Designing airspace for urban air mobility: A review of concepts and approaches

设计城市空中出行空域: 概念与方法的综述

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A B S T R A C T

摘要

The article brings together the academic and industry literature on the design and management of urban airspace. We analyze the proposed airspace concepts, identify their strengths and weaknesses, point to gaps in research, and provide recommendations for a more holistic approach to designing urban airspace. We first identify the structural factors that define the size, capacity, and geometry of urban airspace. These factors are grouped into four categories: safety-related factors, social factors, system factors, and aircraft factors. Second, we review different urban airspace concepts proposed around the world. Third, we assess the airspace concepts based on the identified factors. Most of the reviewed airspace concepts are idealized as abstract networks, with an emphasis on maximizing safety and capacity, and with little regard for factors such as technological complexity, noise, or privacy. Additionally, we find that the airspace structure directly influences the level of safety, efficiency, and capacity of airspace. On the one hand, air vehicles in less structured airspace have more degrees of freedom. They can freely choose their position, altitude, heading, and speed, which increases airspace capacity and reduces flying costs. However, these concepts require high technological capabilities, such as dynamic geofences and advanced sense-and-avoid capabilities, to maintain the required safety levels. On the other hand, airspace concepts with fewer degrees of freedom can accommodate less capable aircraft but require strict operation rules and reduced capacity to ensure safety. Finally, the proposed urban air mobility concepts require extensive ground infrastructures, such as take-off and landing pads and communication, navigation, and surveillance infrastructure. There is a need for a new branch of research that analyzes urban air mobility from the perspective of urban planning, including issues around zoning, air rights, public transportation, real estate development, public acceptance, and access inequalities.

本文汇集了关于城市空域设计与管理的学术和行业文献。我们分析了提出的空域概念，识别了它们的优点和缺点，指出了研究中的空白，并为设计城市空域提供了一个更全面的方法的建议。我们首先确定了定义城市空域大小、容量和几何形状的结构因素。这些因素被分为四类: 与安全相关的因素、社会因素、系统因素和飞行器因素。其次，我们回顾了世界各地提出的不同城市空域概念。第三，我们根据确定的因素评估了空域概念。大多数审查的空域概念被理想化为抽象网络，重点是最大化安全和容量，而对技术复杂性、噪音或隐私等因素考虑较少。此外，我们发现空域结构直接影响空域的安全水平、效率和容量。一方面，在结构较少的空域中，航空器有更多的自由度。它们可以自由选择位置、高度、航向和速度，这增加了空域容量并降低了飞行成本。然而，这些概念需要高技术能力，如动态地理围栏和先进的感知与避让能力，以保持所需的安全水平。另一方面，自由度较少的空域概念可以容纳能力较低的飞行器，但需要严格的操作规则和降低容量以确保安全。最后，提出的城市空中出行概念需要广泛的地基基础设施，如起降坪和通信、导航、监视基础设施。需要一个新的研究领域，从城市规划的角度分析城市空中出行，包括关于分区、空权、公共交通、房地产开发、公众接受度和接入不平等的问题。

1. Introduction

1. 引言

The idea of Urban Air Mobility (UAM), coupled with the technological development in automation and electricity storage, has spurred growth in the urban aviation industry. The concept of UAM comprises a set of rules, procedures, and technologies that enable air traffic operations of cargo and passengers in the urban environment. UAM is a part of the Advanced Air Mobility (AAM), a joint initiative of the FAA, NASA, and the industry to develop an air transportation system that moves passengers and cargo with new electric (i.e. green) air vehicles in various geographies previously underserved by traditional aviation [1]. Companies worldwide are racing to create urban aircraft prototypes and, in partnership with major aerospace suppliers, certify the technologies for urban flying. This push is putting pressure on cities and government agencies to create rules for using urban airspace, which is not an easy task considering the differences in air vehicle designs and sizes, maneuverability, speed, take-off procedures, automation, surveillance, and communication capabilities. These differences make it difficult for air vehicles to use the airspace safely and efficiently and require a standardized set of flying rules and procedures [2].

城市空中出行 (UAM) 的理念，结合自动化和电能储存技术的进步，推动了城市航空产业的增长。UAM 的概念包括一套规则、程序和技术，它们使得在城市环境中进行货运和客运的空中交通运作成为可能。UAM 是高级空中出行 (AAM) 的一部分，这是 FAA、NASA 和业界共同发起的一项倡议，旨在开发一种空中交通系统，使用新的电动 (即绿色) 航空器在各种之前未被传统航空服务到的地理区域运送乘客和货物 [1]。全球各地的公司都在竞相创建城市飞机原型，并与主要航空航天供应商合作，为城市飞行技术认证。这种推动使得城市和政府机构面临制定使用城市空域规则的压力，考虑到航空器设计、尺寸、机动性、速度、起飞程序、自动化、监控和通信能力的差异，这并非易事。这些差异使得航空器难以安全高效地使用空域，并需要一套标准化的飞行规则和程序 [2]。

Today, unmanned aerial systems (UAS), also known as unmanned air vehicles (UAV), or colloquially, drones, are used in civilian applications such as recreation [3], traffic monitoring [4], disaster monitoring [5], fire detection [6], infrastructure inspection [7], mapping [8], forestry [9], and agriculture [10]. These operations, although numerous, are usually contained within specific geographic regions and still do not pose a substantial risk to the everyday operation of the National Airspace System (NAS). However, proposed urban, suburban, and exurban air traffic is expected to create operational and safety challenges that might significantly impact the NAS.

