collision risks and their abilities to respond to the operational input in case of failure. [72]

此外，Gonçalves 等人提出了一种基于 Petri 网的无人机系统 (UAS) 安全评估过程的建模方法，旨在描述无人机在高度碰撞风险中的频率及其在故障情况下对操作输入的响应能力。[72]

JARUS designed the Special Operations Risk Assessment (SORA) method [73] which could evaluate the risk scenarios related to a given hazard by visualizing the scenarios and safety risk management measures. The SORA process starts with risk modeling, then evaluates the risks of UAS midair collision and ground collision, and finally puts forward suggestions for risk mitigation. Denney et al. supplemented the current SORA guidance through a mathematically based risk assessment method. [74]

JARUS 设计了特殊操作风险评估 (SORA) 方法 [73]，该方法可以通过可视化场景和安全风险管理措施来评估与给定风险相关的场景。SORA 过程从风险建模开始，然后评估无人机空中碰撞和地面碰撞的风险，最后提出风险缓解的建议。Denney 等人通过基于数学的风险评估方法补充了当前的 SORA 指导。[74]

Besides, an online risk assessment method for entire UAS traffic was proposed using Bayesian belief networks. [75]

此外，提出了一种使用贝叶斯信念网络的整个无人机交通在线风险评估方法。[75]

8. Conclusions

8. 结论

To sum up, it can be seen that the safe and efficient operation of UAS in the integrated national airspace is a complex system, involving a great many aspects such as regulations and standards, safety separation standards, collision risk prediction, collision avoidance, safety risk assessment and so on. A lot of research work has been carried out by the industry and academic institutions all over the world, many regulations and standards have been issued, and different model algorithms have been put forward. However, there is still a lot of work to be done. Based on the technical requirements of the integration operations and the development plans of ICAO, the United States, Europe, China and other countries, the following areas may be the key areas of future challenges.

总结来说，无人机在集成国家空域中的安全高效运行是一个复杂的系统，涉及许多方面，如法规和标准、安全间隔标准、碰撞风险预测、碰撞避免、安全风险评估等。全世界各行各业和学术机构已经开展了很多研究工作，发布了许多法规和标准，提出了不同的模型算法。然而，还有很多工作要做。基于集成操作的技术要求和 ICAO、美国、欧洲、中国等国家和地区的发展规划，以下领域可能是未来挑战的关键领域。

8.1. Risk decomposition

8.1. 风险分解

The overall safety level of UAS operation in integration airspace depends on many factors. Given the equivalent level of safety, the equivalent risk is required to allocate reasonably and accurately to all aspects of the integration operation air traffic, such as the performance of the communication system, navigation system, monitoring system, UAS, onboard devices, network design, traffic rules, etc. Hence, current state of the art in each part and the economics of the improvements need to be taken into account. Besides, the safety risk indicators need to be converted into reasonable and feasible performance indicators to guide research and system design.

无人机系统 (UAS) 在融合空域中的整体安全水平取决于许多因素。在确保等效安全水平的前提下，需要将等效风险合理且准确地分配到融合运行空中交通的各个方面，如通信系统的性能、导航系统、监控系统、无人机、机上设备、网络设计、交通规则等。因此，需要考虑每个部分当前的技术状态以及改进的经济性。此外，需要将安全风险指标转换为合理可行的性能指标，以指导研究和系统设计。

8.2. Impact of safe separation management method on collision risk

8.2. 安全间隔管理方法对碰撞风险的影响

Safe separation management will lead to the dynamic change of the whole air traffic, including airspace capacity management, route planning, overtake rules, collision avoidance strategies and methods, etc. Each regulation will lead to different risks. Therefore, it will be very challenging to establish the relationship between safe separation management method and collision risk. On the basis of the performance of UAS and CNS, it is necessary to simulate the airspace model and traffic based on multi-agent, analyze and evaluate the error of UAS altitude, position and wind speed, establish a comprehensive risk model of collision in integration airspace, carry out the safety evaluation of the whole system operation, and then analyze the correlation between each safe separation management method and collision risk.

