Recent Research Progress of Unmanned Aerial Vehicle Regulation Policies and Technologies in Urban Low Altitude

城市低空无人机监管政策与技术近期研究进展

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ABSTRACT With the rapid expansion in the number of Unmanned Aircraft Vehicles (UAVs) available and the development of modern technologies, the commercial applications of UAVs in urban areas, such as urban remote sensing (RS), express services, urban road traffic monitoring, urban police security, urban air shows and so on, have increased greatly. However, most UAVs, especially light and small civil UAVs, have been operating in low-altitude airspace, and a conflict may exist between increasing the number of UAVs and the limited low airspace. To promote low-altitude airspace resource development and to standardize the operation and management of UAVs in urban regions, some global laws and regulations and key technologies for urban low-altitude applications of UAVs have been implemented. This paper reviews the development of current policies and key technologies concerning safe and efficient operations of the light-and-small civil UAVs in low altitude in urban areas. Discussions are made progressively on measures and methods of airspace restriction, airspace structuring and air route planning in China primarily and the rest of world. After surveying the practical industry tests and the initial studies of air routes, the survey results indicate that the construction of air route networks is a scientific and effective measure to standardize and improve the efficiency of low-altitude UAV operations. From the view point of safety and efficiency, the most valuable direction for UAV regulation in urban regions involves deepening the research which largely relies on urban RS and Geographic Information System (GIS) technology, and application demonstrations of low-altitude public air route networks.

摘要随着可用无人航空器 (UAVs) 数量的迅速增加和现代技术的发展，UAV 在城市地区的商业应用，如城市遥感 (RS)、快递服务、城市道路交通监控、城市警察安全、城市空中表演等，已经有了大幅增长。然而，大多数 UAV，特别是轻小型民用 UAV，一直在低空空域运行，增加 UAV 数量与有限的低空空域之间可能存在冲突。为了促进低空空域资源开发，规范城市地区 UAV 的运行和管理，已经实施了一些全球性的法律、法规和城市低空 UAV 应用的关键技术。本文回顾了关于城市低空轻小型民用 UAV 安全高效运行的相关政策和技术的发展。主要针对中国以及世界其他地区的空域限制措施、空域构建和航线规划的方法进行了逐步讨论。在调查了实际行业测试和航线初步研究之后，调查结果表明构建航线网络是规范和提高低空 UAV 运行效率的科学有效措施。从安全和效率的角度来看，城市地区 UAV 监管最有价值的研究方向是深化依赖城市遥感和地理信息系统 (GIS) 技术的研究，以及低空公共航线网络的应用示范。

INDEX TERMS Low-altitude airspace, RS and GIS for UAV regulation, UAV regulation technology and policy, Urban region, UAV low-altitude air routes.

索引术语低空空域，UAV 监管的 RS 和 GIS，UAV 监管技术和政策，城市地区，UAV 低空航线。

ABBREVIATION		AGL:	Above Ground Level
3GPP:	Third Generation Partnership Project	NASA:	National Aeronautics and Space Administrati
LBS:	Location Based Service	APF:	Artificial Potential Field
ACO:	Ant Colony Optimization	NSFC:	National Natural Science Foundation of China
LSS:	Low, Slow and Small	ATM:	Air Traffic Management
ADS-B:	Automatic Dependent Surveillance-Broadcast	PSO:	Partial Swarm Optimization
LTE:	Long Term Evolution	C2:	Communication and Command
AFS:	Artificial Fish Swarm	QoS:	Quality of Service
MADG:	Minimum Accidental Damage to Ground	CAAC:	Civil Aviation Administration of China
		RS:	Remote sensing
	The associate editor coordinating the review of this manuscript and	CAS:	Chinese Academy of Sciences
	approving it for publication was Haluk Eren	SA:	Simulated Annealing

缩写		AGL:	地面以上高度
3GPP:	第三代合作伙伴计划	美国国家航空航天局	美国国家航空航天局
LBS:	基于位置的服务	APF:	人工势场
ACO:	蚁群优化	NSFC:	中国国家自然科学基金
LSS:	低、慢和小	ATM:	空中交通管理
ADS-B:	自动依赖监视-广播	PSO:	部分群体优化
LTE:	长期演进	C2:	通信与指挥
AFS:	人工鱼群	QoS:	服务质量
MADG:	最小地面意外损伤	CAAC:	中国民用航空局
		RS:	遥感
	协调本文稿审阅的副编辑	CAS:	中国科学院
	并批准其发表的 Haluk Eren	SA:	模拟退火

CSPG: China Southern Power Grid SESAR: Single European Sky ATM Research DAA: Detect and Avoid TCL: Technology Capability Level DEM: Digital Elevation Model UACS: Unmanned Aircraft Cloud System DSM: Digital Surface Model UAS: Unmanned Aircraft System EASA: European Aviation Safety Agency UAV: Unmanned Aircraft Vehicle FAA: Federal Aviation Administration UOM: UAV Operation and Management FISM: Flight Information Management System USGS: United States Geological Survey GA: Genetic Algorithm USS: UAV Service System GIS: Geographic Information System UTM: Unmanned Aircraft System of Traffic Management GloVis: Global Visualization Viewer UTMISS: UAS Traffic Management Information Service System ICAO: International Civil Aviation Organization uTM-UAS: the urban Traffic Management of Unmanned Aircraft System ISO/IEC JTC: International Organization of Standardization/ International Electrotechnical Commission

CSPG: 中国南方电网 SESAR: 单一欧洲天空空中交通管理研究 DAA: 检测与避免 TCL: 技术能力等级 DEM: 数字高程模型 UACS: 无人机云系统 DSM: 数字表面模型 UAS: 无人机系统 EASA: 欧洲航空安全局 UAV: 无人机 FAA: 联邦航空管理局 UOM: 无人机运行与管理 FISM: 飞行信息管理系统 USGS: 美国地质调查局 GA: 遗传算法 USS: 无人机服务系统 GIS: 地理信息系统 UTM: 无人机交通管理系统 GloVis: 全球可视化查看器 UTMISS: 无人机交通管理信息服务系统 ICAO: 国际民用航空组织 uTM-UAS: 城市无人机交通管理系统 ISO/IEC JTC: 国际标准化组织/国际电工委员会

VLL: Very Low Level

VLL: 超低空

LAANC: Low Altitude Authorization and Notification Capability

LAANC: 低空授权与通知能力

I. INTRODUCTION

I. 引言

As of Sept. 2018, there were more than 1 million UAVs registered with the United States Federal Aviation Administration (FAA) [1]. The global civilian UAV market accounted for US$ 6.56 Bn in 2018 [2]. The increasing number of UAVs and their commercial applications are gradually beginning to affect human life and even change it [3]. According to the statistics of the Civil Aviation Administration of China (CAAC), 82.68% of "low, slow and small (LSS)" UAVs operated below 120 m in 2018 [4] , which indicates that light and small UAVs have been widely used in low-altitude airspace, especially in urban areas, for a variety of applications (express services in cities [5], fast urban infrastructure inspections [6], etc.). However, there are some technological difficulties, such as surveillance with and communication with UAVs in low-altitude airspace, especially in very low level (VLL) airspace. The traditional radar surveillance systems, which are usually applied for medium- and high-altitude airspace, have difficulty capturing the location of LSS UAVs in VLL airspace, which means that the airspace and traffic management departments still lack effective services and management measures for many UAV flights at present.

截至 2018 年 9 月，美国联邦航空管理局 (FAA) 注册的无人机数量超过 100 万架 [1]。2018 年，全球民用无人机市场总计达到 65.6 亿美元 [2]。无人机数量的增加及其商业应用正逐渐开始影响人类生活，甚至改变生活 [3]。根据中国民用航空局 (CAAC) 的统计，82.68% 的“低、慢、小 (LSS)”无人机在 120 m 以下的 2018 [4] 空域内运行，这表明轻小型无人机在低空空域得到了广泛应用，特别是在城市地区，用于各种应用 (城市快递服务 [5]、快速城市基础设施检查 [6] 等)。然而，存在一些技术难题，如在低空空域，尤其是非常低空层 (VLL) 空域中，对无人机的监控和通信。传统雷达监控系统通常用于中高空域，难以捕捉 VLL 空域中 LSS 无人机的位置，这意味着空域和交通管理部门目前仍缺乏对许多无人机飞行的有效服务和管控措施。

To ensure the safety and efficiency of UAVs flying in low-altitude airspace, countries or regions around the world are seeking policy or technical means to control these operations [7]. This paper provides an exploratory study of the regulations and key technologies related to the application of light-and-small civilian UAVs at low-altitude over urban areas in China primarily and the rest of world.

为了确保低空空域中无人机飞行的安全和效率，世界各地国家和地区正在寻求政策或技术手段来控制这些运行 [7]。本文对中国城市上空低空空域轻小型民用无人机的应用及相关法规和关键技术进行了探索性研究，主要以中国为主，同时也涉及世界其他地区。

To incorporate the rapidly increasing number of UAVs into an already crowded airspace, as well as to ensure civilian aviation safety, countries or regions commonly segregate UAV activities from civil aviation in airspace by several measures. Firstly, the maximum flying height of UAVs is specified. For example, the CAAC sets the height of low-altitude airspace, where UAVs flying mostly, at 1000 m [8]. In addition, some permanent or temporary UAV geofences have been constructed and issued to guarantee the security of sensitive areas, such as military restricted zones [9]. However, ”no fly” zones are not enough to clarify how UAVs should fly. Additionally, the general aviation and UAV activity areas overlap in some countries (e.g., in China). To maintain the efficiency of UAV commercial activities, some organizations or commercial entities have proposed exclusive airspace for UAVs, such as airspace reserved exclusively for use by Amazon [10] and Huawei [11]. The proposal of UAV exclusive airspace is great progress toward opening up the airspace for UAV use at low altitude. However, it is still not enough. As the number of UAVs increases, so does the number of UAVs in a certain area and at a same height, so the risk of UAV collisions is rapidly increasing. To ensure safety under a multiple-UAVs scene, some countries or regions have put forward UAV traffic management systems, such as the Unmanned Aircraft Systems Traffic Management (UTM) in the US [12], U-Space in Europe [13], the urban Traffic Management of Unmanned Aircraft System (uTM-UAS) in Singapore [14] and the UAV Operation and Management (UOM) in China [15]. Moreover, the UAV service systems (USS), which aims to reduce the risk of collisions occurring among UAVs, has been embed into UTM, such as fourteen USSs ”Sprints” in projects testing by the National Aeronautics and Space Administration (NASA) [16] and eleven USSs and the data exchange platform in ”UAV cloud system” developed by the CAAC [17]. With the service of USSs, it is possible for UTM to communicate with UAVs by mobile internet technology, to obtain the position information of all UAVs and conduct unified dispatching of UAVs, so as to realize interconnection among cloud systems, near-real-time flight monitoring and operation management of UAVs. In particular, the development of new mobile internet access standards will play an important role in future UAV operations. Therefore, many telecom companies are working on connected UAVs, such as Ericsson in Sweden [18], and China Mobile [19].

为了将迅速增加的无人机数量融入已经拥挤的空域，并确保民用航空安全，各国或地区通常采取多种措施将无人机活动与民用航空在空域中分开。首先，规定了无人机的最大飞行高度。例如，中国民航局设定了低空空域的高度，无人机大多在此空域飞行，高度为 1000 m [8]。此外，还建立了一些永久性或临时性的无人机地理围栏，以确保敏感区域的安全，如军事禁飞区 [9]。然而，”禁飞”区域并不能明确说明无人机应该如何飞行。另外，在一些国家 (例如中国)，通用航空和无人机活动区域存在重叠。为了保持无人机商业活动的效率，一些组织或商业实体提出了为无人机保留专用空域的建议，例如专门为亚马逊 [10] 和华为 [11] 使用的空域。无人机专用空域的建议是向开放低空空域供无人机使用迈出了重大步伐。然而，这仍然不够。随着无人机数量的增加，特定区域和同一高度的无人机数量也在增加，因此无人机相撞的风险正在迅速增加。为了确保多无人机场景下的安全，一些国家或地区提出了无人机交通管理系统，如美国的无人机系统交通管理 (UTM) [12]，欧洲的 U-Space [13]，新加坡的无人机系统城市交通管理 (uTM-UAS) [14] 以及中国的无人机运行与管理 (UOM) [15]。此外，旨在降低无人机之间碰撞风险

的无人机服务系统 (USS) 已经嵌入到 UTM 中，例如美国国家航空航天局 (NASA) 测试项目中的十四个 USS “Sprints” [16] 以及中国民航局开发的“无人机云系统”中的十一个 USS 和数据交换平台 [17]。借助 USS 的服务，UTM 可以通过移动互联网技术与无人机通信，获取所有无人机的位置信息并进行无人机的统一调度，从而实现云系统之间的互联、近实时飞行监控和无人机运行管理。特别是，新的移动互联网接入标准的发展将在未来的无人机运行中发挥重要作用。因此，许多电信公司正在研究连接无人机的技术，如瑞典的爱立信 [18] 和中国的移动 [19]。

Urban areas, however, are characterized by complex surfaces, numerous no-fly zones and agglomerated populations. It is difficult to effectively deal with conflicts between UAVs and ”obstacles” at low-altitudes or near-surface areas merely by using UAV cloud-based control systems and USSs. To ensure the safe and efficient operation of UAVs at low altitude, countries or regions are exploring policies or technical means to manage UAV operations. Among these means, the technical scheme of planning a UAV’s low-altitude air routes based on massive amounts of Remote Sensing (RS) data and Geographic Information Technology (GIS) is increasingly being recognized.

然而，城市区域的特点是表面复杂，禁飞区众多，人口密集。仅通过使用基于云的无人机控制系统和无人机交通管理系统 (USS) 来有效处理无人机在低空或近地表区域的“障碍物”冲突是困难的。为确保无人机在低空的安全和高效运行，各国或地区正在探索管理无人机运行的政策或技术手段。在这些手段中，基于大量遥感 (RS) 数据和地理信息技术 (GIS) 规划无人机低空航路的方案正日益得到认可。

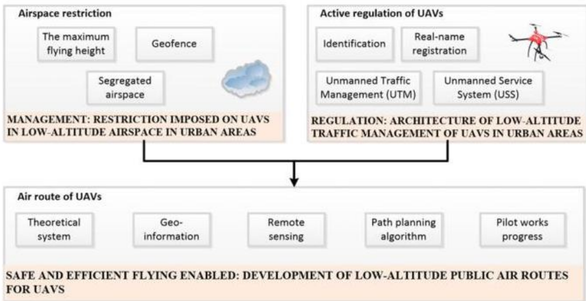

FIGURE 1. Reviewed policy and technology system aiming at safe UAV operations in urban areas.
图 1. 针对城市区域安全无人机运行的政策和技术系统综述。

This paper reviews the development of current policies and key technologies concerning safe UAV operations in low altitude in urban areas. Discussions are made progressively on measures and methods of airspace restriction (section II), active regulation (section III) and air route planning (Section IV) (Fig. 1) in China primarily and the rest of world. In the airspace restriction section, limitation measures imposed on airspace access are briefly summarized, including the maximum flying height of UAVs, and creatively proposes geofence and segregated airspace et al; In the active regulation section, identification and real-name registration of UAVs, works on UTMs and USS are described; In the air route planning section, the construction of air routes as a solution is extensively discussed with key technologies, e.g. GIS, RS and path planning algorithm with great potentials introduced. Finally, this paper compares and analyzes existing UAV management policies or technologies (section V), and summarized open issues and research directions worthy of further explorations.

本文综述了当前关于城市区域低空安全无人机运行的政策和关键技术发展。依次讨论了空域限制措施 (第二节)、积极调控 (第三节) 和航路规划 (第四节)(图 1) 在中国以及世界其他地区的应用。在空域限制部分，简要总结了限制无人机进入空域的措施，包括无人机的最大飞行高度，并创造性提出了地理围栏和隔离空域等；在积极调控部分，描述了无人机的识别和实名注册，以及无人机交通管理系统 (UTMs) 和无人机服务系统 (USS) 的工作；在航路规划部分，广泛讨论了以建设航路作为解决方案，并介绍了 GIS、RS 和具有巨大潜力的路径规划算法等关键技术。最后，本文比较分析了现有的无人机管理政策或技术 (第五节)，并总结了值得进一步探索的开放问题和研究方向。

II. MANAGEMENT: RESTRICTION IMPOSED ON UAVS IN LOW-ALTITUDE AIRSPACE IN URBAN AREAS

II. 管理: 对城市区域低空空域内无人机的限制

To minimize the risks of UAV-triggered incidents or accidents, an increasing number of national and international authorities have introduced legal provisions that mandate ”Go,” ”No go” or ”How to go” statements that either allow, prohibit or restrict UAV operations [20]. Airspace restriction is one of the UAV regulation measures widely adopted in various countries or regions. Especially in countries where UAVs are regulated strictly (e.g., in the U.S. and in China), UAVs are required to apply for airspace before flying. Specifically, on the premise that the UAV is real-name registered and the pilot is certified, the pilot submits the flight plan and airspace application to the airspace management department. Especially in China, it is necessary for the airspace management department to report UAV flight plan to the military. Only with permission of the airspace authority can the UAV operate within the specified time and airspace.