现在，无人航空系统 (UAS)，也被称为无人航空器 (UAV)，或俗称为无人机，被用于民用领域，如娱乐 [3]、交通监控 [4]、灾害监控 [5]、火灾探测 [6]、基础设施检查 [7]、地图绘制 [8]、林业 [9] 和农业 [10]。尽管这些操作数量众多，但通常局限于特定的地理区域，并且目前还没有对国家空域系统 (NAS) 的日常运作构成实质性风险。然而，拟议的城市、郊区和远郊空中交通预计将产生运营和安全挑战，可能会对 NAS 产生重大影响。

Proposed operations will most likely be conducted by electric manned and unmanned air vehicles with vertical take-off and landing. Unlike a traditional helicopter, new air vehicles use multiple motors and propellers, electric engines, and lighter materials, which make them cheaper [11], quieter [12], and more efficient [13]. The operations are expected to cover both urban [14, 15] and rural [16] regions. The operators will compete for the same limited

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space, which will push the industry to adopt smaller separation standards [17]. For this reason, several agencies are developing frameworks for managing urban airspace and ensuring safety.

提议的作业很可能会由电动有人和无人垂直起降航空器进行。与传统直升机不同，新型航空器使用多个电机和螺旋桨、电动引擎和更轻的材料，这使得它们更便宜 [11]、更安静 [12]、更高效 [13]。预计这些作业将覆盖城市 [14, 15] 和乡村 [16] 地区。运营商将在同一有限空间内竞争，这将推动行业采用更小的间隔标准 [17]。因此，一些机构正在开发管理城市空域并确保安全的框架。

This article aims to analyze the leading proposals for managing urban airspace, find their commonalities, and point to the best practices in airspace design. We seek to identify and analyze structural factors that define the physical structure of urban airspace. By "physical structure of urban airspace," we consider the position and size of airspace elements such as flying trajectories, tubes, corridors, and layers, as well as their associated rules of operations.

本文旨在分析管理城市空域的主要提议，找出它们的共同点，并指出空域设计的最佳实践。我们试图识别和分析定义城市空域物理结构的结构性因素。所谓“城市空域的物理结构”，我们考虑的是飞行轨迹、管道、走廊和层级等空域元素的位置和大小，以及与之相关的运行规则。

2.The need for urban airspace

2. 城市空域的需求

The inability of the current air traffic management (ATM) system to manage urban airspace is the primary inhibitor of the development of urban air transportation [17]. Several challenges impede the integration of the existing NAS operations and urban operations: 1) higher number of operations, 2) greater density of operations, 3) lower altitudes of operations, and 4) varying performance of different operators and air vehicles [18]. These challenges stretch the capabilities of the current-day air traffic control (ATC) system and indicate the need for significant changes in the current system.

当前空中交通管理系统 (ATM) 无法管理城市空域是阻碍城市空中交通发展的主要抑制因素 [17]。有几个挑战阻碍了现有国家空域系统 (NAS) 操作与城市操作的整合:1) 操作数量增加，2) 操作密度增大，3) 操作高度降低，以及 4) 不同运营商和航空器的性能差异 [18]。这些挑战考验着当今空中交通控制系统 (ATC) 的能力，并表明当前系统需要进行重大变革。

The International Civil Aviation Organization (ICAO) classifies airspace into controlled and uncontrolled airspace, using seven classes (A, B, C, D, E, F, and G), depending on air traffic services provided and flight requirements. Controlled airspace covers Classes A, B, C, D and E, while uncontrolled airspace covers Classes F and G. Each airspace class contains a set of rules indicating exactly how aircraft should fly and in what way ATC must interact with such aircraft. Therefore, ICAO defines each airspace class by the type of flight it services (instrument flight rules (IFR), visual flight rules (VFR)), provided separations (all aircraft, IFR flown aircraft from VFR flown aircraft, no separation), the type of air traffic service (ATC, traffic information about VFR flights, flight information service), speed limitation and altitude, radio communication requirements (continuous two-way, no communication), and ATC clearances [19].

国际民用航空组织 (ICAO) 将空域分为受控空域和不受控空域，使用七个类别 (A、B、C、D、E、F 和 G)，这取决于提供的空中交通服务类型和飞行要求。受控空域包括 A、B、C、D 和 E 类，而不受控空域包括 F 和 G 类。每个空域类别都包含一套规则，指明飞机应如何飞行以及空中交通管制 (ATC) 必须以何种方式与飞机互动。因此，ICAO 通过它服务的飞行类型 (仪表飞行规则 (IFR)、目视飞行规则 (VFR))、提供的间隔 (所有飞机、IFR 飞行的飞机与 VFR 飞行的飞机之间的间隔、无间隔)、空中交通服务的类型 (ATC、关于 VFR 飞行的交通信息、飞行信息服务)、速度限制和高度、无线电通信要求 (持续双向通信、无需通信) 以及 ATC 的放行许可 [19] 来定义每个空域类别。