安全间隔管理将导致整个空中交通的动态变化，包括空域容量管理、航线规划、超车规则、避障策略和方法等。每项规定都会导致不同的风险。因此，建立安全间隔管理方法与碰撞风险之间的关系将非常具有挑战性。基于无人机 (UAS) 和通信、导航、监视 (CNS) 的性能，有必要基于多代理模拟空域模型和交通，分析评估无人机的高度、位置和风速误差，建立融合空域中碰撞的全面风险模型，对整个系统运行进行安全评估，然后分析每种安全间隔管理方法与碰撞风险之间的相关性。

8.3. Sense and avoid (SAA)

8.3. 感知与避障 (SAA)

Since the collision avoidance of UAS cannot be achieved by the traditional way of see-and-avoid of manned aircraft, one of the main challenges for UAS integration into NAS is to improve the UAS SAA capability to ensure that UAS can maintain a safe distance from other manned and unmanned aircraft and prevent mid-air collisions.

由于无人机的避障不能通过有人驾驶飞机的传统“看到并避开”的方式实现，无人机集成到国家空域系统 (NAS) 的主要挑战之一是提高无人机的 SAA 能力，确保无人机能够与其他有人和无人驾驶飞机保持安全距离，防止空中碰撞。

Collision avoidance is a large-scale complex multi-agent cooperative control and optimization problem with complicated constraints. Researchers from air traffic management and UAS field have proposed many methods. In the integration airspace, the performance of air vehicles and collision avoidance strategies are becoming richer and diverter. In addition, with the continuous expansion of the application fields and the continuous improvement of operation demand, different operation scenarios will also emerge, such as UAS formation operation which can perform tasks simultaneously with the least time and cost, and the complexity of the collision avoidance in these new air traffic scenarios is greatly increased. Therefore, it is required to propose more methods to realize collision avoidance under different scenarios with high real-time performance, scale scalability and overall safety and efficiency.

避碰是一个具有复杂约束的大规模多代理协同控制与优化问题。来自空中交通管理和无人机系统 (UAS) 领域的研究人员提出了许多方法。在融合空域中，航空器的性能和避碰策略正变得更加丰富和多样。此外，随着应用领域的不断扩展和运营需求的持续提高，不同的运营场景也将出现，例如无人机编

队操作，可以在最短时间和成本内同时执行任务，这些新的空中交通场景中的避碰复杂性大大增加。因此，需要提出更多方法，以实现不同场景下的避碰，具备高实时性能、规模可扩展性和整体安全与效率。

Besides, the government and industry are conducting researches on the sensor modes and algorithms involved in SAA, and the concept of AirBorne Sensing and Avoidance (ABSAA) is the main topic. Recent research objectives are flight tests of UAS equipped with different sensor modes, including electro-optical, infrared, radar, traffic warning, collision avoidance systems and ADS-B. The long-term goal is to deploy standardized airborne sensing and avoidance systems. The specific challenges of current researches include the establishment of the definition and performance level of SAA systems, assessment of the use of multiple sensors in SAA systems, and the minimum SAA information set required for collision avoidance maneuvers.

此外，政府和行业正在对 SAA 中涉及的传感器模式和算法进行研究，而机载感知与避碰 (ABSAA) 的概念是主要研究话题。近期的研究目标是进行配备不同传感器模式的无人机的飞行测试，包括电光、红外、雷达、交通警告、避碰系统和 ADS-B。长期目标是部署标准化的机载感知与避碰系统。当前研究的具体挑战包括建立 SAA 系统的定义和性能等级，评估 SAA 系统中多个传感器的使用，以及进行避碰机动所需的最小 SAA 信息集。

Another research highlight in the future would be the study on the compatibility of different UAS sensing technologies as well as UAS and manned aircraft sensing systems, such as TCAS and LIADR. In the meantime, in order to improve the strategic decision-making ability of multi-airspace-users for conflict avoidance, the SAA logic model and algorithm of different types of aircraft will need to be established.