为了最小化无人机引发的事故或事件的风险，越来越多的国家和国际权威机构引入了法律条款，要求制定“飞行”、“不飞行”或“如何飞行”的声明，以允许、禁止或限制无人机的运行 [20]。空域限制是在各种国家或地区广泛采用的无人机监管措施之一。特别是在对无人机进行严格监管的国家 (例如，美国和中国)，无人机在飞行前需要申请空域。具体来说，在无人机实名注册和飞行员获得认证的前提下，飞行员需向空域管理部门提交飞行计划和空域申请。特别是在中国，空域管理部门需要将无人机的飞行计划报告给军方。只有在空域管理部门的许可下，无人机才能在规定的时间和空域内运行。

In addition, in order to manage airspace more effectively and efficiently, ”the maximum flight height”, ”geofence” and ”segregated airspace” measures, which will be further discussed as follows, are conducted by some countries to regulate UAV flight airspace.

此外，为了更有效和高效地管理空域，一些国家采取了“最大飞行高度”、“地理围栏”和“隔离空域”等措施，以下将进一步讨论这些措施，用以规范无人机的飞行空域。

A.THE MAXIMUM FLYING HEIGHT FOR UAVS

A. 无人机的最大飞行高度

The FAA states that the UAV flying height must be less than 122 m (400ft) Above Ground Level (AGL) in uncontrolled or ”Class G” zones [21]. In Japan, the government agency bans flights of UAVs weighing 200 g or more in crowded residential areas, at height 150 m or more above the ground, and near airports [22]. The Department of Civil Aviation in Malaysia stated that UAVs weighing not more than 20 kg are allowed to fly at a maximum height of 122 m (400ft) above the ground, and commercial operations are prohibited without permission. The Korean government proposes 300 m as the maximum UAV flight height [23], while the Chinese government proposes dividing the airspace that below 120 m AGL into airworthiness airspace for light UAVs [24].

美国联邦航空局 (FAA) 规定，无人机在未经控制的或“G 类”区域内的飞行高度必须低于 122 m (400ft) 地面以上 (AGL)[21]。在日本，政府机构禁止重量超过 200 g 或以上的无人机在拥挤的住宅区、地面以上 150 m 或以上的高度以及机场附近飞行 [22]。马来西亚民航局表示，重量不超过 20 kg 的无人机可以在地面以上最高 122 m (400ft) 的空域内飞行，未经许可禁止进行商业运营。韩国政府提议 300 m 作为无人机的最大飞行高度 [23]，而中国政府提议将低于 120 m AGL 的空域划分为适用于轻量级无人机的适航空域 [24]。

Fig. 2 shows the maximum flying heights of UAV for most countries where UAV flights have been in controlled by regulations. More than 99% of the countries require that UAVs fly below 300 m AGL; more than half of the countries permit UAV flights between 122 m and 150 m , and only 5% of the countries allow UAV flights below 60 m , which is VLL airspace with complex ground environments and is close to human beings. Only 6.1% of the countries have banned UAVs, most of which are in Africa and Asia, and 5.7% of the countries, such as Russia, allow UAVs to fly under certain conditions but do not specify height restrictions. In general, the overall progress of UAV airspace policies in Africa varies greatly in different districts with the following three coexisting situations: free flight (such as Algeria), unclear policy orientation (such as Niger) and active openness (such as Rwanda). In contrast, there are higher limits on UAV flights in Europe, North America and South America. In terms of the current development of UAV technology, the maximum flying height is achieved by gridding height-limited map and real-time monitoring of UAVs, such as the test works by CAAC in Shenzhen, China [25].

图 2 显示了大多数国家规定的无人机最大飞行高度，这些国家的无人机飞行受到法规的控制。超过 99% 的国家要求无人机在 300 m AGL 以下飞行；超过一半的国家允许无人机在 122 m 和 150 m 之间飞行，只有 5% 的国家允许无人机在 60 m 以下飞行，这是 VLL 空域，具有复杂的地面环境，且接近人类。只有 6.1% 的国家禁止了无人机，其中大多数位于非洲和亚洲，而 5.7% 的国家，如俄罗斯，允许在特定条件下飞行无人机，但并未指定高度限制。总的来说，非洲无人机空域政策的整体进展在不同地区差异很大，以下三种情况并存: 自由飞行 (如阿尔及利亚)、政策方向不明确 (如尼日尔) 和积极开放 (如卢旺达)。相比之下，在欧洲、北美洲和南美洲，无人机飞行的限制更高。就当前无人机技术的发展而言，最大飞

行高度是通过划分高度限制地图和对无人机的实时监控实现的，例如中国民航局在深圳的测试工作 [25]。

B.UAV GEOFENCE

B. 无人机地理围栏

The risk of small UAVs flying into sensitive areas first came into public view in 2015 when a hobbyist lost control of a UAV that crashed on the southeast side of the 18-acre secure zone around the grounds of the White House, triggering a secret service lockdown of the compound [26]. ”It’s only a matter of time before the threat manifests in a violent way,” Defense Secretary James Mattis told a Senate panel in May [27]. To maintain absolute safety in sensitive areas, especially military zones, the second measure proposed by a variety of countries is publishing permanent or temporary ”no fly” zones in laws and regulations, e.g., UAVs are off-limits in the airspace in the 15-mile radius around Washington and over areas such as the Hoover Dam, the Statue of Liberty and Mount Rushmore [28]. To prevent UAVs from flying into or out of a specific geographical area, geofencing - a core technique that defines virtual boundaries - has been developed [9], for example, US Senator Charles Schumer proposed a law requiring UAV manufacturers to build geofencing constraints to prevent UAVs from flying near airports and sensitive areas in 2016 [29]. Additionally, the Single European Sky ATM Research (SESAR) Center also launched the GEOSAFE project to establish state-of-the-art geofencing solutions regarding UAV traffic management regulations (U-space, in details in 2.1 part) that ensure public safety [30]. In China, the CAAC officially published the ”Unmanned Aerial Vehicle fence” industry standard in 2017, providing a clear definition that specified the scope, configuration, data structure and performance requirements for UAVs [9]. It is the first standard related to a geofence and is widely recognized worldwide. Topxgun.com (a Chinese UAV company) has passed the system safety capability level inspection and has been authorized by CAAC to be the first enterprise with the geofence capability [31]. Some countries or regions have specified the minimum safe distance between UAVs and geofence element to initially supporting safe UAV flights. We counted countries that have clearly specified the safe distance of geofence elements and found that person, airport and buildings accounted for the largest proportions (Annex).

小型无人机飞入敏感区域的风险首次在 2015 年引起公众关注，当时一名爱好者失去了对无人机的控制，无人机在白宫周围 18 英亩安全区域东南侧坠毁，导致秘密服务对该区域进行封锁 [26]。国防部长詹姆斯 · 马蒂斯在 5 月份告诉参议院小组: “威胁以暴力方式显现只是时间问题” [27]。为了在敏感区域，特别是军事区域保持绝对安全，多种国家提出的第二项措施是在法律和法规中发布永久或临时“禁飞”区域，例如，华盛顿周边 15 英里半径内的空域以及胡佛大坝、自由女神像和拉什莫尔山上空禁止无人机飞行 [28]。为了防止无人机飞入或飞出特定地理区域，已经开发了地理围栏技术——定义虚拟边界的核心技术 [9]，例如，美国参议员查尔斯 · 舒默在 2016 年提出了一项法律，要求无人机制造商构建地理围栏约束，以防止无人机在机场和敏感区域附近飞行 [29]。此外，单一欧洲天空空中交通管理研究 (SESAR) 中心还启动了 GEOSAFE 项目，以建立关于无人机交通管理法规 (U 空间，在 2.1 部分详细说明) 的最先进地理围栏解决方案，确保公共安全 [30]。在中国，民航局 (CAAC) 于 2017 年正式发布了《无人机围栏》行业标准，为无人机提供了明确定义，规定了范围、配置、数据结构和性能要求 [9]。这是与地理围栏相关的第一个标准，并在全球范围内得到广泛认可。Topxgun.com(一家中国无人机公司) 通过了系统安全能力级别检查，并被民航局授权为第一个具有地理围栏能力的公司 [31]。一些国家或地区规定了无人机与地理围栏元素之间的最小安全距离，以初步支持安全无人机飞行。我们统计了明确规定了地理围栏元素安全距离的国家，发现人员、机场和建筑占据了最大比例 (附录)。

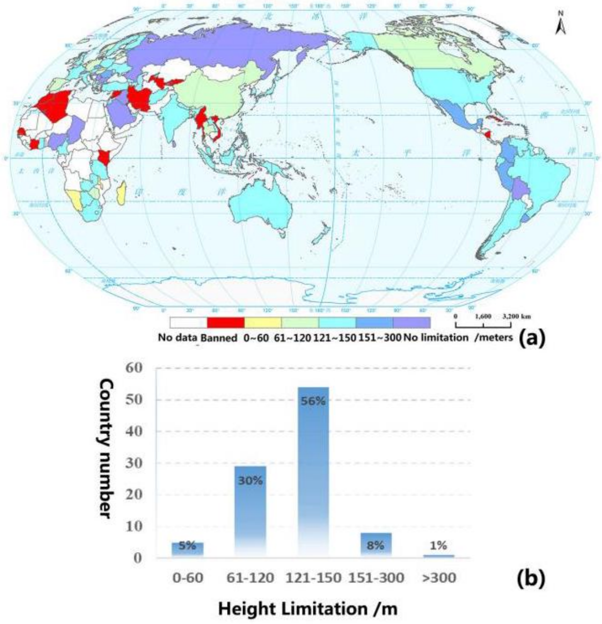

FIGURE 2. (a) Distribution of the maximum flying height for different countries and its (b) analysis for countries with specific limitations. (Note: Both professional and entertainment UAVs at micro, light or large scales were surveyed, and the height limitations here were the maximum values for different types and different scales of UAVs. Data available from: https://uavcoach.com/drone-laws/, https://droneregulations.info/, https://droneregulations.info/ and the websites of each national civil aviation administration or government department).

图 2. (a) 不同国家最大飞行高度的分布及其 (b) 对具有特定限制的国家的分析。(注: 本次调查涵盖了微型、轻型和大型规模的商用和娱乐无人机，此处的飞行高度限制为不同类型和不同规模无人机的最大值。数据来源:https://uavcoach.com/drone-laws/、https://droneregulations.info/ 以及各个国家民航局或政府部门的网站。)

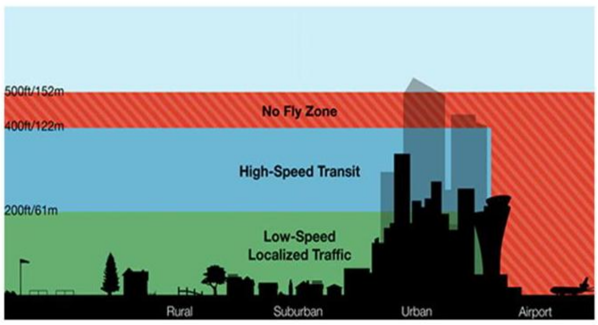

FIGURE 3. Airspace division for UAVs proposed by Amazon [10].

图 3. 亚马逊提出的无人机空域划分方案 [10]。

Essentially, a UAV geofence is a complex system consisting of a public dataset published by government departments to specify no-fly zones and geofencing technologies, which currently focus on the geofence design, static geofence, dynamic geofence and real-time geofence alerts, etc. Statistically, the public dataset mainly includes people, structures, roads, airports, and so on. Most of the public datasets list some geofencing factors and give some empirical parameter values, e.g., operating at 50 m from people and at 150 m from structures, vehicle and vessels. In China, the CAAC published specific geographical boundaries for 174 civilian airports in 2018 [32], [33], which could contribute to accurately managing UAVs near the airports to promote space utilization efficiency. DJI.com (a Chinese company of UAVs) has updated its own data for all UAV limitations.

本质上，无人机地理围栏是一个复杂系统，包括政府部门发布的公共数据集，用于指定禁飞区，以及目前主要关注地理围栏设计、静态地理围栏、动态地理围栏和实时地理围栏警报等地理围栏技术。统计上，公共数据集主要包括人员、建筑物、道路、机场等。大多数公共数据集列出了一些地理围栏因素，并

给出了一些经验参数值，例如，在 50 m 处距离人员以及在 150 m 处距离建筑物、车辆和船舶。在中国，民航局于 2018 年发布了 174 个民用机场的具体地理边界 [32]、[33]，这有助于准确管理机场附近的无人机，提高空间利用效率。大疆创新 (一家中国的无人机公司) 更新了所有无人机限制的自身数据。

C. SEGREGATED AIRSPACE FOR UAV FLIGHTS

C. 无人机飞行隔离空域

The CEO of the AscTec UAV company stresses that "legislation and policymaking is lagging way behind the technology". This lag creates a significant barrier to research and development, as scientific projects are hindered [34], including both private and public innovations. To solve this problem, some national aviation authorities and international organizations are already moving to "modernize" the first wave of regulations; they seek to accommodate user demands and recent technological developments while still aiming to maintain safe operations, especially for industrial applications.

AscTec 无人机公司的首席执行官强调，“立法和政策制定远远落后于技术的发展”。这种滞后对研发造成了重大障碍，因为科学项目受到了阻碍 [34]，包括私人及公共创新。为了解决这个问题，一些国家航空部门和国际组织已经在努力“现代化”第一波规定；他们试图满足用户需求并适应最近的技术发展，同时仍旨在保持安全运行，尤其是对于工业应用。

In the "Prime Air" project proposed by Amazon in 2015, a general idea and conceptual map of dividing the airspace into exclusive airspace for UAV use concerning logistics industry applications was formed [10] (Fig. 3). It divided the airspace as follows: the airspace between 200 $\sim$ 400ft is defined as the exclusive zone for UAVs, which consists of a high-speed zone in the airspace between 200 $\sim$ 400ft and a low-speed zone in the airspace below 200ft ; the airspace between 400 $\sim$ 500ft is defined as the no-fly zone.

在亚马逊于 2015 年提出的“Prime Air”项目中，形成了一个关于将空域划分为物流行业应用专属的无人机空域的一般概念和概念图 [10](图 3)。它将空域划分为以下部分: 200 $\sim$ 400ft 之间的空域被定义为无人机的专属区域，包括 200 $\sim$ 400ft 之间的空域中的高速区域和 200ft 以下空域中的低速区域；400 $\sim$ 500ft 之间的空域被定义为禁飞区。

In 2017, Huawei, together with the CAAC and China Mobile, tested the low-altitude cellular network coverage and business characteristics in different urban scenes, such as the central zone and industrial parks in Nanjing, etc [11]. They tested and passed the position verification of UAVs under the cellular network, specified the end-to-end data delay under the 4 G network (50 $\sim$ 300 ms) , and tested and passed the Location Based Services (LBS) verification test of the UAV geofence (referring to the ability to obtain the location information of mobile terminal users through the cellular radio communication network [9]). It was concluded that the mobile cellular network meets the UAV industry application requirement in most scenes below 120 m and the business requirements of the UAV safe flight link in most areas below 300 m . They defined the exclusive low-altitude airspace of UAVs as follows: 120 m is defined as the exclusive airspace for agriculture and patrol UAVs within the height-limit surveillance fence supported by cellular mobile communications and Automatic Dependent Surveillance-Broadcast (ADS-B) technology; the 300 $\sim$ 1000 m airspace, which is the maximum communication height of 5 G technology, is defined as the exclusive airspace of medium-sized UAVs within the space-limit surveillance fence; the 1000 $\sim$ 3000 m airspace is defined exclusively for large UAVs supported by ADS-B technology (Fig. 4).