ICAO, as a regulatory body, allows its member states to select airspace classes that fit their requirements. For example, in the United States (Fig. 1), controlled airspace consists of Class A and B airspace (where clearance from air traffic control is mandatory), Class C and D airspace (where two-way ATC communications are mandatory), and Class E airspace (where it is not mandatory to contact the ATC or to obtain clearance to enter). These five classes are further divided by altitudes: Class A, between altitudes 18,000 and 60,000 ft above sea level; Class B, around the nation's busiest airports; Class C, around medium-sized airports; Class D, around smaller airports with air traffic control towers; and Class E, around smaller airports without air traffic control towers. Uncontrolled airspace, defined as Class G, is airspace below 1200ft , not equipped with any air traffic management service, where pilots rely on visual flight rules (VFR). Class F airspace is not used [20]. Within the classes of airspace, safety is preserved by maintaining a required separation between two aircraft.

国际民航组织 (ICAO) 作为一个监管机构，允许其成员国选择符合其需求的空域类别。例如，在美国 (图 1)，受控空域包括 A 类和 B 类空域 (在此空域内必须获得空中交通管制许可)，C 类和 D 类空域 (在此

空域内必须进行双向空中交通管制通信)，以及 E 类空域 (在此空域内不必与空中交通管制联系或获得进入许可)。这五类空域进一步按高度划分:A 类，海拔 18000 至 60000 英尺之间；B 类，全国最繁忙机场周围；C 类，中型机场周围；D 类，设有空中交通管制塔台的较小机场周围；E 类，没有空中交通管制塔台的较小机场周围。未受控空域，定义为 G 类，是指 1200ft 以下的空域，未配备任何空中交通管理服务，飞行员依赖目视飞行规则 (VFR)。F 类空域未被使用 [20]。在空域类别内，通过保持两架飞机之间的所需间隔来确保安全。

Nearly all aircraft operations in controlled airspace today are managed under an airspace-based operation. In airspace-based operation, separation management and trajectory assignment are transferred from one sector to another and handled by controllers within each sector. Airspace-based operations are unlikely to be feasible for the UAM because urban flights are likely to occur in all airspace classes, except Class A [21]. One way of integrating UAM operations with the current system is to increase its capacity and enable ATC to control and manage all the operations within the respected airspace classes [21]. However, this approach requires a drastic overhaul in all aspects of NAS, which is a long and expensive process. It is more likely that UAM operations will be conducted within a separate, newly created airspace with a new set of rules and standards [22].

如今，几乎所有的受控空域内的飞行操作都是在基于空域的操作下管理的。在基于空域的操作中，间隔管理和轨迹分配从一个扇区转移到另一个扇区，并由每个扇区内的管制员处理。基于空域的操作不太适用于城市空中交通 (UAM)，因为城市飞行很可能会在所有空域类别中发生，除了 A 类 [21]。将 UAM 操作与当前系统整合的一种方法是提高其容量，使空中交通管制 (ATC) 能够控制和管理各自尊重的空域类别内的所有操作 [21]。然而，这种方法需要对国家空域系统 (NAS) 的所有方面进行彻底的改革，这是一个漫长且昂贵的过程。更有可能的是，UAM 操作将在一个单独的、新创建的空域内进行，该空域有一套新的规则和标准 [22]。

Such a system will be more complex than the airspace under ICAO's current seven classes of airspace. The difficulty of safely separating air vehicles in dense urban airspace can be reduced through the careful design of additional airspace structures as they can minimize complexity and increase throughput [23]. There is, however, no clear consensus on the type of airspace design that should be implemented. As presented in Section 4, several studies argue that predefined paths and zones are required to handle high traffic densities [1, 22, 24] , while others argue that airspace should be unrestricted and open only to fully autonomous vehicles [25, 26] . Most studies start from the proposition that the airspace structure should be optimized for capacity and safety. It is implied that the optimal airspace design is achieved by minimizing damage (collisions with buildings and other aircraft) while maximizing capacity and throughput. In section 3, we show that safety and capacity are only two of the multiple variables required to design functioning urban airspace.

这样的系统将比国际民航组织当前七类空域下的空域更为复杂。通过对额外空域结构的精心设计，可以降低在密集城市空域中安全分离航空器的难度，因为它们可以最小化复杂性并提高吞吐量 [23]。然而，对于应该实施何种类型的空域设计，尚无明确的共识。如第 4 节所述，一些研究认为需要预定义的路径和区域来处理高交通密度 [1, 22, 24] ，而其他研究则认为空域应该是无限制的，仅向完全自主的航空器开放 [25, 26] 。大多数研究从这样一个命题出发，即空域结构应该优化容量和安全。这意味着最佳空域设计是通过最小化损害 (与建筑物和其他航空器的碰撞) 同时最大化容量和吞吐量来实现的。在第 3 节中，我们展示了安全和容量是设计功能性的城市空域所需的多个变量中的两个。