未来另一个研究重点将是研究不同 UAS 感知技术之间的兼容性，以及 UAS 与有人驾驶飞机感知系统 (如 TCAS 和 LIADR) 的兼容性。同时，为了提高多空域用户避免冲突的战略决策能力，需要建立不同类型飞机的 SAA 逻辑模型和算法。

8.4. Construction and evaluation of safety separation model for integrated operations

8.4. 构建和评估综合运营的安全间隔模型

The standardization and evaluation of safety separation of manned aircraft and unmanned aircraft are among the fundamental work. Further studies need to be carried out in the following aspects, including UAS safety protection zone model, evaluation model of manned aircraft and UAS safety separation, correlation of safety separation criteria and collision avoidance in different scenarios, airspace collision risk assessment model for integrated operation of multi-type aircraft and UAS, and fast spatial-temporal deduction algorithm for the safety situation of integrated operations.

无人驾驶飞机与有人驾驶飞机的安全间隔标准化和评估是基础工作之一。以下方面需要进一步研究，包括无人机系统 (UAS) 安全保护区模型、有人驾驶飞机与 UAS 安全间隔的评估模型、不同场景下安全间隔标准与避障的相关性、多类型飞机与 UAS 综合运行的空域碰撞风险评估模型，以及综合运行安全状况的快速时空推理算法。

Finally, a complex and large-scale mixed environment with multi-type aircraft integrated poses a serious challenge to the safe operation, and how to ensure a safe separation between UASs and between UAS and manned aircraft and avoid collisions in order to achieve a safe and efficient operation in integrated airspace has become a common challenge. Many key factors, involved in the safety separation management and collision avoidance problem in the integration national airspace system, are highly coupled with each other and include route network design, air traffic rules, capacity management, collision avoidance, and equipment performance. For example, given the route network and flight missions, traffic rules determine the collision risk of the route, while error and uncertainties will lead to unstable operation safety of the route network. Hence, it is needed to further optimize the design of the route network. Besides, the performance indexes of the communication, navigation, and surveillance systems are the basis of the operation and closely related to the operation risks.

最后，多类型飞机综合的大型混合环境对安全运行提出了严重挑战，如何确保 UAS 之间以及 UAS 与有人驾驶飞机之间的安全间隔，避免碰撞，实现在综合空域中的安全高效运行，已成为共同的挑战。在综合国家空域系统中，涉及安全间隔管理和避障问题的关键因素相互高度耦合，包括航线网络设计、空中交通规则、容量管理、避障和设备性能等。例如，在给定的航线网络和飞行任务下，交通规则决定了航线的碰撞风险，而误差和不确定性将导致航线网络运行安全的不稳定。因此，需要进一步优化航线网络的设计。此外，通信、导航和监视系统的性能指标是运行的基础，并与运行风险密切相关。

For safe and efficient operation, the standardization of scenarios, devices, rules and processes is required. It can be predicted that the way forward will be very challenging due to the inconsistent pace of progress in all aspects. Despite this, the current researches from UAS operation and air traffic management field on the aspects of safety separation standards, collision risk prediction, collision avoidance, and safety risk assessment will provide some insights for further researches, and the development process of UAS integration into the national airspace system will continue to accelerate.

为了实现安全和高效的运行，需要对场景、设备、规则和流程进行标准化。可以预见，由于各方面进展步伐的不一致，前进的道路将充满挑战。尽管如此，当前无人机运行和空中交通管理领域关于安全间隔标准、碰撞风险预测、避障和安全风险评估的研究将为进一步研究提供一些见解，无人机融入国家空域系统的进程将继续加快。

Acknowledgements

致谢

This study was co-supported by the National Natural Science Foundation of China (Nos. U1933130, U1533119 and 71731001) and the Major Project of Technological Innovation, China (No. 2018AAA0100800).

本研究得到了中国国家自然科学基金会 (编号:U1933130、U1533119 和 71731001) 以及中国重大技术创新项目 (编号:2018AAA0100800) 的共同资助。

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