在 2017 年，华为与中国民航局 (CAAC) 以及中国移动合作，在不同城市场景中测试了低空蜂窝网络覆盖和业务特性，例如南京的中央区域和工业园区等 [11]。他们在蜂窝网络下测试并通过了无人机的位置验证，规定了 4 G 网络下的端到端数据延迟 (50 $\sim$ 300 ms) ，并测试通过了无人机地理围栏的位置基于服务 (LBS) 验证测试 (指的是通过蜂窝无线电通信网络获取移动终端用户位置信息的能力 [9])。结论认为，移动蜂窝网络在大多数场景下满足了无人机行业应用的要求 120 m ，并且在大多数区域下满足了无人机安全飞行链路的业务要求 300 m 。他们定义了无人机的专属低空空域如下: 120 m 被定义为农业和巡逻无人机在由蜂窝移动通信和自动依赖监视-广播 (ADS-B) 技术支持的限高监控围栏内的专属空域；300 $\sim$ 1000 m 空域，即 5 G 技术的最大通信高度，被定义为中型无人机在空间限制监控围栏内的专属空域；1000 $\sim$ 3000 m 空域被定义为 ADS-B 技术支持的的大型无人机的专属空域 (图 4)。

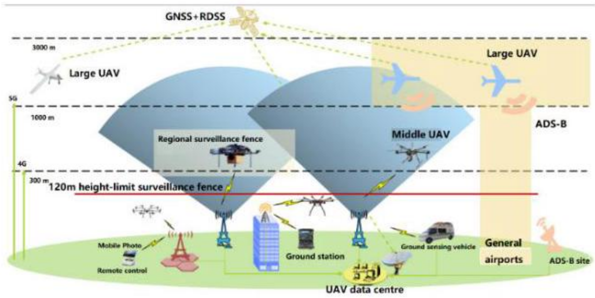

FIGURE 4. Airspace division for cellular-networking UAVs proposed by CAAC and Huawei [11].
图 4。中国民航局和华为提出的基于蜂窝网络的无人机空域划分 [11]。

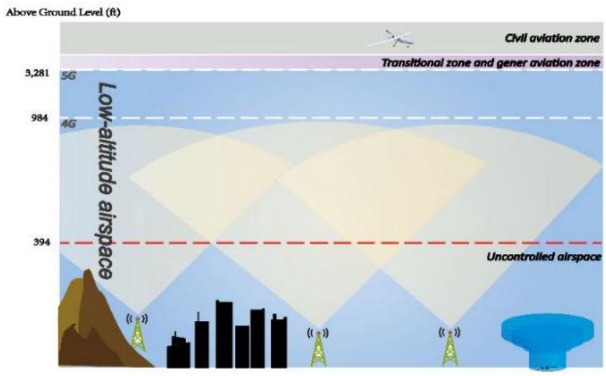

FIGURE 5. Low-altitude airspace classification for UAVs proposed by Chinese Academy of Sciences (CAS).
图 5。中国科学院 (CAS) 提出的无人机低空空域分类。

Liao et al. [35]-[37] defined the low-altitude airspace as follows (Fig. 5): low enough to be affected by ground facility and natural geomorphology; low enough to be covered by a ground mobile communication signal; and low enough to be away from traditional general aviation and civil aviation activities. The actual height of low-altitude varies from place to place and from time to time. They defined 120 m and 500 m as the UAV low floor and ceiling height of the high-speed path planning, respectively, that is, defining the scope of the airspace as exclusive UAV flight airspace according to the "Test report for the safe flight of low-altitude networked UAVs" as well as the "Interim regulations on flight management of UAVs (draft for comments)". Moreover, a low-speed air route below 120 m was planned to be the transit area between air routes and taking off- and landing- points, solving "the last kilometer" problem, such as a community route.

Liao 等人 [35]-[37] 将低空空域定义如下 (图 5): 足够低，以至于受到地面设施和自然地貌的影响；足够低，以至于被地面移动通信信号覆盖；足够低，以至于远离传统的通用航空和民航活动。低空的实际高度因地点和时间而异。他们定义了 120 m 和 500 m 分别为无人机低空路径规划的高速路径的底层和顶层高度，即根据《低空网络化无人机安全飞行测试报告》以及《无人机飞行管理暂行规定 (征求意见稿)》将空域范围定义为专属无人机飞行空域。此外，规划了低于 120 m 的低速航线作为航线与起降点之间的过渡区域，解决了“最后一公里”问题，例如社区路线。

III. REGULATION: ARCHITECTURE OF LOW-ALTITUDE TRAFFIC MANAGEMENT OF UAVS IN URBAN AREAS

III. 规制: 城市区域无人机低空交通管理架构

From the strategic view, urban low-altitude traffic management is about airspace utilization, focusing on the establishment and use limitations of airspace concerning segregated or non-segregated operations of UAVs. Low-altitude traffic management is mainly realized by setting various geofences in the segregated airspace. At the tactical level, urban low-altitude management is about determining the types and levels of air traffic services for UAVs. For UAVs that do not need to be registered (mainly micro and small consumer UAVs), a loose, or even open policy is adopted. UAVs are managed by the operator themselves according to laws and regulations. For real-name registered UAVs, risk assessment is conducted based on the submitted flight plan details, and airspace use is restricted and approved based on the assessment results. It focuses on the design of the UTM operation concept and the development of key systems (namely, UTM system) under segregated airspace operation.

从战略视角来看，城市低空交通管理涉及空域利用问题，重点是关于隔离或非隔离无人机操作的空域建立和使用限制。低空交通管理主要通过在隔离空域设置各种地理围栏来实现。在战术层面，城市低空管理是关于确定无人机所需空中交通服务的类型和级别。对于不需要注册的无人机 (主要是微型和小型消费无人机)，采用宽松甚至开放的策略。无人机由操作者根据法律法规自行管理。对于实名注册的无人机，根据提交的飞行计划细节进行风险评估，并根据评估结果对空域使用进行限制和批准。它着重于设计隔离空域操作下的 UTM(无人机交通管理系统) 运行概念和关键系统 (即 UTM 系统) 的开发。

A. IDENTIFICATION AND REAL-NAME REGISTRATION OF UAVS

A. 无人机的识别和实名注册

Identification, which effectively enables responsible ownership and serves to allow the safe integration of UAVs into airspace, is the foundation of managing the low-altitude UAV traffic. The core content of identification includes the aircraft information (complete machine, flight control, engine, propeller and required communication performance, etc.), owner or possessor information, and operator information. Currently, the International Organization of Standardization/ International Electrotechnical Commission (ISO/IEC), the International Civil Aviation Organization (ICAO) and other international organizations have not yet formulated relevant standards for UAV identification. Only the ISO/IEC JTC 1/SC 17 established the WG12 working group on the UAV license and UAV identification module, focusing on UAV related communication protocols, password security, identification and other standardization work. ICAO established the UAV system research group, the members of which consist of global major UAV application countries and districts. Its main task is to coordinate UAV management and operation works among different countries and districts and to define authoritative concepts and formulate regulations for UAV systems.

识别，有效地实现了责任归属，并服务于允许无人机安全地融入空域，是管理低空无人机流量的基础。识别的核心内容包括飞机信息 (完整机器、飞行控制、发动机、螺旋桨以及所需的通信性能等)、所有者或持有者信息，以及操作者信息。目前，国际标准化组织/国际电工委员会 (ISO/IEC)、国际民用航空组织 (ICAO) 等其他国际组织尚未制定无人机识别的相关标准。仅有 ISO/IEC JTC 1/SC 17 成立了关于无人机许可证和无人机识别模块的 WG12 工作组，专注于无人机相关的通信协议、密码安全、识别等标准化工作。ICAO 成立了无人机系统研究组，其成员由全球主要无人机应用国家和地区的代表组成。其主要任务是协调不同国家和地区之间的无人机管理和运营工作，并为无人机系统定义权威概念和制定规定。

Except for the ”Unique Identity”, it is necessary to be registered uniformly and to be ”Real-name Recorded” in national files for UAVs to have access to the UTM system. In January 2016, the FAA implemented registration requirements for UAVs in the US, requiring that UAVs weighing between 0.55 and 55 pounds must be registered. After logging into the ”FAADroneZone” website [38], users must complete and submit the UAV and personal information and then accept a UAV license with the owner’s name and license code issued by the FAA if approved. In China, the CAAC launched the real-name registration system in May 2017, which requires UAV users to submit information about the UAV manufacturer, product model, product name, product serial number, registration time, owner’s name or company name and contact information. Recently, more than 340,000 UAVs has been registered through this website. The use of real-name registration systems for the standardized management of UAVs has received strong support. In UK, the increasing number of UAV strikes is also accelerating the government’s move to make real-name registration a mandatory tool to improve UAV safety [39]. In India, the unique identification number of UAV is required [40]. However, for most countries, the registration of UAVs is not proposed yet, such as in Australia, Belgium, Canada and in Japan, et al [40].

除了“唯一识别码”之外，无人机要接入无人机交通管理系统 (UTM 系统)，还需要在国家档案中进行统一注册并实行“实名记录”。2016 年 1 月，美国联邦航空管理局 (FAA) 实施了无人机注册要求，规定重量在 0.55 磅至 55 磅之间的无人机必须进行注册。用户登录“FAADroneZone” 网站 [38] 后，必须完成并提交无人机和个人信息，然后在获得批准后接受由 FAA 颁发的带有所有者姓名和许可证编码的无人机许可证。在中国，民航局 (CAAC) 于 2017 年 5 月启动了实名注册系统，要求无人机用户提交无

人机生产商、产品型号、产品名称、产品序列号、注册时间、所有者姓名或公司名称及联系方式等信息。最近，已有超过 34 万台无人机通过该网站注册。使用实名注册系统对无人机进行标准化管理得到了强烈支持。在英国，无人机撞击事件的增加也正在加速政府将实名注册作为提高无人机安全的强制性工具的步伐 [39]。在印度，无人机需要具备唯一识别号码 [40]。然而，对于大多数国家来说，如澳大利亚、比利时、加拿大和日本等，尚未提出无人机的注册要求 [40]。

B. UNMANNED AIRCRAFT SYSTEM TRAFFIC MANAGEMENT SYSTEM

B. 无人机系统交通管理系统

The UTM System is an important means to ensure that UAVs do not collide with buildings and other aircrafts. In recent years, under the impetus of developed countries and regions, such as the US and Europe, the ICAO and JARUS are developing a UTM framework and operational guidance materials to improve the safety, security, efficiency, effectiveness, scalability and privacy of civilian and small UAVs. At the strategic level, various airspace planning problems for civilian small UAVs are necessary to be solved by the UTM, including forbidden areas, restricted areas, available airspace (low-altitude segregated recreational and operating airspaces), etc. At the tactical level, the operation process of civilian and small UAV management should be strictly followed by the UTM, including preflight planning approval and conflict warnings, in-flight air traffic services, conflict detection and route dynamic planning, etc. Currently, three mainstream UAV management systems have been planned, including UTM in the US, U-space in Europe, and UOM in China. Additionally, the uTM-UAS in Singapore is planned for densely populated urban areas.

UTM 系统是确保无人机不会与建筑物和其他飞行器相撞的重要手段。近年来，在发达国家或地区如美国和欧洲的推动下，国际民航组织 (ICAO) 和 JARUS 正在开发 UTM 框架和操作指导材料，以提高民用和小型无人机的安全、保安、效率、有效性、可扩展性和隐私性。在战略层面，UTM 需要解决各种民用小型无人机的空域规划问题，包括禁飞区、限制区、可用空域 (低空隔离娱乐和运行空域) 等。在战术层面，民用和小型无人机的管理过程应严格遵守 UTM 的规定，包括飞行前规划审批和冲突预警、飞行中空中交通服务、冲突检测和航线动态规划等。目前，已经规划了三种主流的无人机管理系统，包括美国的 UTM、欧洲的 U-space 和中国的 UOM。此外，新加坡的 uTM-UAS 计划用于人口密集的城区。

The UTM [12] in the US is designed to manage unregulated operations of UAVs in VLL airspace below 400ft . It can serve FAA by integrating industry capabilities, such as the capabilities of the USS. It is characterized by connecting the official system (Flight Information Management System, FISM) and the industry system (USS) and aiming to develop, improve and test low-altitude airspace requirements for large UAVs flying within and beyond the line-of-sight. The project was divided into four Technology Capability Levels (TCL) test with increasing complexity. So far, the fourth TCL, which can be used for UAV operations in densely populated suburbs, was partly tested in Nevada and Texas from June to August 2019 [41].

美国的 UTM[12] 旨在管理 VLL 空域以下无人机的非监管运行 400ft 。它可以通过整合行业能力，如 USS 的能力，为 FAA 提供服务。其特点在于连接官方系统 (飞行信息管理系统，FISM) 和行业系统 (USS)，并旨在开发、改进和测试大型无人机在视距内和视距外的低空空域要求。该项目分为四个技术能力等级 (TCL) 的测试，难度逐渐增加。到目前为止，第四个 TCL，可用于人口密集郊区的无人机运行，已于 2019 年 6 月至 8 月在内华达州和德克萨斯州进行了部分测试 [41]。

The U-Space project jointly led by the SESAR and the European Aviation Safety Agency (EASA) was proposed in March 2017 [42]. It is a set of new services and procedures designed to support safe, efficient and secure access to airspace by Unmanned Aircraft System (UAS). It plans to gradually realize ordered flights in low-altitude airspace for UAVs following four services, which are as follows: U1 - basic services, including electronic registration, identification and electronic fences; U2 - initial services, supporting UAV operations management, which may include flight planning, tracking, and traditional interactions, etc.; U3 - senior services, supplying services for more complicated operations in traffic-dense areas, such as automatic collision detection and obstacle avoidance, etc.; and U4 - full service, realizing high automation, connection, and digitization between UAVs and U-space systems.

U-Space 项目是由 SESAR 和欧洲航空安全局 (EASA) 联合领导的，于 2017 年 3 月提出 [42]。它是一套旨在支持无人机系统 (UAS) 安全、高效和可靠进入空域的新服务和程序。它计划通过以下四个服务逐步实现无人机在低空空域的有序飞行:U1 - 基础服务，包括电子注册、识别和电子围栏；U2 - 初级服务，支持无人机操作管理，可能包括飞行计划、跟踪和传统交互等；U3 - 高级服务，为交通密集区域提

供更复杂操作的服务，如自动碰撞检测和避障等；以及 U4 - 完全服务，实现无人机与 U-space 系统之间的高度自动化、连接和数字化。

The UOM project, led by the CAAC and launched in January 2019, aims to construct a "multi-management and multiservice" structure to realize the safe and flexible operation of light-and-small UAVs below 120 m [15]. The flight information management subsystem Unmanned Aircraft System Traffic Management Information Service System (UTMISS) [25], which is the core component of UOM, consists of an administrative management platform, an operation management platform, a collaboration platform and a public service platform. It was developed to construct an information synergy management mechanism through industry management, airspace control, government coordination and social service to promote the development and application of low-altitude flying pilot tests. At present, UTMISS has been used in pilot works for UAV air traffic control information services in Shenzhen, China. It aims to form an information-based system to construct a set of efficient management methods between users and management departments, that is, transmit the management requirements of relevant departments to users and report UAV operation information to air traffic control and relevant security departments in a timely manner.

中国民航局 (CAAC) 领导的 UOM 项目于 2019 年 1 月启动，旨在构建“多管理、多服务”的结构，以实现低于 120 m 的小型轻量级无人机的安全灵活运行 [15]。UOM 的核心组件无人机系统交通管理信息服务系统 (UTMISS)[25]，包括行政管理平台、运行管理平台、协作平台和公共服务平台，旨在通过行业管理、空域控制、政府协调和社会服务构建信息协同管理机制，推动低空飞行试点测试的发展和运用。目前，UTMISS 已在中国深圳的无人机空管信息服务试点工作中使用。它旨在形成一个信息化系统，构建用户与管理部门之间的一套高效管理方法，即及时将相关部门的管理要求传达给用户，并将无人机运行信息报告给空管和相关的安全部门。

The uTM-UAS, proposed by a team from Nanyang Technological University, Singapore, is a framework for the urban traffic management of UAS [14]. It aims to reduce UAV flight risks in low-altitude airspace over cities with tactical and strategic mitigation measures and to increase utilization of low-altitude airspace resources. Specifically, this framework consists of the following four research areas: hierarchical network management (signal coverage, data fusion and visualization in AirMatrix), urban airspace management (geo-fencing and airspace structure design), flight management (flight simulation and authorization), and risk management (risk assessment and alert). The above four functions are embedded in the uTM-UAS framework as modules and are used in the form of interfaces by specific users in specific scenarios. In addition, some countries are developing UAV management system with supports by issuing relative policies. For example, the Republic of Korea Ministry of Land, Infrastructure and Transport (ROK MOLIT) has specified the UAV flight standards for each level of airspace by UAV weights and has promoted flight approvals for the plans that fulfill UAV particulars [43].

由新加坡南洋理工大学的团队提出的 uTM-UAS，是一种用于城市无人机交通管理的框架 [14]。它旨在通过战术和战略缓解措施，减少城市低空空域中的无人机飞行风险，并提高低空空域资源的利用率。具体而言，该框架包括以下四个研究领域: 分层网络管理 (AirMatrix 中的信号覆盖、数据融合与可视化)、城市空域管理 (地理围栏和空域结构设计)、飞行管理 (飞行模拟和授权) 以及风险管理 (风险评估和警报)。上述四个功能作为模块嵌入到 uTM-UAS 框架中，并由特定用户在特定场景下以接口的形式使用。此外，一些国家正在开发带有政策支持的无人机管理系统。例如，韩国土地、基础设施和运输部 (ROK MOLIT) 根据无人机的重量为不同空域级别的无人机飞行制定了标准，并推动了满足无人机特定要求的飞行计划的审批 [43]。

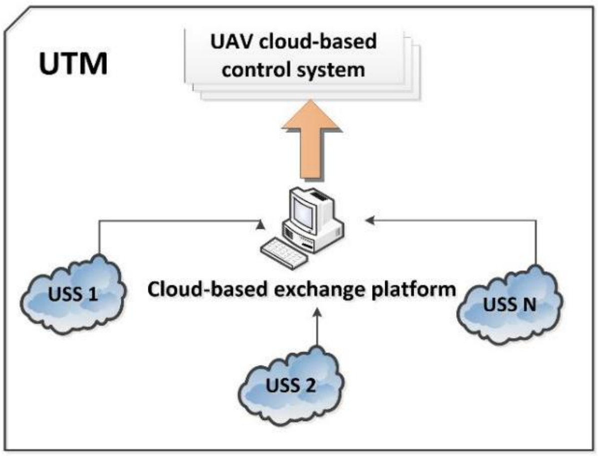

FIGURE 6. Relationship among the UTM, UAV cloud-based control system, USS and cloud-based exchange system.