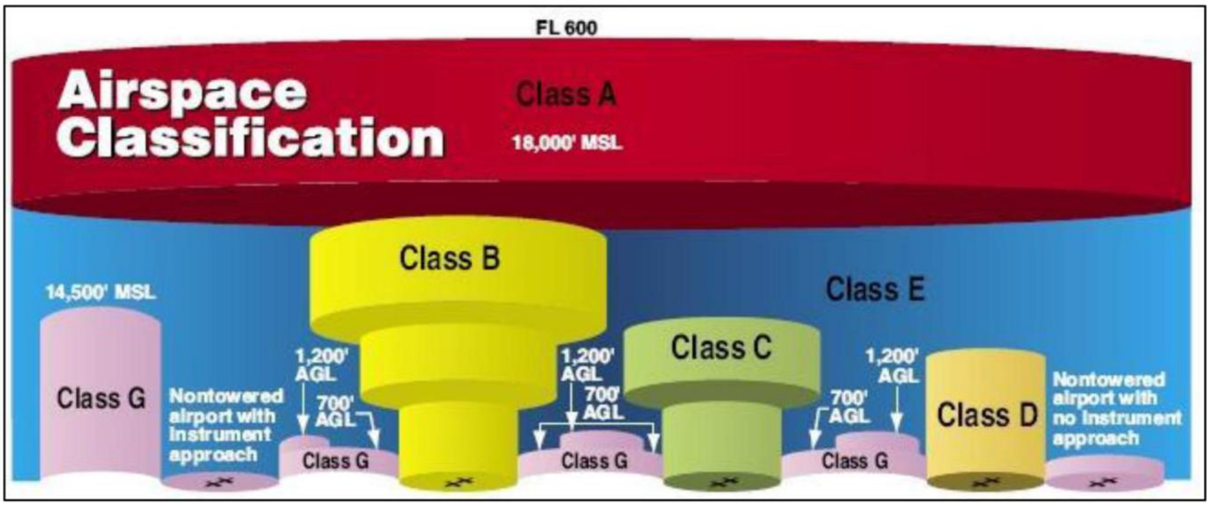


Fig. 1. Airspace classes in the US in accordance with ICAO guidelines [20].

图 1. 根据国际民航组织指南 [20]，美国空域分类。

3. Factors that determine the geometry of urban airspace

3. 决定城市空域几何形状的因素

We start by conceptualizing how different factors might have a physical effect on urban airspace. Safety considerations (and common sense) require aircraft to avoid collisions with buildings. Buildings are then the ”no-fly” zones where flying is, understandably, prohibited. The space outside of the no-fly zone can be used for flying. A factor, in this case, safety, creates a spatial envelope, where everything inside the envelope is a no-fly zone, and everything outside it is open for flying, as presented in Fig. 2a. A step further would be to consider another factor, such as wind gusts, that create unsafe flying space in the proximity of tall buildings. Again, this unsafe space could be visualized by a clearance envelope that defines the outer boundary of the no-fly zone. As we add more factors, the clearance envelope expands, as does the no-fly zone. The resulting airspace fills the space beyond the no-fly zone, which is created by superimposing different clearance boundaries of all the considered factors (Fig. 2).

我们首先构思了不同因素如何可能对城市空域产生物理影响。出于安全考虑 (和常识)，飞机需要避免与建筑物相撞。建筑物因此成为“禁飞”区域，飞行在此区域显然是被禁止的。禁飞区域外的空间可用于飞行。在这种情况下，一个因素，即安全，创造了一个空间包络，其中包络内的一切都是禁飞区，而包络外的一切则开放供飞行，如图 2a 所示。更进一步，可以考虑另一个因素，如阵风，它在高层建筑附近产生不安全的飞行空间。同样，这个不安全空间可以通过一个清除包络来可视化，该包络定义了禁飞区的外部边界。随着我们添加更多的因素，清除包络和禁飞区都会扩大。由此产生的空域充满了超出禁飞区的空间，这是通过叠加所有考虑因素的不同清除边界而创建的 (图 2)。

We use this logic to identify the factors that might restrict movement and influence the position of space open to flying. The factors are divided into four groups: 1) safety-related factors, 2) social factors, 3) operational factors related to the characteristic of the system, and 4) operational factors related to aircraft characteristics.

我们使用这个逻辑来识别可能限制运动并影响开放飞行位置的因素。因素分为四组:1) 与安全相关的因素，2) 社会因素，3) 与系统特性相关的运营因素，以及 4) 与飞机特性相关的运营因素。

3.1. Safety-related factors

3.1. 安全相关因素

The Federal Aviation Administration (FAA) has identified the safety of people, vehicles, and property as the most important factor for the successful adoption of urban air mobility [1]. Safety can be improved by reducing risk. Risk is reduced by lessening the severity of the accident or lowering the likelihood that an accident will occur. In the context of airspace, risk cannot be eliminated altogether, but it can be reduced by avoiding objects, areas with turbulences, and areas with weather that can endanger the flight.

美国联邦航空管理局 (FAA) 将人员、车辆和财产的安全视为城市空中出行成功采用的最重要因素 [1]。通过降低风险可以提高安全性。通过减轻事故的严重性或降低事故发生的可能性来减少风险。在空域的背景下，风险无法完全消除，但可以通过避开物体、湍流区域和可能危及飞行的天气区域来降低风险。

3.1.1. Object avoidance

3.1.1. 物体避让

The idea of defining urban airspace as a space free of buildings can be found in Refs. [25,27-29]. Control algorithms identify the obstacle space, while the remaining space is open to flying. Apart from avoiding buildings, aircraft also need to maintain a safe separation from other aircraft and minimize the probability of a mid-air collision [30]. Separation from other objects is the cornerstone of the safety of the traditional Air Traffic Management system. Present-day separation standards are unambiguous: two aircraft cannot be separated by less than 5 nautical miles (NM) en-route and 3NM in the terminal area using radar wake vortex separation, or 1.5 min using time-based wake turbulence separation [31]. However, these distances are too prohibitive and not suitable for urban air traffic. The concept of separation in UAM is being reimagined since fixed distance spacing is proving to be too rigid for UAM operations. The literature suggests three distinct approaches to defining separation in UAM:

城市空域定义为无建筑物的空间这一想法可以在参考文献 [25,27-29] 中找到。控制算法识别障碍空间，而剩余空间则开放给飞行使用。除了避开建筑物，飞机还需要与其他飞机保持安全距离，并最小化空中相撞的概率 [30]。与其他物体分离是传统空中交通管理系统安全的基础。现今的分离标准是明确的: 两架飞机在航路上不能相隔少于 5 海里 (NM)，在终端区域使用雷达尾涡分离 3NM，或 1.5 min 使用基于时间的尾流分离 [31]。然而，这些距离对于城市空中交通来说过于限制性，不适合使用。在城市空中交通 (UAM) 中，分离的概念正在被重新构想，因为固定的距离间隔对于 UAM 操作来说过于死板。文献提出了三种定义 UAM 中分离的不同方法:

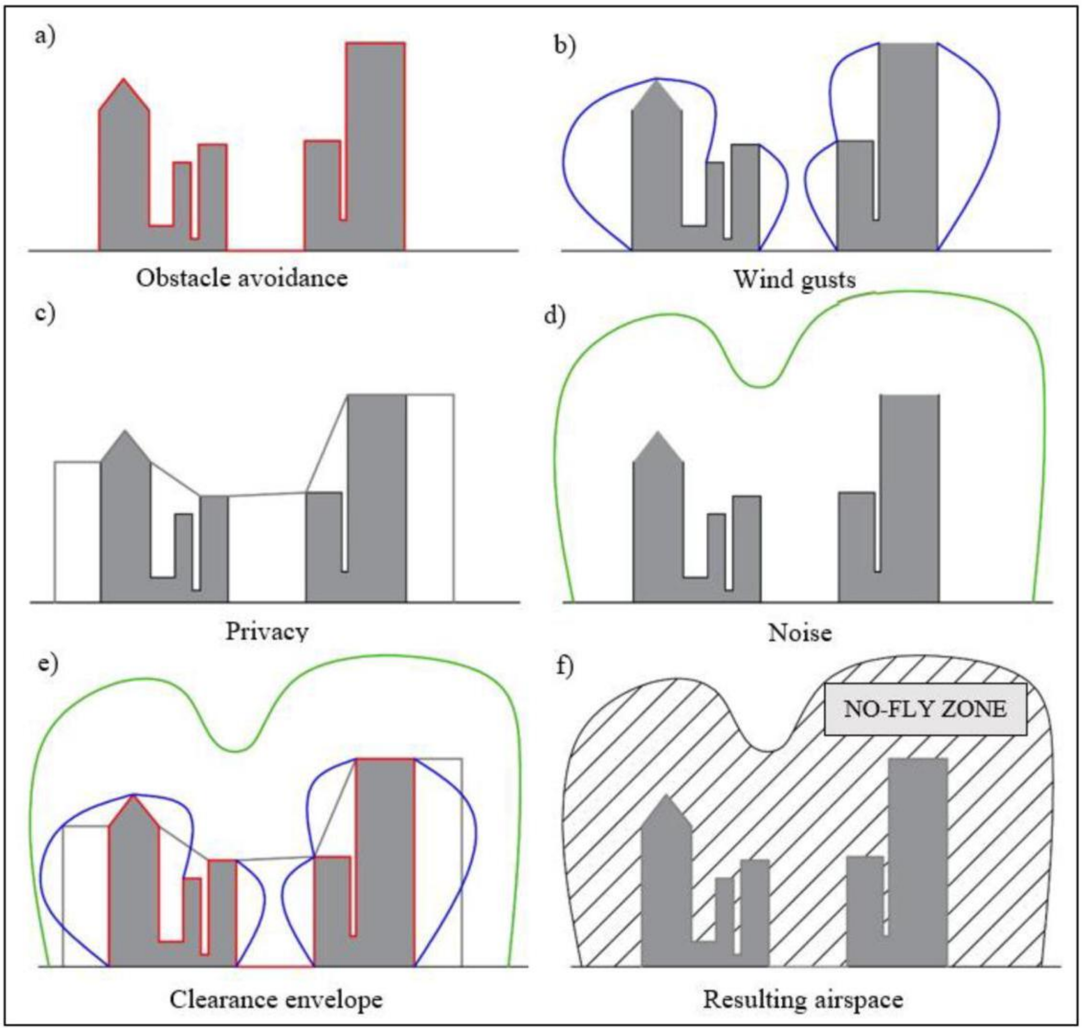


Fig. 2. Clearance depends on the selected variables: (a) obstacle avoidance; (b) wind gusts; (c) privacy; (d) noise; (e) clearance envelope; (f) resulting airspace.