图 6. UTM、基于云的无人机控制系统、USS 和基于云的交换系统之间的关系。

In the context of mature manned aviation system, the coordinated development of UTM and ATM is also worthy of attention. Under the FAA program, UTM is a "traffic management" ecosystem for UAV operation, which is independent of ATC control and is complementary to ATM system [44]. In China, UTM is adopted in the segregated airspace, while UTM is integrated into the ATM in the non-segregated airspace, so as to realize the integration of unmanned and manned aviation and the integration of UAV traffic management system and traditional manned aviation system. ICAO envisions UTM as a subset of ATM and aims to manage UAVs safely, economically and efficiently through the provision of facilities and a seamless set of services in collaboration with all parties [45]. It indicates an integration tendency between the ATM and UTM in some countries. UTM systems are therefore envisaged to be interoperable and consistent with the existing ATM systems, in order to facilitate safe, efficient and scalable operations.

在成熟的有人驾驶航空系统背景下，无人机交通管理系统 (UTM) 与空中交通管理系统 (ATM) 的协调发展也值得注意。在美国联邦航空局 (FAA) 的项目中，UTM 是一个针对无人机操作的“交通管理”生态系统，独立于空中交通管制 (ATC) 控制，并与 ATM 系统互补 [44]。在中国，UTM 在隔离空域中得到应用，而在非隔离空域中，UTM 与 ATM 整合，以实现无人机与有人机航空的整合，以及无人机交通管理系统与传统有人机航空系统的整合。国际民航组织 (ICAO) 将 UTM 视为 ATM 的一个子集，旨在通过提供设施和与各方协作的无缝服务，安全、经济、高效地管理无人机 [45]。这表明在一些国家 ATM 与 UTM 之间存在整合趋势。因此，UTM 系统被设想为应与现有的 ATM 系统互操作并保持一致，以便促进安全、高效和可扩展的运行。

C.UAV SERVICE SYSTEM AND THE DATA EXCHANGE PLATFORM

C. 无人机服务系统与数据交换平台

The USS and the data exchange platform are core components of UTM, providing real-time operation and manufacture data of UAVs from different operators to the UAV cloud-based control system (Fig. 6). The influential service system in the service currently includes the USA-UTM oriented Low Altitude Authorization and Notification Capability (LAANC) scheme, the U-space oriented Drone Enhanced Airspace Management System and the UOM oriented cloud system solution.

无人机服务系统 (USS) 和数据交换平台是 UTM 的核心组成部分，它们为基于云的无人机控制系统提供来自不同运营商的无人机实时运行和制造数据 (见图 6)。当前服务中具有影响力的服务系统包括面向美国 UTM 的低空授权与通知能力 (LAANC) 计划、面向 U-space 的无人机增强空域管理系统以及面向无人机运营管理 (UOM) 的云系统解决方案。

LAANC's core business is realized by USS, which automatically authorizes the UAV flights in the mosaic area according to the gridding height-limit map (VLL airspace formed by the geographic fence) provided by the FAA. NASA has planned a series of "Sprints" to work with industry partners to develop and test a USS discovery system to better enable USSs to find and communicate with each other. There are mainly fourteen approved USSs, including Aeronyde, Airbus, Airmap, AiRXOS, Altitude Angel, Converge, DJI, Harris Corporation, Kittyhawk, Project Wing, Skyward, Thales Group, UASidekick and Unify [16].

LAANC 的核心业务是通过 USS 实现的，USS 根据 FAA 提供的格子高度限制图 (由地理围栏形成的 VLL 空域) 自动授权无人机在拼贴区域内的飞行。NASA 已经计划了一系列的“冲刺”活动，与行业合作伙伴一起开发和测试 USS 发现系统，以更好地使 USS 相互查找和通信。主要有十四个经过批准的 USS，包括 Aeronyde、Airbus、Airmap、AiRXOS、Altitude Angel、Converge、DJI、Harris Corporation、Kittyhawk、Project Wing、Skyward、Thales Group、UASidekick 和 Unify[16]。

TABLE 1. Information of UAV cloud-based system in China.

表 1. 中国无人机云系统信息。

USS	Approcal Time	Capability	Website of UACS or USS
U-cloud	2016.3.12	Real-time	https://www.u -cloud.cn/
U-care	2016.3.21	UAV and pilot management, flight mission and service management, data analysis and management, airspace resources query Pilot registration,	http://www.u- care.net.cn/
BD- cloud	2017.8.28	training management, flight plan, tracking、geofence, collision avoidance、path optimization, climatology service	http://www.cc ompass.com.c n/
5U	2018.1.1	B-level control of authorized UAVs	http://www.5u -cloud.com/
Air Dwing.c om	2018.3.1	Monitoring, path planning, data 3D visualization	https://www.a irdwing.com/
Qianxu n SI.com	2018.3.21	4D spatiotemporal geofence, data analysis and management	https://www.q XWZ.com/
TY.IW. com	2018.6.3	Airspace query、climatology service, UAV issurance	http://www.tia nyujingwei.co m/
XAG.co m	2018.9.19	Spraying mission	https://www.x a.com/about
TopGun .com	2019.2.12	Airspace query, climatology service	http://www.to pxgun.com/
China- Skynet	2019.4.4	Real-time regulation, low-altitude air route network planning	http://skygrid.mapscloud.cn

USS	接近时间	能力	UACS 或 USS 网站
U-云	2016.3.12	实时	https://www.u-cloud.cn/
U-关怀	2016.3.21	无人机及飞行员管理，飞行任务与服务管理，数据分析与管理，空域资源查询飞行员注册，	http://www.u-care.net.cn/
BD-云	2017.8.28	培训管理、飞行计划、跟踪、地理围栏、避障、路径优化、气候服务	http://www.compass.com.cn/
5U	2018.1.1	B 级授权无人机的控制	http://www.5u-cloud.com/
AirDwing.com	2018.3.1	监控、路径规划、数据三维可视化	https://www.airding.com/
Qianxun SI.com	2018.3.21	4D 时空地理围栏、数据分析与管理	https://www.qXWZ.com/
TY.IW. com	2018.6.3	空域查询、气候服务，无人机保险	http://www.tia nyujingwei.co m/
XAG.co m	2018.9.19	喷洒任务	https://www.x a.com/about
TopGun .com	2019.2.12	空域查询，气候服务	http://www.to pxgun.com/
中国天网	2019.4.4	实时调控，低空航线网络规划	http://skygrid.mapscloud.cn

China's UAV cloud-based system is the only one that introduces cloud computing and defines the access requirements in detail [46]. It requires that the type II and IV UAVs, flying in the sensitive areas and the airport clearance area, should be connected to the cloud system [4]. It is a dynamic database system for the operation of light-and-small civilian UAVs and provides navigation services and meteorological services to UAV users and conducts real-time monitoring of the operational data of civilian UAVs (including operational information, position, altitude, speed, etc.). The UAVs connected to the system must upload flight data immediately, and the UAV cloud system must signal an alarm when UAVs are intruding into the geofence.

中国的无人机云系统是唯一一个引入云计算并详细定义接入要求的系统 [46]。它要求在敏感区域和机场净空区域飞行的 II 型和 IV 型无人机应连接到云系统 [4]。它是一个轻小型民用无人机运行动态数据库系统，为无人机用户提供导航服务和气象服务，并对民用无人机的运行数据 (包括运行信息、位置、高度、速度等) 进行实时监控。连接到系统的无人机必须立即上传飞行数据，当无人机侵入地理围栏时，无人机云系统必须发出警报。

There are eleven USSs that have been issued a "Unmanned Aircraft Cloud System (UACS) Approval Letter" by the CAAC in China, and ten of them are currently in service [4]. Those USSs are operated by different operators in different function structures and service focuses, as follows (other details are shown in Table 1): The U-cloud system is the first UAV cloud system approved by the CAAC. The U-care system is the first UAV cloud system that is in line with the civil aviation industry standards and data transmission standards of airspace-control radar in China. The U-care system has the same interface as the military and civil aviation airspace-control monitoring system. The BD-cloud system authorizes access to the data of enterprises that focusing on UAV plant protection application, such as XAG.com (a Chinese company), which accounts for a large proportion of UAV agricultural plant protection market in China, has already connected its UAV data to this system. The 5U system is the only cloud system supplier authorized by CAAC to achieve B-level control. The Air Dwing.com system is characterized by collaborative planning and scheduling commands of UAV tasks. The Qianxun SI.com system can construct a 4D space-time electronic fence to conduct dynamic and fine supervision. The TY.IW. com system is the first UAV big data service platform based on network measurement and control in China. The XAG.com system is only used for agricultural plant protection. The TopGun.com system is a global professional research and production provider of UAV flight control systems and UAV solutions. The China-Skynet system is the only public cloud, and it is jointly researched and developed by research institutes and businesses; this system effectively supports the unified UAV operation management system based on holographic map and cloud computing technologies and an embedded air route construction module. Furthermore, the cloud-based exchange platform developed by CAAC is the only one that supports data exchange and sharing from different operators that assess the UTM. This platform realizes UAV data exchange and sharing by receiving real-time UAV operation data reported by various USSs, exchanging, recording and storing data among USSs through data distribution technology.

| 中国民航局 (CAAC) 已向十一个无人机系统供应商 (USS) 颁发了“无人机云系统 (UACS) 批准函”，其中十个目前正处于服务中 [4]。这些 USS 由不同的运营商在不同的功能结构和业务重点下运营，具体如下 (其他详细信息见表 1):U-cloud 系统是首个获得 CAAC 批准的无人机云系统。U-care 系统是首个符合中国民航行业标准和空管雷达数据传输标准的无人机云系统。U-care 系统与军事和民航空管监控系统具有相同的接口。BD-cloud 系统授权企业访问专注于无人机植保应用的数据，例如 XAG.com(一家中国公司)，其在中国无人机植保市场中占据了很大比例，并已将其无人机数据连接至该系统。5U 系统是唯一获得 CAAC 授权实现 B 级控制的云系统供应商。AirDwing.com 系统以协同规划和调度无人机任务命令为特点。Qianxun SI.com 系统能够构建 4D 时空电子围栏进行动态和精细监控。TY.IW.com 系统是中国首个基于网络测量和控制的无人机大数据服务平台。XAG.com 系统仅用于农业植保。TopGun.com 系统是全球专业的无人机飞行控制系统和解决方案提供商。China-Skynet 系统是唯一的公共云，由研究机构和商业企业共同研发；该系统能有效支持基于全息地图和云计算技术的统一无人机运行管理系统，并具有嵌入式航线构建模块。此外，CAAC 开发的基于云的交换平台是唯一支持不同运营商之间进行无人机交通管理系统 (UTM) 数据交换和共享的平台。该平台通过接收各种 USS 实时报告的无人机运行数据，实现无人机数据的交换和共享，并通过数据分发技术在 USS 之间交换、记录和存储数据。

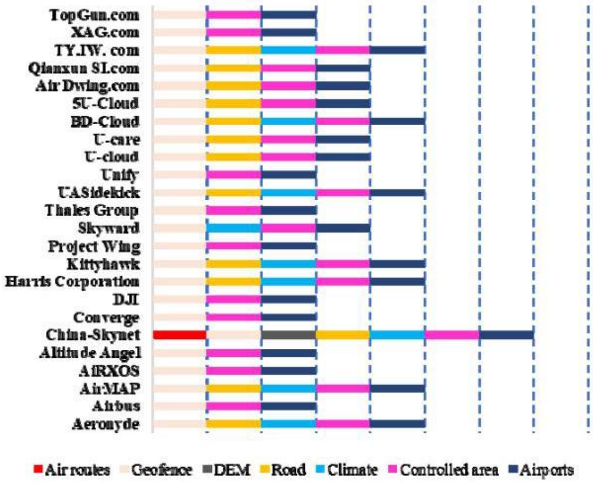

FIGURE 7. UAV cloud service systems around the world.
图 7. 世界各地的无人机云服务系统。

However, there is a common problem: an air route network even with any degree of flexibility is still inadequate for supporting the present UTM and UAV cloud-based systems (Fig. 7). The correlation between air routes and UTM is like that between roads and ground traffic management (Fig. 8).

然而，存在一个普遍问题: 即使具有任何程度的灵活性，航空路线网络仍然不足以支持当前的通用空中交通管理系统 (UTM) 和基于无人机云的系统 (图 7)。航空路线与 UTM 之间的关系就像道路与地面交通管理之间的关系 (图 8)。

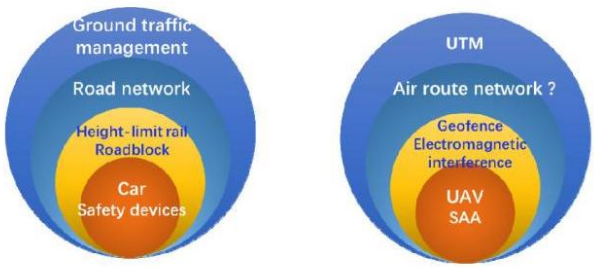

FIGURE 8. Comparison between safety management of vehicles and UAVs.
图 8. 车辆与无人机的安全管理比较。

To ensure vehicle safety, although vehicles are equipped with many types of safety devices, the road network, with height-limit rails and roadblocks, is still necessary for the ground traffic management. Similarly, although some measures, such as geofences and electromagnetic interference, are conducted for UAVs equipped with "Detect and Avoid (DAA)" devices, an air route network with certain degree of flexibility where possible is still necessary for UTM. Therefore, to manage UAV traffic and avoid obstacles accurately and efficiently, some countries and districts have been explored the construction of relatively fixed UAV air routes over cities based on fine digital elevation maps, thus providing the basis for long-distance transport UAV flight evaluations for management agencies.

为了确保车辆安全，尽管车辆配备了多种安全设备，但是带有高度限制栏杆和路障的道路网络对于地面交通管理仍然是必要的。同样，尽管为配备了“检测与避让 (DAA)”设备的无人机采取了一些措施，例如地理围栏和电磁干扰，但具有一定灵活性的航空路线网络对于 UTM 仍然是必要的。因此，为了准确高效地管理无人机交通并避开障碍物，一些国家和区域已经探索在城市上方基于精细数字高程地图建立相对固定的无人机航空路线，从而为管理部门进行远程运输无人机飞行评估提供了基础。

IV. SAFE AND EFFICIENT FLYING ENABLED: DEVELOPMENT OF LOW-ALTITUDE PUBLIC AIR ROUTES FOR UAVS

IV. 实现安全高效飞行: 为无人机开发低空公共航线。

The exclusive low-altitude flight path of UAVs - the ”UAV low-altitude public air route network” - is not only able to ensure the separation of civil aviation and navigation from UAVs but can also provide a solution to safe UAV low-altitude flights. Further, the support of technologies, such as precise navigation and positioning technology, remote sensing and dynamic updating of complex surface information, and ground mobile communication, etc., makes it possible to accurately control the UAVs in the air route. Among all, data and technology from UAV remote sensing is vital in the construction of the digital air routes across or over things like concrete buildings blocks. Therefore, this research direction is becoming a leading hot spot of UAV application research worldwide. At present, studies on UAV low-altitude air routes could be classified into the following two levels: one is from the theory and key technologies research to practical applications, with scientific research institutions as the research object; the other is from the application practice of pilot demonstrations to the relatively fixed industrial application route, with civil aviation, the UAV industry and enterprises as the main participants.

无人机的专属低空飞行路径 - ” 无人机低空公共航线网络” - 不仅能够确保民用航空与无人机导航的分离，还能为安全无人机低空飞行提供解决方案。进一步地，技术的支持，如精确导航与定位技术、遥感以及复杂地表信息的动态更新，以及地面移动通信等，使得在航线中准确控制无人机成为可能。其中，来自无人机遥感的资料和技术在构建跨越或覆盖混凝土建筑块等物体的数字航线中至关重要。因此，这一研究方向正成为全球无人机应用研究的热点。目前，对无人机低空航线的研究可以分为以下两个层次: 一是从理论与关键技术研究到实际应用，以科研机构为研究对象；二是从试点示范的应用实践到相对固定的工业应用路径，以民航、无人机行业和企业为主要参与者。

A. THEORETICAL SYSTEM OF THE LOW-ALTITUDE AIR ROUTES

A. 低空航线的理论体系

Teams from China and Singapore were the first to propose and make fast progress in constructing theoretical systems of UAV low-altitude air routes. The former focuses on constructing air routes by geographic information and remote sensing technology, and the latter is progressing rapidly in the construction of routes within a densely populated city. Specifically, Liao et al. [36] from China first proposed a relatively complete route construction process in 2017, and successfully applied it to experiments of national route planning and local route planning in the Beijing-Tianjin-Hebei district; they then developed a detailed technical design funded by the National Natural Science Foundation of China (NSFC) and cooperated with the CAAC to plan a low-altitude logistics air route of UAVs in the demonstration area of Hangzhou in 2019; specifically, they developed the initial system for planning the low-altitude public air route [47]. Low K. H. et al. [48] from Singapore proposed the novel concept of building a route system over cities in 2014 and improved it in 2017 [49]. In the past four years, they have explored key technologies and formed an overall concept. The key technologies include UAV take-off and landing [50], [51], autonomous formation flying [52], visual servo [53]-[55], automatic capture [56] and others supporting UAV transportation, and core algorithms, such as risk assessment and dynamic path-planning [57], [58]; the overall designs include UAV operational management [59] and urban airspace management [14], [60].

来自中国和新加坡的团队最先提出并迅速推进了无人机低空航线理论体系的构建。前者专注于利用地理信息和遥感技术构建航线，而后者在人口密集城市的航线构建方面进展迅速。具体来说，中国的廖等人 [36] 在 2017 年首次提出了相对完整的航线构建过程，并成功将其应用于北京-天津-河北地区的国家航线规划和地方航线规划实验；随后，他们在国家自然科学基金委 (NSFC) 的资助下，与民航局合作，于 2019 年在杭州示范区规划了一条无人机低空物流航线；具体而言，他们开发了规划低空公共航线的初始系统 [47]。来自新加坡的 Low K. H. 等人 [48] 在 2014 年提出了在城市上方构建航线系统的创新概念，并在 2017 年 [49] 进行了改进。在过去四年中，他们探索了关键技术并形成了整体概念。这些关键技术包括无人机的起飞和降落 [50]，[51]，自主编队飞行 [52]，视觉伺服 [53]-[55]，自动捕捉 [56] 等支持无人机运输的技术，以及风险评估和动态路径规划 [57]，[58] 等核心算法；整体设计包括无人机运行管理 [59] 和城市空域管理 [14]，[60]。

In addition, due to the multidisciplinary characteristics of UAV low-altitude air routes, such as aviation, transportation, geographic information and remote sensing technology, many researchers explored it from different professional perspectives, as follows:

此外，由于无人机低空航线具有多学科特性，如航空、交通、地理信息和遥感技术等，许多研究者从不同的专业角度进行了探索:

UAV activities in urban areas are challenging due to the various interferences from radio link communications in complicated ground environment. With the rapid development of cellular mobile network technologies, the study of network-connected UAVs has become a hot topic for research. Standards agencies are currently exploring the possibility of providing cellular network services for commercial UAVs. The industry is beginning to explore early prototypes of flight base stations on user equipment, and academic researchers are working on solving key algorithms for UAV flights in cellular networks, such as the base station layout [61]. Specifically, the Third Generation Partnership Project (3GPP) defined a study item in March 2017 to investigate UAV traffic requirements, build channel models for air-to-ground propagation characteristics, assess the capabilities of the existing Long-Term Evolution (LTE) infrastructure to serve aeronautical equipment, and define required enhancements. It is concluded that the existing LTE cellular operators can provide services for UAVs on the basis of the existing infrastructure under the premise of limited airborne equipment and no heavy load on the network [62]. Companies such as Huawei launched the "Digital Sky Initiative" project and joined forces with mobile operators to create an end-to-end ecosystem in Shanghai, China to test the possibility of Communication and Command (C2) links between cellular network service UAVs and ground control stations [63]. Additionally, Huawei has proposed effective measures, such as optimizing antenna distribution, controlling upstream and downstream power, automatic elimination of interference by artificial intelligence technology, coordinating multi-base stations, and adding stations, to ensure the quality of cellular communication for the area under extreme conditions, such as signal interference and weak coverage on the basis of 4 G communication coverage test results and 5G technology [11]. The TLC operator has been invited to the DRNet project for the measurement and assessment of the 4G, 4G+ and the next 5G mobile radio network to provide Quality of Service (QoS) for connected UAVs [64]. Academics such as Khuwaja et al. [65] summarized the channel models of most UAV communications, and Yang et al. [66] constructed a res-onable UAV path loss communication model based on urban environmental measurement data. Zhou et al. [67] explored the relationships between the coverage of urban low-altitude cellular mobile communications and UAV height and track index and UAV density; further, the optimal height for UAV flights was obtained.

城市区域中的无人机活动因复杂地面环境中各种无线电链路通信的干扰而具有挑战性。随着蜂窝移动网络技术的快速发展，网络连接的无人机研究已成为研究的热点。标准机构目前正在探索为商业无人机提供蜂窝网络服务的可能性。业界开始探索在用户设备上飞行基站的原型，学术研究人员正在研究无人机在蜂窝网络中飞行的关键算法，如基站布局 [61]。具体来说，第三代合作伙伴计划 (3GPP) 于 2017 年 3 月定义了一项研究项目，以调查无人机流量需求，建立用于空对地传播特性的信道模型，评估现有长期演进 (LTE) 基础设施为航空设备服务的能力，并定义所需的改进。得出的结论是，现有的 LTE 蜂窝运营商可以在有限的机上设备和网络不过载的前提下，基于现有基础设施为无人机提供服务 [62]。华为等公司启动了“数字天空倡议”项目，并与移动运营商合作，在中国上海创建了一个端到端的生态系统，以测试蜂窝网络服务无人机与地面控制站之间的通信指挥 (C2) 链路的可能性 [63]。此外，华为提出了有效措施，如优化天线分布、控制上下行功率、通过人工智能技术自动消除干扰、协调多个基站和增加站点，以确保在极端条件下，如信号干扰和弱覆盖区域，基于 4 G 通信覆盖测试结果和 5G 技术，为该区域提供蜂窝通信质量 [11]。TLC 运营商已被邀请参与 DRNet 项目，以测量和评估 4G, 4G+ 以及下一代 5G 移动无线电网络，为连接的无人机提供服务质量 (QoS) [64]。像 Khuwaja 等人 [65] 总结了大多数无人机通信的信道模型，而杨等人 [66] 则基于城市环境测量数据构建了一个合理的无人机路径损耗通信模型。周等人 [67] 探讨了城市低空蜂窝移动通信覆盖与无人机高度和轨迹指数以及无人机密度之间的关系；进一步获得了无人机飞行的最佳高度。

With the increasing number of UAVs, the conflict between the limited low-altitude airspace resources and the unlimited UAV activities will become increasingly prominent. Therefore, one of the research hotspots is to divide the urban airspace in advance and evaluate its capacity. Bai et al. [68] proposed planning rules for the UAV channels over cities based on the actual situation of buildings and residents from the perspective of airspace resources utilization and the contradiction between the space and surface. Kwon et al. [69] defined the flight airspace levels of UAVs at different heights by classifying the building height levels and then formed a UAV airspace map over the city in Yeonpyeong, Seoul. Bulusu et al. [70] evaluated the capacity performance of urban low-altitude airspace based on throughput and other indicators; Bahabry et al. [71] provided a layout for UAV charging piles in cities and researched the collision-free navigation of UAVs.

随着无人机数量的增加，有限的低空空域资源与无限的无人机活动之间的冲突将日益突出。因此，研

究热点之一是预先划分城市空域并评估其容量。白等人 [68] 从空域资源利用和空间与地表矛盾的角度出发，提出了基于建筑物和居民实际情况的城市上空无人机通道规划规则。权等人 [69] 通过对建筑物高度级别进行分类，定义了不同高度的无人机飞行空域层级，然后在首尔延平形成了城市上空的无人机空域图。Bulusu 等人 [70] 基于吞吐量等指标评估了城市低空空域的容量性能；Bahabry 等人 [71] 提供了城市中无人机充电桩的布局，并研究了无人机的碰撞自由导航。

In the construction of a UAV air route network over cities, the Air Traffic Management Research Institute proposed a homogeneous and exhaustive route network based on Air-Matri which consists of many air blocks. It determines the airspace performance by evaluating the C2 link coverage, GPS coverage, flight risk, security measures, etc., and forms a network by connecting the conflict-free nodes and links after first checking whether the nodes and links conflict with the city's infrastructure (mainly buildings). Essentially, the network is obtained by a exhaustive technology, including all urban airspace except the airspace occupied by urban infrastructures. Salleh et al. [14] proposed an air route network over buildings or urban roads. In this method, air route nodes are set above buildings or roads, and all the nodes above buildings are built to generate the air route network, or all air route nodes are placed at a certain height above roads, so that the air route follows the road contour.

在城市上空构建无人机航线网络时，空中交通管理研究所提出了一种基于 Air-Matri 的同质且详尽的航线网络，该网络由许多空气区块组成。它通过评估 C2 链接覆盖率、GPS 覆盖率、飞行风险、安全措施等来确定空域性能，并在首先检查节点和链接是否与城市基础设施 (主要是建筑物) 冲突之后，通过连接无冲突节点和链接来形成一个网络。本质上，该网络是通过详尽技术获得的，包含了除城市基础设施占用的空域之外的所有城市空域。Salleh 等人 [14] 提出了在建筑物或城市道路上方的航线网络。在这种方法中，将航线节点设置在建筑物或道路上方，并构建所有建筑物上方的节点以生成航线网络，或者将所有航线节点放置在道路上方的一定高度，使航线沿着道路轮廓行进。

In addition, Feng et al. provided a more in-depth study of the UAV air route by using a series of key technologies, such as extracting the digital terrain from a LiDAR-based system [72]; further, the automatic construction of air corridor based on laser point cloud data was performed and visualized [73], and a low-altitude airspace warning map [74] and a management platform [75] were generated. Primat-esta et al. focused on calculating the population risk [76], planning population-risk-based flight path [77], and constructing a real-time risk-aware system based on multi-risk layers [78].

此外，冯等人对无人机航线进行了更深入的研究，使用了一系列关键技术，如从基于 LiDAR 的系统中提取数字地形 [72]；进一步地，基于激光点云数据自动构建了空走廊并进行可视化 [73]，并生成了低空空域预警图 [74] 和管理平台 [75]。Primat-esta 等人专注于计算人口风险 [76]，规划基于人口风险的飞行路径 [77]，并构建了基于多风险层的实时风险感知系统 [78]。

B. GEO-INFORMATION AND LOW-ALTITUDE AIR ROUTES

B. 地理信息与低空航线

Section II mentioned the concept of the geofence and the extensive flight negative constraints set, which affect low-flying UAVs. In fact, the surface also conducts and contributes to UAV flights and related factors are named as the "positive constraints set". The positive constraint set refers to objects where UAVs must go or are suggested to go and is essentially the Minimum Accidental Damage to Ground (MADG) zone provided by the planning department. It includes the ground mobile communication infrastructure, ground road network and service facilities, such as refueling/gas stations along the road, urban green land and waters, etc. The above constraints all belong to the category of surface geographic information. Geographic information has been concluded to be indispensable in air route planning. Reasonable utilization of geographic information not only helps UAVs to avoid adverse factors but also makes full use of the existing ground infrastructure.

第二节提到了地理围栏的概念和设置的广泛飞行负约束，这些约束影响着低飞行的无人机。实际上，地表也进行导电并对无人机飞行做出贡献，相关的因素被命名为“正约束集”。正约束集指的是无人机必须前往或建议前往的对象，本质上是由规划部门提供的最小地面意外损害区域 (MADG)。它包括地面移动通信基础设施、地面道路网络和服务设施，如沿途的加油/燃气站、城市绿地和水域等。上述约束都属于地表地理信息的范畴。地理信息已被确定在航线规划中不可或缺。合理利用地理信息不仅帮助无人机避开不利因素，也充分利用了现有的地面基础设施。

However, from the perspective of the current development of UAV obstacle avoidance technology, UAVs cannot completely avoid or make full use of the geographic information at flight time. Therefore, it is necessary to pre-construct a path planning environment.

然而，从当前无人机避障技术的发展角度来看，无人机在飞行时无法完全避开或充分利用地理信息。因此，有必要预先构建路径规划环境。

Due to the difficulty in obtaining high-precision ground geographic data, as well as incomplete geographical elements, a simulated ground environment is mostly considered when constructing air routes at present. This paper, by examining approximately 360 articles related to UAV path searching indexed in Web of Science over the past 15 years, concluded the following: 8.6% of the articles considered the atmospheric environmental impact, such as wind speed; approximately 11.9% of the papers considered the terrain; 7.5% considered radar electromagnetic interference, such as communication; only 1.7% considered no-fly zones; and 0.3% involved mobile coverage (Fig. 9). El-Sallabi [79] used ground pylons to contribute to UAV communication in the case of losing the GPS signal. The current research mainly focuses on natural constraints and is inadequate in regulations, such as geofence regulations, and rarely considers UAV communication.

由于获取高精度地面地理数据的难度，以及地理元素的不完整，目前在构建航线时大多考虑模拟地面环境。本文通过审查过去 15 年间 Web of Science 索引的大约 360 篇与无人机路径搜索相关的文章，得出以下结论: 8.6% 的文章考虑了大气环境的影响，如风速；大约 11.9% 的论文考虑了地形；7.5% 考虑了雷达电磁干扰，如通信；只有 1.7% 考虑了禁飞区；而 0.3% 涉及了移动覆盖 (图 9)。El-Sallabi [79] 在 GPS 信号丢失的情况下，使用地面塔架来协助无人机通信。当前研究主要关注自然约束，而在规定方面，如地理围栏规定，存在不足，并且很少考虑无人机的通信。

A large amount of geographic data in various types and different scales is necessary to construct a planning environment for UAV air routes. Therefore, how to efficiently and flexibly store and present geographic data is urgent to be considered. According to the investigation, the air route planning environment can be constructed using visibility graph [80], Voronoi diagram [81], [82], probabilistic [83] and cell decomposition [84] methods. The visibility graph method formed routes from a connectivity graph network of a non-directed graph. Only polygonal obstacles are considered and only vertices that are visible in the sense that each vertex can be seen from the other are included. A Voronoi diagram is a connectivity graph generated by forming polygons around obstacles. Probabilistic methods work by a random selection of neighborhood points that meet some metric (e.g. the shortest length) resulting in a probabilistic random road map (PRR). The cell decomposition method divides the environment into non-overlapping grids and generates possible routes by connecting adjacent free grids, which means that the grid is not occupied by obstacles. Obstacles are simply divided in this method and is thus convenient for organization and storage. It is in line with the high-dynamic updating requirements and rapid expansion characteristics of geographic information. Therefore, the cell decomposition method is often used to construct the planning environment. For example, Filippis et al. [85] constructed a gridding terrain of obstacles and urban environments and established a three-dimensional environment matrix for subsequent computation. The vertical and horizontal spacing of grids is fixed by the resolution of Digital Elevation Model (DEM) data; the resolution along the third dimension is decided by the vertical speed of the UAV. The obstacles are represented as parallelepipeds or cubes, which is very simple and is useful in reproducing the characteristics of cluttered environments to test the path-searching algorithm. However, there is a problem: for any one grid cell in the computing framework, whether important or not, the resource-intensity and expressions are the same. This problem may not only lead to greater computing resource waste but also may lead to ignorance of important qualitative-change points in the process of geoscience due to the average effect. To reduce memory utilization, Kambhampari and Davis [86] proposed the quadtree and octree representation methods. To reduce the loss of feature points, Pei et al. [87] proposed a spatiotemporal point process model, which refers to a geoscience data processing and calculation model based on the event unit. It abstracts research objects into discrete spatiotemporal point sets.

构建无人机航线规划环境需要大量各种类型和不同比例尺的地理数据。因此，如何高效灵活地存储和呈现地理数据是迫切需要考虑的问题。根据调查，航线规划环境可以使用可见性图 [80]、Voronoi 图 [81]、[82]、概率方法 [83] 和单元分解 [84] 等方法构建。可见性图方法从无向图的连通图网络中形成路由。仅考虑多边形障碍物，并且只包括在视觉上可见的顶点，即每个顶点可以从其他顶点看到。Voronoi 图是由围绕障碍物形成多边形而生成的连通图。概率方法通过随机选择满足某些度量 (例如最短长度) 的邻域点来工作，从而形成概率随机路线图 (PRR)。单元分解方法将环境划分为非重叠网格，并通过连接相邻的空闲网格来生成可能的路线，这意味着网格没有被障碍物占据。这种方法简单地将障碍物划分，因此便于组织和存储。它符合地理信息高动态更新要求和快速扩展的特点。因此，单元分解方法常用于构建规划环境。例如，Filippis 等人 [85] 构建了障碍物和城市环境的网格化地形，并为后续计算建立了一个三维环境矩阵。网格的垂直和水平间距由数字高程模型 (DEM) 数据的分辨率固定；第三维的分辨率由无人机的垂直速度决定。障碍物表示为平行六面体或立方体，这非常简单，并且在复制杂乱环境特征以测试路径搜索算法时很有用。然而，存在一个问题: 在计算框架中的任何一个网格单元，无论其重要与否，资源

密集度和表达式都是相同的。这个问题可能导致计算资源浪费更大，也可能由于平均效应而在地学过程中的重要质变点被忽视。为了减少内存利用率，Kambhampari 和 Davis [86] 提出了四叉树和八叉树表示方法。为了减少特征点的损失，Pei 等人 [87] 提出了一个基于事件单元的地学数据处理和计算模型，即时空点过程模型。它将研究对象抽象为离散的时空点集。

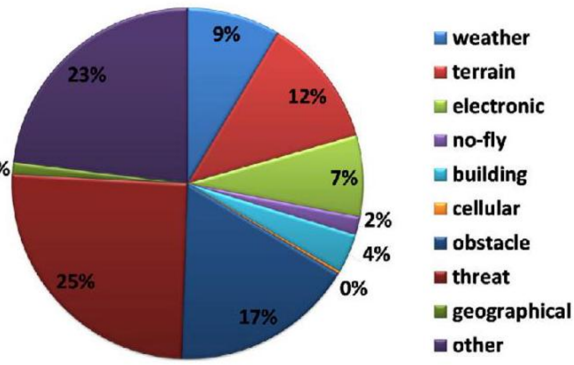

FIGURE 9. Reference statistics of flight constraints for UAVs.
图 9. 无人机飞行约束的参考统计数据。

C.UAV REMOTE SENSING AND LOW-ALTITUDE AIR ROUTE

C. 无人机远程遥感与低空航线

As mentioned above, geographical constraints have a great impact on the low-altitude air routes, especially ground obstacles such as terrain, high-rise buildings, power lines (poles) and wind power facilities, as well as favorable geographical elements such as green land and waters. However, there are so many flight constraints with different scales, short update cycles, and a wide range of areas, that cannot be obtained or updated in time by only surface observation instruments or manpower. Remote sensing images, which contain a large amount of information on the spectrum, texture and shape of the ground objects, is an effective and convenient measure to obtain geographical information in a large area. Especially, UAV remote sensing, characterized by high flexibility, unlimited time, and high observation accuracy, has been increasingly applied to extract features recently [88]. Therefore, the acquisition of UAV remote sensing data and accurate extraction of key ground object information are important prerequisites for the construction of low-altitude air routes.