图 2. 清除取决于所选变量:(a) 障碍物规避; (b) 阵风; (c) 隐私; (d) 噪音; (e) 清除包络; (f) 形成的空域。

1. Fixed separation - The traditional way of defining separation is to determine a distance all users must maintain. Since 3NM is too large for urban environments, some authors suggest smaller separation standards, such as 0.3NM, or even 0.1NM horizontal and 100 ft vertical separation [32], or 0.36NM horizontal and 450 ft vertical separation [33]. These authors argue that UAM aircraft are much smaller and nimbler, which allows reduced separation. As the systems become more mature, separation standards can change [34].

1. 固定分离 - 传统定义分离的方式是确定所有用户必须保持的距离。由于 3NM 对于城市环境来说太大，一些作者建议更小的分离标准，例如 0.3NM，或者甚至 0.1NM 水平方向 100 英尺垂直分离 [32]，或者 0.36NM 水平方向和 450 英尺垂直分离 [33]。这些作者认为 UAM 飞机尺寸更小，更灵活，这允许减少分离距离。随着系统变得更加成熟，分离标准可以改变 [34]。

2. Dynamic separation - The second approach is so-called dynamic separation, a predetermined distance unique for each aircraft based on its class [35,36]. Each aircraft has different technological capabilities and characteristics. High-capability aircraft require smaller separations because they can detect and avoid nearby aircraft effectively, or their systems can predict the trajectories in advance and prevent the incident. In comparison, a poorly equipped

aircraft may require larger separation due to limited maneuverability [26, 37]. Therefore, the capacity of airspace depends on the features of the aircraft within that airspace, and it changes as new users enter the airspace [27]. Some authors argue that distance-based separation needs to be abandoned altogether and replaced with time-based thresholds that account for aircraft performance and maneuverability [38].

2. 动态间隔 - 第二种方法被称为动态间隔，它是基于每架飞机的类别而确定的预定距离 [35,36]。每架飞机具有不同的技术能力和特性。高能力飞机需要更小的间隔，因为它们能够有效探测并避开附近的飞机，或者它们的系统能够预先预测轨迹并防止事故发生。相比之下，装备较差的飞机可能需要更大的间隔，因为它们的机动性有限 [26, 37]。因此，空域的容量取决于该空域内飞机的特性，并且随着新用户的进入而变化 [27]。一些作者认为，基于距离的间隔需要完全放弃，取而代之的是基于时间的阈值，这些阈值考虑了飞机的性能和机动性 [38]。

3. No standardized separation - Currently, flights in Class G airspace do not receive separation guidance from the air traffic controllers [18]. Safety is ensured through the ”see and avoid” approach, where the pilot visually maintains a safe distance from other aircraft. A technological equivalent to see-and-avoid is sense-and-avoid [39-41], a mix of hardware and software that enables UAV to detect obstacles and steer away from them. Smaller UAVs do not have the required payload or energy capacity to use radars or LIDARs, and most sense-and-avoid systems rely on cameras to scan their surroundings [37]. Although simple, this approach of avoiding collisions is essentially a greedy algorithm where each UAV looks only to resolve imminent conflict. In a dense traffic environment, uncoordinated ”greedy” routing reduces airspace throughput and safety. Although sense and avoid cannot solve navigation and safety problems on its own, it is one of the prerequisites for safe urban flying [40-42].

3. 没有标准化的间隔 - 目前，在 G 类空域中的飞行不会从空中交通管制员那里接收到间隔指导 [18]。安全是通过“看到并避开”的方法来保证的，即飞行员通过视觉与其他飞机保持安全距离。看到并避开的技术等效方法是感知并避开 [39-41]，这是一种结合了硬件和软件的方法，使得无人机能够探测障碍物并避开它们。较小的无人机没有足够的载重或能源容量来使用雷达或 LIDAR，而且大多数感知并避开系统依赖于摄像头来扫描周围环境 [37]。尽管这种方法简单，但避免碰撞的方法本质上是一种贪心算法，其中每个无人机只关注解决即将发生的冲突。在交通密集的环境中，未协调的“贪心”路由会降低空域的吞吐量和安全性。尽管感知并避开本身无法解决导航和安全问题，但它是在城市安全飞行中的先决条件之一 [40-42]。

Sense-and-avoid is not the only method of navigating through a dense urban environment. Strategic, trajectory-based collision avoidance is a necessary complement to the sense-and-avoid procedure, as it further reduces the likelihood of an incident [27-29]. Apart from the sense-and-avoid approach, collision avoidance can be done by strategic collision avoidance algorithms [28,43], avoidance maps [44], and path-planning [36,38,45].

避障并不是在密集城市环境中导航的唯一方法。基于轨迹的战略避障是对避障程序的必要补充，因为它进一步降低了事故发生的可能性 [27-29]。除了避障方法外，还可以通过战略避障算法 [28,43]、避障地图 [44] 和路径规划 [36,38,45] 来实现避障。

In addition to separation, sense-and-avoid, and collision avoidance procedures, risk can also be reduced by using geofences. Geofence is a virtual airspace boundary that prohibits or restricts access to some or all aircraft to a specific part of airspace [46]. Objects on the ground, such as critical infrastructure (airports, high voltage pylons, hospitals) or protected areas (military bases, recreational areas, nature reserves) are the most likely candidates for geofences. Geofence concepts were proposed by The European Organization for Civil Aviation Equipment (EURO-CAE) [47] and The National Aeronautics and Space Administration (NASA) [46], as shown in Fig. 3.