如上所述，地理约束对低空航线有着重大影响，尤其是地面障碍物，如地形、高层建筑、电力线路 (电杆) 和风力发电设施，以及有利于航线的地理要素，如绿地和水域。然而，存在许多不同规模、更新周期短、范围广泛的飞行约束，这些约束无法仅通过地面观测仪器或人力及时获取或更新。遥感图像包含了地面物体在光谱、纹理和形状上的大量信息，是一种有效且方便的大范围获取地理信息的措施。特别是无人机遥感，以其高灵活性、无时间限制和高观测精度等特点，近年来在特征提取方面得到了越来越广泛的应用。因此，获取无人机遥感数据并准确提取关键地面物体信息，是构建低空航线的重要前提条件。

Due to the different requirements for geographic elements, accuracy at different levels of routes, as well as, the different spectrum and morphology features of different objects, the UAV remote sensing observation systems used to obtain different geographic elements are different. For small areas, multi-rotor UAV platforms equipped with tilt cameras [89], [90] enable UAV remote sensing observation systems to obtain three-dimensional tilt images. For large areas, such as China Southern Power Grid (CSPG) [91], helicopters equipped with LiDAR obtain laser point cloud data in order to build three-dimensional images of the power corridor. Then subsequent image quality checking, pre-processing (geometric correction and geo-coding, etc.), checking of three-dimensional encryption, image stitching and other pre-processing mechanism are used to extract information. In addition, some researchers proposed a UAV remote sensing networking observation technology to realize the simultaneous acquisition of multi-source and multi-scale remote sensing data in order to improve the efficiency of UAV remote sensing data acquisition in a large area [92].

由于不同地理要素对地理位置元素的要求不同，不同路线级别的精度要求不同，以及不同对象的不同频谱和形态特征，用于获取不同地理要素的无人机遥感观测系统也有所不同。对于小区域，配备倾斜相机 [89]、[90] 的多旋翼无人机平台能够使无人机遥感观测系统获得三维倾斜图像。对于大区域，如中国南

方电网 (CSPG)[91]，配备激光雷达的直升机获取激光点云数据，以构建电力走廊的三维图像。然后通过后续的图像质量检查、预处理 (几何校正和地理编码等)、三维加密检查、图像拼接等预处理机制来提取信息。此外，一些研究者提出了无人机遥感网络观测技术，以实现多源、多尺度遥感数据的同步获取，从而提高大区域无人机遥感数据采集的效率 [92]。

Current research on information extraction from UAV remote sensing images is mostly about single element feature extractions, such as road detection [93] and buildings identification [94]. In order to improve the accuracy of feature extraction, some researchers use auxiliary information to achieve better results, such as Zhang. et al. in extracting road intersections based on geometric and attribute information of road intersections in vector maps [95]. In the actual extraction process, multi-source, multi-scale UAV remote sensing data can be used as typical constraint elements to establish a UAV remote sensing standard database to increase the amount of information in remote sensing images, as well, multi-index information can be used to classify features and improve recognition accuracy.

当前关于无人机遥感图像信息提取的研究 mostly 是关于单一要素特征提取，例如道路检测 [93] 和建筑物识别 [94]。为了提高特征提取的准确性，一些研究者使用辅助信息以获得更好的结果，如张等人在基于矢量地图中道路交叉口的几何和属性信息提取道路交叉口 [95]。在实际提取过程中，多源、多尺度的无人机遥感数据可以作为典型的约束要素，建立无人机遥感标准数据库，以增加遥感图像中的信息量，同时，可以使用多指标信息对特征进行分类，提高识别精度。

D. PATH SEARCHING ALGORITHM

D. 路径搜索算法

The global paths are planned firstly using path-searching algorithms in a preconstructed geographic information environment and local paths are corrected or re-planed based on the precise features extraction from remote sensing images automatically or semi-automatically. In nature, path optimization is a multimodal problem. Bionic intelligent algorithms have advantages in solving multimodal problems and can plan paths in various complex environments consisting of unstructured geographic constraints and dynamic constraints that are difficult to deal with in an approximate manner. Therefore, a bionic intelligent optimization algorithm is adopted in global path planning. However, it is necessary to integrate bionic intelligent algorithms with other local path planning algorithms for fast path planning in local dynamic programming to avoid the problems associated with slow planning.

全球路径首先在预先构建的地理信息环境中使用路径搜索算法进行规划，局部路径则基于从遥感图像中自动或半自动提取的精确特征进行校正或重新规划。在自然界中，路径优化是一个多模态问题。仿生智能算法在解决多模态问题方面具有优势，并且能够在由非结构化地理约束和难以用近似方法处理的动态约束组成的各种复杂环境中规划路径。因此，在全局路径规划中采用了仿生智能优化算法。然而，为了在局部动态规划中实现快速路径规划，有必要将仿生智能算法与其他局部路径规划算法相结合，以避免与缓慢规划相关的问题。

There are many bionic intelligent algorithms for path searching in complex environments, among which, the Ant Colony Optimization (ACO) algorithm has great advantages in multi-objective planning, parallel computing and scalabil-ity. This algorithm was first proposed by Dorigo [96], [97] in 1992, and it not only successfully and efficiently solved the problem of travel agents [98] but has also been used by many scholars in UAV path-planning studies. However, there are some problems, such as slow convergence speed and a high probability of falling into local minima. Some researchers have improved the algorithm using pheromone updates, state transition rules and integration with other algorithms. In terms of the pheromone update, Lin [99] proposed a dynamic adaptive selection strategy for waypoints and a dynamic adaptive adjustment criterion to effectively overcome information volatiles. Talbi [100] and Stutzle [101] used the Tabu Search algorithm to improve the secondary allocation of ants. In the Elite Strategy Ant Colony System [102], the global optimal path is weighted and the ants passing through these paths are recorded as ”Elitist” to improve their selection probability. Similarly, there is a rank-based AS [103] on the path length. In terms of state transition rules, the distance heuristic factor [104] and angle factor [105] can be improved to take the path length and path direction as the search guidance signals, respectively, to realize fast convergence. In addition, the ACO algorithm is easy to combine with other heuristic algorithms due to its excellent distributed computing ability. The most common method is using crossover and mutation of the Genetic Algorithm (GA) to obtain new varieties to enrich the ants’ diversity [106].In addition, the Artificial Potential Field (APF) is used as prior knowledge to reduce the blindness of the initial path search [107]. Other algorithms include the Particle Swarm Optimization (PSO) algorithm [108], Simulated Annealing (SA) algorithm [109] and Artificial Fish Swarm (AFS) algorithm [110]. The integration of ACO and other algorithms have made great progress in the study of this algorithm, both in breadth and depth, and its application range is also expanding. There is a broad prospect of the comprehensive application of ACO and other algorithms.

在复杂环境中的路径搜索有许多仿生智能算法，其中，蚁群优化 (ACO) 算法在多目标规划、并行计算和可扩展性方面具有很大优势。该算法最初由 Dorigo [96]、[97] 于 1992 年提出，它不仅成功且高效地解决了旅行代理问题 [98]，还被许多学者应用于无人机路径规划研究。然而，该算法存在一些问题，如收敛速度慢和高概率陷入局部最小值。一些研究者通过信息素更新、状态转移规则以及与其他算法的融合来改进算法。在信息素更新方面，Lin [99] 提出了针对航点的动态自适应选择策略和动态自适应调整准则，以有效克服信息素的挥发性。Talbi [100] 和 Stutzle [101] 使用禁忌搜索算法改进了蚂蚁的二次分配。在精英策略蚁群系统 [102] 中，全局最优路径被加权，经过这些路径的蚂蚁被记录为“精英”，以提高它们的选取概率。同样，基于路径长度的排名策略蚁群算法 [103]。在状态转移规则方面，距离启发式因子 [104] 和角度因子 [105] 可以被改进，分别以路径长度和路径方向作为搜索引导信号，实现快速收敛。此外，由于 ACO 算法卓越的分布式计算能力，它易于与其他启发式算法结合。最常见的方法是使用遗传算法 (GA) 的交叉和变异来获得新的品种，以丰富蚂蚁的多样性 [106]。此外，将人工势场 (APF) 作为先验知识，以减少初始路径搜索的盲目性 [107]。其他算法包括粒子群优化 (PSO) 算法 [108]、模拟退火 (SA) 算法 [109] 和人工鱼群 (AFS) 算法 [110]。ACO 与其他算法的结合在研究的广度和深度上均取得了巨大进展，其应用范围也在不断扩大。ACO 与其他算法的综合性应用具有广阔的前景。

Local dynamic three-dimensional path planning requires high efficiency. Tarokh [111] proposed a two-stage genetic planning method to coordinate the discrepancy between global and local planning. That is, global planning is conducted first by inputting the sensory information from planners and then conducting online preplanning once a previously unknown or unencountered obstacle is detected. Dong et al. [112] proposed a new fuzzy virtual force method with a fixed step size to meet the online real-time requirements. Kermani and Afzalian [113] proposed an online path method based on GA, which meets the objectives of minimum distance, no collisions, maximum communication convergence and support of some no-fly zones. Wang et al. [114] proposed a collaborative method combining static and dynamic path planning by improving the PSO algorithm. Bruijnen et al. [115] compared and analyzed a variety of real-time path planning algorithms and found that the APF method has low computation requirements and good real-time performance of several milliseconds. The APF algorithm, introduced in 1986 by Khatib, compares the motion environment of UAVs to an artificial force field. UAVs reach the target point on the premise of avoiding obstacles under the common function of obstacle repulsion and target point gravity. Because of the simple model, the small calculation amount and good real-time performance, this method has been widely used for real-time obstacle avoidance [116]-[119]. However, the algorithm may fall into a local minimum so that UAVs may wander around the repulsive field and may not find the path to the target point. To solve this problem, Zhen et. al. [120] improved the APF by applying chaos theory to the function formulas of the repulsive force field and gravitational field. This algorithm changed the repulsive force coefficient of obstacles and the gravity coefficient of the target and decreased the calculation time by 46% . Tian et al. [121] introduced velocity vectors for the relative positions of the target and obstacles in the gravitational and repulsion field functions, respectively, integrated the dynamic change information of positions, and introduced proportional adjustment factors, such as relative position gravity, relative velocity gravity, relative position repulsion and relative velocity repulsion. This improved algorithm, a shorter path than traditional one can be resulted in a shorter path than traditionally obtained and, as well, moving obstacles can be avoided more efficiently and at a higher speed. Mac et al. [122] introduced the relative distance between the UAV and the target into the repulsive force formula and took the speed of the UAV into account. The results in the simulated and real environments indicated that the improved algorithm could contribute to helping UAVs to avoid obstacles quickly and safely.

局部动态三维路径规划需要高效率。Tarokh [111] 提出了一种两阶段遗传规划方法，以协调全局和局部规划之间的差异。即，首先通过输入规划器的感知信息进行全局规划，然后在检测到先前未知或未遇到的障碍物时进行在线预规划。Dong 等人 [112] 提出了一种新的固定步长的模糊虚拟力方法，以满足在线实时要求。Kermani 和 Afzalian [113] 提出了一种基于 GA 的在线路径方法，该方法满足最小距离、无碰撞、最大通信收敛以及支持某些禁飞区的目标。Wang 等人 [114] 提出了一种通过改进 PSO 算法结合静态和动态路径规划的合作方法。Bruijnen 等人 [115] 比较和分析了许多实时路径规划算法，发现 APF 方法具有低计算要求，并且具有数毫秒的良好实时性能。APF 算法由 Khatib 在 1986 年提出，将无人机的运动环境比作一个人工力场。在障碍物排斥和目标点引力的共同作用下，无人机避开障碍物到达目标点。由于模型简单、计算量小和良好的实时性能，这种方法已被广泛应用于实时避障 [116]-[119]。然而，算法可能会陷入局部最小值，导致无人机在排斥场周围徘徊，可能找不到通往目标点的路径。为了解决这个问题，Zhen 等人 [120] 通过将混沌理论应用于排斥力场和引力场的函数公式，改进了 APF。该算法改变了障碍物的排斥力系数和目标的引力系数，并通过 46% 减少了计算时间。Tian 等人 [121] 分别在引力和排斥场函数中引入了目标和障碍物相对位置的速度向量，整合了位置的动态变化信息，并引入了比

例调整因素，如相对位置引力、相对速度引力、相对位置排斥和相对速度排斥。这种改进的算法可以比传统算法得到更短的路径，并且可以更有效和高速地避开移动障碍物。Mac 等人 [122] 将无人机与目标之间的相对距离引入排斥力公式，并考虑了无人机的速度。模拟和真实环境的结果表明，改进的算法有助于无人机快速、安全地避开障碍物。

E. PILOT WORK PROGRESS OF THE LOW-ALTITUDE AIR ROUTE FOR UAVS

E. 无人机低空航线试点工作进展

Recently, UAV technology tests have been performed worldwide to overcome the technical challenges for the low-altitude flights of UAVs. Further, a variety of countries or districts have established seperate channels for UAVs to provide test sites, to ensure airspace safety and to avoid interference with the security of manned aircrafts and public security and privacy. Among them, the US, China and Singapore are typical representatives.

最近，全球范围内进行了无人机技术的测试，以克服无人机低空飞行面临的技术挑战。此外，许多国家或地区为无人机设立了单独的频道，提供测试场地，以确保空域安全，并避免干扰有人机安全和公共安全及隐私。其中，美国、中国和新加坡是典型的代表。

In September 2017, the US first proposed a UAV traffic management corridor and constructed an 80-kilometer long UAV flight corridor between Rome and Syracuse cities in New York state. The corridor is equipped with radar and ground sensors for low-altitude detection and tracking of small UAVs to ensure safe intervals separating them [123]. Airbus proposed ”Project Skyway” in 2017 and defined the terminal route in detail in the blueprint published in 2018. In February of the following year, the Singapore Civil Aviation Authority launched the ”Skyways” project to test the ability of UAVs to transport parcels in predefined air corridors [124].

2017 年 9 月，美国首次提出无人机交通管理走廊，并在纽约州的罗马和锡拉丘兹市之间建立了一个长 80 公里的无人机飞行走廊。该走廊配备了雷达和地面传感器，用于对小型无人机的低空探测和跟踪，以确保它们之间的安全间隔 [123]。空中客车在 2017 年提出了“Skyway 项目”，并在 2018 年发布的蓝图详细定义了终端航线。次年 2 月，新加坡民航局启动了“Skyways”项目，以测试无人机在预设空中走廊运输包裹的能力 [124]。

Benefiting from the rapid expansion and development of the global market share of innovative UAVs, such as DJI’s quadcopters, UAVs have been widely used in various industries [125]. The actual UAV pilot work in China has been conducted nationally and has been supported by CAAC in the ”Guidance on promoting the development of civilian UAVs” (Draft for Comment) [126]. This work clearly defines the construction and operation of low-altitude public air routes as one of the key tasks and objectives for civilian unmanned aircraft. It is also recognized by IEEE and was used to establish an IEEE-SA P1939.1 working group-”Standard for a Framework for Structuring Low Altitude Airspace for UAV Operation”- that was promoted by CAS, aiming to form a national standard of low-altitude operation and management [127]. China’s pilot work can be divided into the three levels of ”Point-Line-Area”. ”Point” refers to the pilot testing of UAVs in a small areas, such as the industry-led test for UAVs and the CAS-led separated airspace test in a UAV verification field, e.g., the UAV remote sensing network route test conducted in Tianjin in July 2019 [128]. ”Line” refers to the transport line, such as a long-distance logistics transportation line, short-distance express transportation line, power inspection line, etc. In November 2018, CSPG conducted an automatic high-precision patrol around towers, consisting of automatic charging and path-planning, automatic patrol, automatic defect analysis and other whole-process intelligent scene applications based on self-developed mul-tirotor autonomous UAVs [129]. ”Area” refers to the UAV transportation area, with the related demonstrations headed by SF.com [130], JD.com [131] and other Chinese logistics enterprises and mobile communication companies. In June 2017, SF.com promoted a demonstrated airspace covering five townships and conducted a normal operational test with the airspace management agency in Nankang, Ganzhou and in the eastern theater [130]; from June 2017 to present, JD.com has been continually demonstrating the normal operation of UAV logistics in Shanxi, Jiangsu and Hainan, Qinghai, Guangdong, Sichuan and other districts in order to assess UAV capabilities [131]: in January 2019, China mobile received approval for an 800 km^2 airspace for a UAV base station inspection test [132], and Xunyi.com received approval to perform UAV express deliveries over cities in Hangzhou and to jointly promote the planning and application of low-altitude logistics air routes in the demonstration zone with CAAC and CAS.

得益于创新无人机 (如大疆的 quadcopters) 在全球市场份额的快速扩张和发展，无人机已被广泛应

用于各个行业 [125]。在中国，实际的无人机飞行员工作已在全国范围内进行，并得到了民航局 (CAAC) 在《关于促进民用无人机发展的指导意见 (征求意见稿)》[126] 的支持。这项工作明确将低空公共航路的构建和运营定义为民用无人机的关键任务和目标之一。这一工作也得到了 IEEE 的认可，并被用于成立 IEEE-SA P1939.1 工作组——“无人机运行结构化低空空域框架标准”，该工作组由中国科学院 (CAS) 推动，旨在形成低空运行和管理国家标准 [127]。中国的飞行员工作可分为“点-线-面”三个层级。“点”指的是在小型区域内进行的无人机试点测试，例如行业主导的无人机测试和中国科学院主导的无人机验证场分离空域测试，例如 2019 年 7 月在天津进行的无人机遥感网络路线测试 [128]。“线”指的是运输线，例如长途物流运输线、短途快递运输线、电力巡检线等。2018 年 11 月，中国石油学会 (CSPG) 进行了围绕塔楼的自动高精度巡逻，包括基于自主研发的多旋翼自主无人机自动充电和路径规划、自动巡逻、自动缺陷分析等全流程智能场景应用 [129]。“面”指的是无人机运输区域，相关的演示由顺丰 (SF.com)[130]、京东 (JD.com)[131] 等中国物流企业和移动通信公司牵头。2017 年 6 月，顺丰 (SF.com) 推动了一个覆盖五个乡镇的示范空域，并与南康、赣州的空域管理机构以及东部战区进行了正常运行测试 [130]；从 2017 年 6 月至今，京东 (JD.com) 一直在山西、江苏、海南、青海、广东、四川等地区持续展示无人机物流的正常运行，以评估无人机的能力 [131]:2019 年 1 月，中国移动获得了进行无人机基站检查测试的 800 km^2 空域批准 [132]，迅蚁 (Xunyi.com) 获得了在杭州市进行无人机快递投送的批准，并与民航局 (CAAC) 和中国科学院共同推动示范区内低空物流航路的规划与应用。

V. DISCUSSION AND CHALLENGES

V. 讨论与挑战

The following is a comprehensive analysis of the implementation status and challenges of UAV regulation policies or technologies in various countries, as well as the open issues that need to be focused on in the future. The first part summarizes the current situation of UAV regulatory policies or technologies in various countries and analyzes the existing problems and challenges as well as possible future research trends. The second part introduces two important open research issues from the perspective of geographic information data which need to be studied in the next step.

下文是对各国无人机监管政策或技术在实施现状及挑战方面的全面分析，以及未来需要关注的开性问题。第一部分总结了各国无人机监管政策或技术的现状，并分析了存在的问题和挑战，以及可能的研究趋势。第二部分从地理信息数据的角度介绍了两个重要的开放研究问题，下一步需要对其进行研究。

A. SUMMARY AND CHALLENGES

A. 总结与挑战

This paper summarized the progress of latest policies and key technologies to ensure the safe flight of UAVs at low-altitude over cities considering three progressive and complementary means or measures - ”airspace restriction”, ”active regulation” and ”air route planning”. Restricting UAV flight by imposing a maximum height and spatial range (geofence) can distinguish civil aviation, navigation and UAV activities effectively and initially integrate UAV’s safely into the urban airspace. After constructing the UAV traffic management system, real-time monitoring and unified scheduling of tasks and time as well as reasonable allocation of airspace can be performed for networked and registered UAVs to realize active regulation of UAVs. In addition, the public air route planning for UAVs is internationally advanced and feasible based on cross-disciplinary technologies, such as RS, GIS and mobile communication. However, due to the complexity of the urban environment, privacy policy and public security, etc., operating UAVs within urban areas is still in the exploratory stage, and some problems still exist. We summarized the statutes and problems in Table 2 to achieve the optimal configuration of safe operations.

本文总结了为确保城市低空无人机安全飞行所采取的最新政策和关键技术进展，考虑了三种逐步且互补的手段或措施——“空域限制”、“主动监管”和“航线规划”。通过限制无人机飞行高度和空间范围 (地理围栏) 可以有效区分民用航空、导航和无人机活动，并初步将无人机安全地融入城市空域。构建无人机交通管理系统后，可以对联网和注册的无人机进行实时监控和任务及时间的统一调度，以及空域的合理分配，以实现无人机的主动监管。此外，基于跨学科技术 (如遥感、地理信息系统和移动通信) 的无人机公共航线规划在国际上是先进且可行的。然而，由于城市环境的复杂性、隐私政策和公共安全等问题，城市区域内的无人机运行仍处于探索阶段，仍存在一些问题。我们在表 2 中总结了法规和问题，以实现安全运行的最佳配置。

According to Table 2, the current policies or key technology studies have jointly fashioned the early form of the urban low-altitude UAV traffic management system. However, each policy or technology has its own advantage and limitation, and there are still some open issues and challenges to be solved:

根据表 2，当前的政策或关键技术研究共同塑造了城市低空无人机交通管理系统的早期形态。然而，每一项政策或技术都有其自身的优势和局限性，仍有一些开放性问题与挑战需要解决:

For the current airspace policies, the maximum flying height can effectively protect the safety of civilian aircraft. However, the height limit in some areas is too low to hinder the UAV industry development in the future when the number of UAVs is expanding rapidly. From the perspective of communication link security of UAVs, the height limit can be extended to 5 G communication coverage height (such as 500 m); The geofence can protect sensitive areas from UAVs' interference. However, some sensitive geographic data need to be kept strictly confidential. How to legally release classified data when ensuring safe flights is thus a technical issue to be considered. In addition, how to rapidly and dynamically update geographic information, while it is difficult to carry out depends on the traditional surveying and mapping means, is also one of the restrictions. The "segregated airspace" for UAVs makes their operations more efficient and safer. However, if the use of exclusive airspace cannot be adjusted dynamically and flexibly, the utilization rate of airspace may be reduced. In view of the above issues existing in the current airspace policy, some technologies can be used to solve them, which are also challenges worth researching. Firstly, a set of automatic/semi-automatic processes based on RS and GIS technology can be designed to quickly acquire and update geographic data to enrich the geofence database. Secondly, further refine airspace for UAVs and planning an optimal airspace structure. For example, Sunil et al. [133] proposed three UAV airspace structures (layer, zones and tubes) and assessed their safety and efficiency. It was found that the layer concept was the optimal airspace structure for UAV delivery. Thirdly, construct a four-dimensional gridding airspace to efficiently organize and flexibly utilize segregated airspaces by gridding and coding technology.

对于当前的空域政策，最大飞行高度可以有效保护民用航空器的安全。然而，当无人机数量迅速增长时，某些区域的高度限制过低，可能会阻碍未来无人机产业的发展。从无人机通信链路安全的角度来看，可以将高度限制扩展到 5 G 通信覆盖高度 (例如 500 m)；地理围栏可以保护敏感区域免受无人机的干扰。但是，某些敏感地理数据需要被严格保密。如何在确保安全飞行的同时合法发布分类数据，因此是一个需要考虑的技术问题。此外，如何在难以采用传统测量和绘图手段的情况下，快速动态地更新地理信息，也是其中一项限制。为无人机设置的“隔离空域”可以使它们的运行更加高效和安全。然而，如果无法动态和灵活地调整专用空域的使用，空域利用率可能会降低。鉴于当前空域政策中存在的上述问题，可以使用一些技术来解决它们，这些技术也是值得研究的挑战。首先，可以设计一套基于遥感 (RS) 和地理信息系统 (GIS) 技术的自动/半自动流程，以快速获取和更新地理数据，丰富地理围栏数据库。其次，进一步细化无人机的空域，并规划最优的空域结构。例如，Sunil 等人 [133] 提出了三种无人机空域结构 (层、区域和管道) 并评估了它们的安全性和效率。发现层概念是无人机配送的最优空域结构。第三，构建一个四维网格空域，通过网格化和编码技术有效地组织并灵活利用隔离空域。

The three factors "active regulation", identification and real-name registration can provide the basis for precisely regulating UAVs and their owners. However, until a global unified standard is formed and real-name registration is applied for all types of UAVs the above three factors alone are insufficient. The joint application of UTMs and USSs can provide real-time monitoring, unified scheduling of tasks and time, and reasonable allocation of airspace for registered and networked UAV, which is a favorable supporting technology for active regulation of UAVs. However, UAV traffic operation and management are problems to be solved due to the lack of high-precision geographic information and air route services.

三个因素“主动调控”、身份识别和实名注册可以为精准调控无人机及其所有者提供基础。然而，在形成全球统一标准并应用于所有类型的无人机实名注册之前，上述三个因素单独是不够的。UTMs 和 USSs 的联合应用可以为已注册并联网的无人机提供实时监控、任务和时间统一调度以及合理的空域分配，这是无人机主动调控的有利支撑技术。然而，由于缺乏高精度地理信息和航线服务，无人机交通运行和管理是待解决的问题。

B. OPEN ISSUES

B. 未解决的问题

Based on the above discussion, this section presents some open issues and their possible solutions or techniques. Firstly, the GIS and RS are effective means to rapidly acquire and dynamically update the geographic information which support the UAV precision regulatory. It is urgent to break through the technical bottleneck of GIS and RS technology in UAV traffic management; Secondly, in order to further refine the accessible and no-fly areas of UAVs and enhance the guidance of UAV flight activities, it is necessary to construct a set of quantifiable geofence constraints that set clearance boundaries in UAV corridors sufficient to achieve practical, safe low-altitude air routes. This method is to expend and deepen the research of airspace policy (especially geofence). These are discussing in the following.

基于上述讨论，本节提出了某些开放性问题及其可能的解决方案或技术。首先，GIS 和 RS 是快速获取和动态更新支持无人机精准调控的地理信息的有效手段。迫切需要突破 GIS 和 RS 技术在无人机交通管理中的技术瓶颈；其次，为了进一步细化无人机可飞行和禁飞区域，增强对无人机飞行活动的指导，有必要构建一套量化的地理围栏约束，为无人机走廊设置足够的 clearance boundaries 以实现实用、安全的低空航线。这种方法是扩展和深化空域政策 (特别是地理围栏) 研究。以下将讨论这些内容。

TABLE 2. Problems and future direction of current policies and management technologies for low-altitude UAV flying.

表 2. 当前低空无人机飞行政策和管理工作技术的問題及未来方向。

Types	Method/ Measurement	Summary	Countries or districts	Advantages	Limitation	Challenges
Airspace restriction	The maximum flying height	Majority of limits are below 150 m .	Almost all countries with published UAV policies have specified the maximum flying height of UAV.	It seperates UAV activities from civil aviation activities to protect civil aviation flights from UAV interference.	In some areas, the low limited height may limit the UAV industry development in a future when the number of uses is expanding rapidly.	1) Enrich the geographic fence database by UAV RS and GIS technology; 2) Airspace should be further divided and airspace structure design should be carried out; 3)
	Geofence	Only civil airports and its special-use airspace were published for most countries or districts.	22 countries listing in Annex	It protects sensitive areas (e.g. military area) from UAV interference.	Data confidentiality and release issue; There is a difficult for data updating without the support of geographic information and fast data acquisition means	Gridding and coding technology are recommended to construct a four- dimensional geographical fence (longitude, latitude height and effective time) to facilitate efficient
	Segregated airspace	Only very few countries or	China, organization in U.S.	Segerated airpace for UAVs makes its	Without dynamical and flexible adjustment	organization and flexible utilization and release of
		industries proposed segregated airspace.		flights more safe and efficient.	measures to the segerated airspace of UAVs, it will cause airspace resources waste.	airspace resources
Active regulation	Identification Real-name registration	Three major international organizations (ISO, IEC and ITU) jointly proposed and promoted international standards. More than 30% of the UAVs sold were registered by the FAA in the US or by the CAAC in China.	U.S., JARUS in Europe, China U.S., China, U.K.	It provide basis for precisely regulating UAVs and their owners.	There is no uniform global UAV recognition standard; The promotion of real- name registration of UAVs in most countries is not enough.	Form an internationally recognized unique identification standard for UAVs; this task is urgent. Expand the scope of registration to achieve global and full-category coverage.
	UTM USS	NASA-UTM in US, U-Space in Europe, UOM in China, and uTM- UAS in Singapore. Ten UAV cloud- based systems are authorized by CAAC in China, and fourteen cloud-based systems are allowed by the FAA in the US.	U.S., Europe, China, Singapore, Korea U.S., China	It enables real-time monitoring, unified scheduling of tasks and time as well as reasonable allocation of airspace for real- name registered and networked UAVs, and realizes active control of UAVs.	The relationship between UTM and ATM is not clear; Without support of geographic information and without service of air routes.	Embed the UAV air route network. Improve geo-information support and service.
Air route planning	Low-altitude air route network	The concept of the air route is formed and the key technology is emphasized.	China, Singapore	There is currently no mature technical system.	Lacking support of geographic information	Build a safe and practical urban low-altitude air route; this is also urgent; and a system —"air route planning and simulating (ARPS)" is being developed by CAS.

类型	方法/测量	概述	国家或地区	优势	限制	挑战
空域限制	最大飞行高度	大多数限制都低于 150 m 。	几乎所有公布无人机政策的国家都规定了无人机的最大飞行高度。	它将无人机活动与民用航空活动分开，以保护民用航空飞行不受无人机干扰。	在某些区域，低限高可能会限制未来无人机数量的迅速扩张时无人机产业的发展。	1) 通过无人机遥感 (RS) 和地理信息系统 (GIS) 技术丰富地理围栏数据库；2) 应进一步划分空域并开展空域结构设计；3)
	地理围栏	大多数国家或地区仅公布了民用机场及其特殊用途空域。	附件中列出的 22 个国家	它保护敏感区域 (例如军事区域) 不受无人机干扰。	数据保密和发布问题；在没有地理信息支持和快速数据获取手段的情况下，数据更新存在困难	推荐使用网格化和编码技术构建四维地理围栏 (经度、纬度、高度和有效时间)，以便高效
	分隔空域	只有非常少数的国家或	中国、美国的组织	为无人机设置的隔离空域使其	没有动态和灵活的调整	组织以及灵活的使用和释放
		行业提出了隔离空域的建议。		飞行更加安全和高效。	对无人机的隔离空域采取的措施不当，将会导致空域资源的浪费。	空域资源
积极调控	实名制登记	三个主要的国际组织 (ISO、IEC 和 ITU) 共同提出并推广国际标准。超过 30% 的无人机销售在美国由 FAA 注册，在中国由民航局 (CAAC) 注册。	美国、欧洲的 JARUS、中国、英国。	它为精确规范无人机及其所有者提供了基础。	没有统一的全球无人机识别标准；大多数国家推广的无人机实名注册还不够。	形成国际上公认的无人机唯一识别标准；这项任务很紧迫。扩大注册范围，实现全球和全类别的覆盖。
	UTM USS	美国的 NASA-UTM、欧洲的 U-Space、中国的 UOM 以及新加坡的 uTM-UAS。中国的民航局授权了十个基于云的无人机系统，美国的 FAA 允许使用十四个基于云的系统。	美国、欧洲、中国、新加坡、韩国、美国、中国。	它能够实现对实名注册并联网的无人机的实时监控、任务和时间统一调度以及空域的合理分配，实现对无人机的主动控制。	UTM 与 ATM 之间的关系不明确；没有地理信息支持，也没有航线服务。	集成无人机航线网络，提高地理信息支持和服务的水平。
航线规划	低空航线网络	形成了航线概念并强调了关键技术。	中国、新加坡	目前还没有成熟的技术体系。	缺乏地理信息支持	建立一个安全实用的城市低空航线；这也是迫切需要的；中国科学院校正在开发一个系统——" 航线规划与模拟系统 (ARPS)"。

1) BOTTLENECK OF GEOGRAPHIC INFORMATION AND REMOTE SENSING TECHNOLOGY APPLICATION IN UAV LOW-ALTITUDE TRAFFIC IN URBAN AREAS

1) 城市地区低空无人机交通中地理信息和遥感技术应用瓶颈

Acquiring and using high-accuracy and high-resolution land surface geographic information is essential for UAV urban low-altitude flights, especially regarding the terrain, buildings and other sensitive geofencing data. At present, there are many data sharing platforms around the world that provide users with free or fee-based basic geographic information services, such as the United States Geological Survey (USGS) Global Visualization Viewer (GloVis), available for remote sensing data [134], and the National Earth System Science Data Centre [135]. For terrain, global DEM data(30m)is free to download, but payment is required to receive the higher-accuracy data. Regardless, terrain data in submeter resolution is required when UAVs are flying between mountain peaks in mountainous cities, such data is difficult to acquire from traditional satellite remote sensing. Building data are available from Digital Surface Model (DSM) data from satellite remote sensing images, such as the 15 m DSM data provided by the ZY03 satellite in China. Current geofence data are available from departments but these only include civilian airports and their special use airspace data. The other factors released only include some specific distances from sensitive regions, such as 150 m for buildings.