除了分离、避障和避撞程序外，使用地理围栏也可以降低风险。地理围栏是一个虚拟的空域边界，它禁止或限制某些或所有飞行器进入空域的特定部分 [46]。地面上的物体，如关键基础设施 (机场、高压电线塔、医院) 或受保护区域 (军事基地、休闲区域、自然保护区) 最有可能成为地理围栏的候选对象。地理围栏的概念由欧洲民用航空设备组织 (EURO-CAE)[47] 和美国国家航空航天局 (NASA)[46] 提出，如图 3 所示。

In more general terms, geofences can be static and dynamic. Static geofences can be used to define flying corridors [40] and support obstacle avoidance [49]. Dynamic geofences can be inserted into the airspace at any point as a result of ongoing events, emergency missions, or severe weather. Once the geofences are set, the remaining space is open for flying, and the resulting flying path may or may not consider additional factors such as third-party risk [50].

更一般地说，地理围栏可以是静态的也可以是动态的。静态地理围栏可以用来定义飞行走廊 [40] 并支持障碍物避让 [49]。动态地理围栏可以根据正在进行的事件、紧急任务或恶劣天气在任何时间插入空域。一旦设置了地理围栏，剩余的空间就可以用于飞行，而由此产生的飞行路径可能会考虑也可能不会考虑其他因素，如第三方风险 [50]。

3.1.2. Wind gusts

3.1.2. 阵风

According to the National Weather Service, a wind gust is a brief, sudden increase in wind speed. In urban environments, friction between wind and buildings creates eddies that cause sudden changes in wind speed and direction (Fig. 4). Aircraft's energy consumption can increase due to the additional power required to maintain a steady flight. More importantly, wind gusts can cause loss of control and overcome the aircraft's ability to maintain position, altitude, and stability [51].

根据国家气象服务局的说法，阵风是风速的短暂、突然增加。在城市环境中，风与建筑物之间的摩擦会产生涡流，导致风速和方向的突然变化 (图 4)。飞机的能量消耗可能会增加，因为需要额外的动力来维持稳定的飞行。更重要的是，阵风可能会导致失去控制，并超出飞机保持位置、高度和稳定性的能力 [51]。

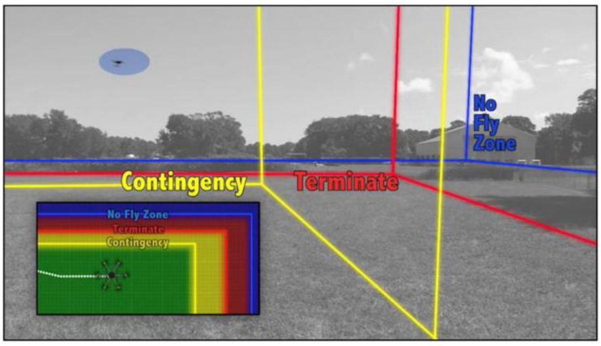


Fig. 3. Geofence "SafeGuard" developed by NASA [48].

图 3. 美国宇航局开发的地理围栏"SafeGuard"[48]。

Urban canyons and even individual buildings can cause flows with significant levels of turbulence [53-55], which can endanger the aircraft. Even the most advanced trajectory control algorithms cannot guarantee accurate navigation or object avoidance in unpredictable wind environments [56]. One of the reasons is that wind velocity is difficult to predict [57] and wind turbulences can happen in locations where they were not expected [58]. Studies show that wind gusts can affect the altitude [59, 60] and position of urban aircraft [61, 62] and that in these situations, the autopilot can "overcorrect" and deviate from the planned path [63], which can cause a collision. Some drone manufacturers specify that small air vehicle can tolerate a wind speed up to $10 \mathrm{~m/s}$; however, initial tests by NASA show that small UAS cannot safely fly in wind flow with speeds greater than $5 \mathrm{~m/s}$ [64].

城市峡谷甚至单个建筑物都可能导致具有显著湍流水平的流动 [53-55]，这可能会危及飞机。即使是最先进的轨迹控制算法也无法在不可预测的风环境中保证精确导航或避障 [56]。其中一个原因是风速难以预测 [57]，并且风湍流可能发生在之前未预料到的位置 [58]。研究表明，阵风可以影响城市飞机的飞行高度 [59, 60] 和位置 [61, 62]，在这些情况下，自动驾驶仪可能会"过度校正"并偏离计划路径 [63]，这可能导致碰撞。一些无人机制造商指出，小型飞行器可以承受风速高达 $10 \mathrm{~m/s}$；然而，NASA 的初步测试表明，小型无人机在风速超过 $5 \mathrm{~m/s}$ 的风流中无法安全飞行 [64]。

Should areas with wind gusts be avoided, or can high-precision algorithms and propellers maintain the control under sudden winds? Early experiments show that control cannot always be maintained [65] and that areas with wind gusts should be avoided [52].