获取和使用高精度、高分辨率的陆地表面地理信息对于无人机城市低空飞行至关重要，特别是关于地形、建筑物以及其他敏感的地理围栏数据。目前，全球有许多数据共享平台向用户提供免费或付费的基础地理信息服务，例如美国地质调查局 (USGS) 的全球可视化查看器 (GloVis)，可用于遥感数据 [134]，以及国家地球系统科学数据中心 [135]。对于地形，全球数字高程模型 (DEM) 数据 (30 米) 可以免费下载，但获取更高精度的数据需要付费。然而，在山区城市中，当无人机在山峰之间飞行时，需要亚米级分辨率的地形数据，这类数据难以从传统的卫星遥感中获取。建筑物数据可以从卫星遥感图像的数字表面模型 (DSM) 数据中获得，例如中国 ZY03 卫星提供的 15 m DSM 数据。当前的地理围栏数据可以从相关部门获取，但这些数据仅包括民用机场及其特定使用空域的数据。其他发布的影响因素仅包括敏感区域的一些特定距离，例如 150 m 对于建筑物。

With the development of UAV platform, load, position, and communication technologies, UAV remote sensing has gradually become the main mechanism for acquiring remote sensing data at cm-level high-resolution and in reasonable time (hours-response). Both currently and in the near future, these data are necessary complement to satellite remote sensing and airborne remote sensing. Compared with traditional satellite and manned remote sensing, UAV remote sensing is characterized by fast and real-time spatial information acquisition, flexibility and high spatial resolution, and it has incomparable advantages for the acquisition and updating of national high-precision geographic information. However, due to the limitations of current UAV hardware and software, a single UAV is typically unable to meet the requirements of high-precision mapping in a large range of low vertical-height areas. Therefore, multiple UAVs need to work together to complete these necessary tasks. To meet the requirements of low-altitude flights of UAVs for large-scale and high-precision geographic information, a large-scale remote sensing observation network of light-and-small UAVs can be built in the future to realize fast and accurate remote sensing observations through effective deployment of UAVs resources [92]. A caution: compared with traditional remote sensing data, the current massive amount of remote sensing data from civilian UAVs are characterized by deficient processes: ”decentralized control”, heterogeneous multi-source, small single coverage areas, uneven quality, lack of unified spatiotemporal references, and no standardized data processing. With the increasing accumulation of UAV remote sensing data, there is great potential to realize the value-added benefit of stock data platforms. In this regard, Liao et al. proposed the development of a data carrier as a future development direction [136]. The platform will form a nationwide UAV remote sensing network through seamless docking with UAVs, dynamically acquiring high-resolution UAV remote sensing images, building a national geographic information big data system, and serving urban low-altitude UAV traffic management. In essence, a low-altitude air route library facility which primarily is a mega data repository of well-ordered, uniform, high resolution, consistent, accessible, connected and usable civilian UAV data.

随着无人机平台、载荷、位置和通信技术的发展，无人机遥感逐渐成为获取厘米级高分辨率遥感数据并在合理时间 (小时级响应) 内的主要机制。无论是现在还是不久的将来，这些数据都是卫星遥感和航空遥感的必要补充。与传统卫星和有人遥感相比，无人机遥感具有快速实时获取空间信息、灵活性和高空间分辨率的特点，对于获取和更新国家高精度地理信息具有无可比拟的优势。然而，由于当前无人机硬件和软件的限制，单个无人机通常无法满足在大范围低垂直高度区域高精度制图的要求。因此，需要多架无人机协同工作来完成这些必要任务。为了满足无人机在大规模和高精度地理信息低空飞行要求，未来可以构建大规模轻小型无人机遥感观测网络，通过有效部署无人机资源实现快速准确的遥感观测 [92]。需要注意的是，与传统遥感数据相比，当前大量民用无人机产生的遥感数据存在不足: 去中心化控制、异质多源、单次覆盖区域小、质量不均、缺乏统一时空参考以及没有标准化的数据处理。随着无人机遥感数据的不断积累，实现库存数据平台增值效益的潜力巨大。在这方面，廖等人提出了开发数据载体作为未来的发展方向 [136]。该平台将通过与无人机的无缝对接，形成全国无人机遥感网络，动态获取高分辨率无人机遥感图像，构建国家地理信息大数据系统，服务于城市低空无人机交通管理。本质上，这是一个低空航线库设施，主要是一个有序、统一、高分辨率、一致、可访问、连通且可用的民用无人机大数据存储库。

2) CONSTRUCTION A QUANTITATIVE CLEARANCE BOUNDARY SYSTEM FOR A GEOFENCE CONTAINING MOST OF THE FLIGHT CONSTRAINTS

2) 为包含大多数飞行限制的地理围栏构建一个定量的清晰边界系统

Most of the geofencing databases that are published by different countries or districts so far only have accurate clearances for airports and their ancillary special-purpose airspace areas. For other geographic elements (e.g., person and vehicles), only a vague safe distance and operational rules for UAV access to them have been published. The current geofencing policy is far from advanced enough to support the fine-grained management of UAV traffic. Due to the complex urban low-altitude environment and numerous and miscellaneous irregular ground protrusions, to help UAVs avoid dangerous or sensitive objects or areas accurately, building a quantitative and dynamic-updating system of the geofence clearance boundary that includes most natural or artificial elements greatly affecting UAV flights is urgently needed. Therefore, how to quickly and accurately extract multisource and heterogeneous geographic elements based on remote sensing images and then construct a headroom three-dimensional model based on a risk rating evaluation and the physical affected space of each element is a core problem to be solved. From the perspective of geofence elements, the database should at least include ”obstacles” that hinder the low-altitude flights of UAVs, such as high-rise buildings, power lines (or poles), wind-power generation equipment, and low-altitude areas with extreme turbulence (Annex). To provide a safe distance from constraints, it is useful to construct a three-dimensional clearance boundary model and quantify the spatial distribution of risks for each constraint, as well as to set up operational rules for each constraint. In addition, the government often sets up some temporary no-fly zones for UAVs due to some politically sensitive activities, which requires the rapid establishment of geofences. Therefore, it is necessary to extend the current three-dimension geofence to a four-dimensional geofence (longitude, latitude, altitude and time). For countries or regions that have already published access standards for geofencing data (e.g., China), a geofencing database can be constructed following the existing metadata requirements and docking with UAV cloud system requirements.

迄今为止，不同国家或地区发布的地理围栏数据库大多数仅对机场及其辅助专用空域区域有准确的清

晰度。对于其他地理要素 (例如，人员和车辆)，仅发布了模糊的安全距离和无人机进入这些区域的操作规则。当前的地理围栏政策远远未能先进到足以支持无人机交通的细致管理。由于复杂的城市低空环境和众多杂乱无章的地表凸起，为了帮助无人机准确避开危险或敏感物体或区域，迫切需要建立一个包含大多数对无人机飞行产生重大影响的自然或人工要素的定量和动态更新系统，即地理围栏清晰度边界。因此，如何基于遥感图像快速准确提取多源异质地理要素，然后根据风险评级评估和每个要素的物理影响空间构建头顶三维模型，是一个需要解决的核心问题。从地理围栏要素的角度来看，数据库至少应包括阻碍无人机低空飞行的高层建筑、“障碍物”，如电线 (或电线杆)、风力发电设备以及极端湍流低空区域 (附件)。为了提供安全距离约束，构建三维清晰度边界模型并量化每个约束的风险空间分布，以及为每个约束制定操作规则是有用的。此外，政府通常因一些政治敏感活动而设立无人机临时禁飞区，这需要快速建立地理围栏。因此，有必要将当前的地理围栏扩展到四维地理围栏 (经度、纬度、高度和时间)。对于已经发布地理围栏数据访问标准的国家或地区 (例如，中国)，可以按照现有的元数据要求构建地理围栏数据库，并与无人机云系统要求对接。

TABLE 3. The minimum safe distance between UAV and Geofence element for different countries.

表 3. 无人机与不同国家地理围栏元素之间的最小安全距离。

Countries	Geofence	Clearly-defined constraints
Australia	> 30 m of a person who is not directly associated with the operation of the Remote Pilot Aircraft (RPA) UAV.	person
Austria	> 2500 m from airport only with permission of the owner.	airport
Belgium	> 2778 m (1.5 nm) distance from airports > 50 m from buildings, persons,	person, airport. animal
	> 2 km from temporary landing points for manned aircrafts; > 5 km from national boundary lines and > 2 km form borderlines; > 1000 m form military reservation; > 200 m form party and government offices nuclear power stations; > 5000 m from radio observations; > 2000 m m thunder heads; 100 ~ 200 m from warehouses with inflammable and explosive objects, electric power facilities, petrol stations; > 1 km from buildings, tall towers, power grids, wind power; > 500 m from high-speed railway; > 200 m from mountains	airport, national boundary lines and borderlines military, party and government offices. nuclear power stations, radic satellite earth stations, thunder heads, warehouses. buildings, tal towers, power grids wind power, rail- way, et. Al.
Czech Republic	> 100 m from 3rd persons; > 150 m from congested area	Person, congested area
Croatia	> 30 m from people and structures; > 150 m from group of approach/departure zone	person, structure, airport
Germany	people, accident and disaster areas. prisons, military installations. industrial areas and power stations	person, airport and no-fly zone
Ireland	> 8 km from airport; > 150 m from assembly of people; > 150 m from person, vessel, vehicle and structure; ≥ 2 km from aircraft in flight	person, airport and structure, vehicle, vessel
Italy	> 150 m from congested area; 50 m from persons and property; > 5 km	person, airport and property, congested
Japan	> 30 m from persons or properties: Do not operate UAs over event sites where many people gather.	person, property
Latvia	> 50 m from people, property on ground; > 3 km from another aerodrome	person, airport and property
Lithuania	> 50 m from vehicles, people and buildings; > 1.8 km from airfield: 1852 (1 nm) ~ 5556 (3 nm) from obstacles	person, airport and structure, obstacles vehicle
Malta	> 150 m from congested area. infrastructure, assembly of m from vessel, vehicle, structure; > 7.5 km from aerodrome.	person, airport and structures obstacles, vehicle vessel
Netherland S	> 150 m from building-up area crowds of people, main roads; > 50 m from railway, industrial area	person, road railway, industrial area
Poland	> 5 km from airport; safe enough distance from people and property	airport
Slovenia	> 300 m above crowds; > 50 m from powerlines, roads, railways etc	person, obstacles
Africa	road and from any structure or building > 122 m within a radius of 10 km from an airport/within restricted/prohibited airspace/adjacent to or above nuclear powerplant, prison, police station, crime scene, court of law. national key points or strategic installations	person, airport and structure, road
Spain	> 8 km from airport	airport
Sweden	> 50 m from people, animals and property	person, property
Switzerlan d	> 100 m away from crowds; > 5 km	person, airport
UAE	> 150 m from public, private > 5 km from Airports, Heliports and airfields or in controlled airspace.	person, airport, heliport,
UK	m from person, object, vehicle	person, structure vehicle, congested area

国家	地理围栏	明确定义的约束
澳大利亚	未经远程驾驶航空器 (RPA) 无人机操作直接关联的人的 > 30 m 。	个人
奥地利	仅在获得所有者许可的情况下，从机场出发的 > 2500 m 。	机场
比利时	> 2778 m (1.5 nm) 与机场的距离 > 50 m 与建筑物、个人的距离	个人、机场、动物
	从有人机临时着陆点的 > 2 km ；> 5 km 从国界线以及 > 2 公里处边界线；> 1000 m 从军事管区；> 200 m 从党和政府机关、核电站；> 5000 m 从无线电观测；> 2000 m 从雷雨云；100 ~ 200 m 从储存易燃易爆物品的仓库、电力设施、加油站；> 1 km 从建筑物、高大塔楼、电网、风力发电；> 500 m 从高速铁路；> 200 m 从山脉	机场、国界线和边界线、军事、党和政府机关、核电站、卫星地球站、雷暴云、仓库、建筑物、高大塔楼、电网、风力发电、铁路等
捷克共和国	> 100 m 来自第三方；> 150 m 来自拥挤区域	个人、拥挤区域
克罗地亚	> 30 m 来自人群和建筑；> 150 m 来自接近/离开区域群组	个人、建筑、机场
德国	人群、事故和灾害区域、监狱、军事设施、工业区以及电站	个人、机场和禁飞区
爱尔兰	> 8 km 来自机场；> 150 m 来自人群聚集；> 150 m 来自个人、船舶、车辆和建筑；≥ 2 km 来自飞行中的飞机	个人、机场和建筑、车辆、船舶
意大利	来自拥挤区域的 > 150 m ；来自人员与财产的 50 m ；> 5 km	人员、机场与财产、拥堵
日本	来自人员或财产的 > 30 m ；不要在许多人聚集的事件现场上空操作无人机。	人员、财产
拉脱维亚	来自地面的人员、财产的 > 50 m ；来自另一个机场的 > 3 km	人员、机场与财产
立陶宛	来自车辆、人员与建筑的 > 50 m ；来自机场的 > 1.8 km ；来自障碍物的 1852 (1 nm) ~ 5556 (3 nm)	人、机场和建筑物障碍物车辆
马耳他	> 150 m 来自拥挤区域的、基础设施，m 的组装来自船舶、车辆、建筑；距离机场 > 7.5 公里。	人、机场和建筑物障碍物、车辆船舶
荷兰	> 150 m 来自建成区的人群，主要道路；> 50 m 来自铁路、工业区	人、道路铁路、工业区
波兰	> 5 km 来自机场；与人和财产保持足够的安全距离	机场
斯洛文尼亚	> 300 m 高于人群；> 50 m 来自电线、道路、铁路等	人、障碍物
非洲	道路以及机场/限制/禁空区域内的任何结构或建筑物 > 122 m 在半径 10 km 内的核电站、监狱、警察局、犯罪现场、法院、国家关键点或战略性设施	人、机场和建筑物、道路
西班牙	> 8 km 从机场	机场
瑞典	> 50 m 从人、动物和财产	人员、财产
瑞士	> 100 m 远离人群；> 5 km	人、机场
阿联酋 (UAE)	" > 150 m 来自公共、私人 > 5 km 来自机场、直升机机场和机场或受控空域。"	个人、机场、直升机机场。
英国 (UK)	" m 来自个人、物体、车辆"	个人、建筑物、车辆、拥挤区域

Note: Data come from policy documents for each country issued
备注: 数据来源于每个国家发布的政策文件
by national airspace management department.
由国家空域管理部门发布。

VI. CONCLUSION

VI. 结论

To ensure the safe and legal operation of UAVs at low-altitudes in urban areas, some relevant policies have been developed and some initial studies conducted, including airspace policies, identification and real-name registration for UAVs, and UAV regulation systems. However, the main contradiction between the current development trend and the constraints of UAVs lies in the low-altitude airspace. The current cloud-based regulation systems are not targeted at the safe and efficient operation of UAVs at low altitude. Building an air route network at low-altitude is a scientific and effective measure to actively regulate and promote the operation of UAVs at low altitude. Some preliminary results (e.g., CAS in China) have already proved the feasibility of constructing air route networks supported by precise and high-resolution geo-information through surveying and mapping technology in RS, GIS and geographical grid technology. Furthermore, due to changeable ground environments, there will be a frequent requirement to adjust the air route. And this is the major difference between surface road and air route networks. It indicated that air routes will largely rely on high-precision and high-dynamic-updating data based on remote sensing technology. The initial research will play an important role in air route planning for different application scenarios.

为了确保在城市低空无人机安全合法的运行，已经制定了一些相关政策并进行了一些初步研究，包括空域政策、无人机的识别和实名注册，以及无人机监管系统。然而，当前无人机发展趋势与无人机约束之间的主要矛盾在于低空空域。现有的基于云的监管系统并未针对低空无人机安全高效运行而设计。构建低空航路网络是积极调控和促进低空无人机运行的科学有效措施。一些初步成果 (例如中国的 CAS) 已经证明了通过遥感技术 (RS)、GIS 和地理格网技术的测绘，构建支持精确和高分辨率地理信息的航路网络的可行性。此外，由于地面环境的可变性，将频繁需要调整航路。这是地面道路与航路网络之间的主要区别。这表明航路将很大程度上依赖于基于遥感技术的高精度和高动态更新数据。初步研究在为不同应用场景规划航路方面将发挥重要作用。

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CONFLICTS OF INTEREST

利益冲突

The authors declare no conflict of interest.

作者声明不存在利益冲突。

ANNEX

附录

See Table 3.

参见表 3。

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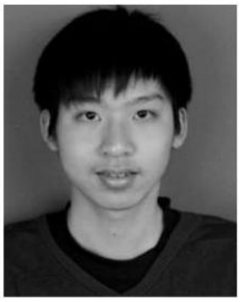

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