应该避开有阵风的区域，还是高精度算法和螺旋桨能在突然的风中保持控制？早期实验表明，控制并不总是能够维持 [65]，并且应该避开有阵风的区域 [52]。

3.1.3. Weather

3.1.3. 天气

In aviation, adverse weather conditions regularly cause delays and cancellations of airline flights. In any given year, between 25% and 50% of all aviation accidents are weather-related [61]. However, the severity of weather-related accidents has been steadily reduced due to better nationwide weather prediction and warning systems [66]. Although traditional aviation has benefited from these technological improvements, they are not accurate enough to provide real-time support to urban operations [67]. This gap is a severe constraint to UAM integration, mainly because the weather can disrupt urban air traffic through:

在航空领域，不利气象条件经常导致航班延误和取消。在任意一年中，约有 25% 到 50% 的航空事故与天气相关 [61]。然而，由于全国范围内天气预测和预警系统的改善，天气相关事故的严重性已稳步降低 [66]。尽管传统航空从这些技术改进中受益，但它们并不足以准确地为城市运行提供实时支持 [67]。这一差距是对城市空中交通管理系统 (UAM) 整合的严重制约，主要是因为天气可以通过以下方式干扰城市空中交通:

- Reduced mission endurance - Strong winds can decrease battery performance and interfere with the integrity of the flight. Precipitation can increase resistance to the movement of aircraft and cause the malfunction of onboard electronics. Low temperatures can decrease battery life. Icing can build up on airframes or propellers and increase the weight of the drone.
- 降低任务续航能力 - 强风会降低电池性能并干扰飞行的完整性。降水会增加飞机运动的阻力并导致机上电子设备故障。低温会缩短电池寿命。积冰会在机翼或螺旋桨上积聚，增加无人机的重量。
- Reduced safety - Wind and storms can be dangerous to low altitude aircraft due to the lack of space to correct position, heading, or altitude. Changes in barometric pressure can cause miscalibration of altimeter and cause altitude errors. Visibility and low ceiling could reduce the effectiveness of sense-and-avoid avionics.
- 降低安全性 - 风暴对低空飞行的飞机构成危险，因为缺乏调整位置、航向或高度的空间。气压变化可能导致高度表校准错误，引发高度误差。能见度和低云层可能会降低感知避障航电设备的有效性。

Weather risks can be reduced by creating dynamic geofences that move with the weather. However, a dynamic geofence is only as good as the weather forecasts supporting it. Accurate forecasts are critical to UAM safety [68] and route planning [69], especially because weather avoidance procedures decrease flight endurance of en-route aircraft

通过创建随天气移动的动态地理围栏可以降低天气风险。然而，动态地理围栏的有效性取决于支持它的天气预报的准确性。准确的天气预报对于 UAM 的安全 [68] 和航线规划 [69] 至关重要，特别是由于避航程序会减少在途飞机的续航能力。[70].

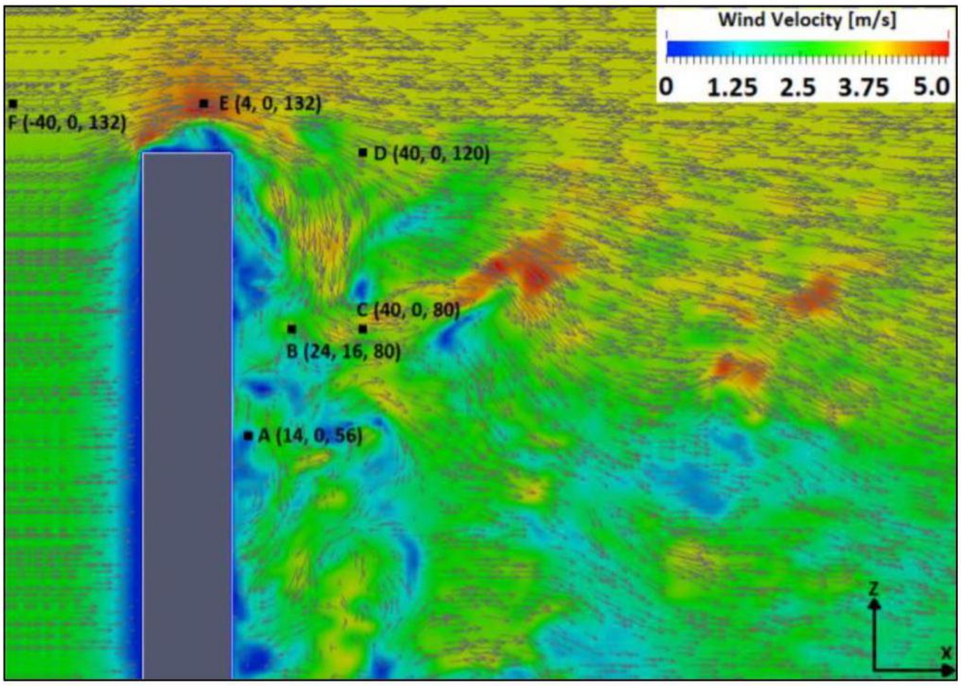


Fig. 4. Wind speed and direction around a building. Source: [52].
图 4. 建筑物周围的风速和风向。来源:[52]。

3.2. Social factors

3.2. 社会因素

Local communities have increasingly influenced the operations of airlines and airports in their jurisdictions [71]. Flights occurring at low altitudes may expose individuals to negative externalities such as air pollution, noise, degradation of the living environment or reduction in property values [72]. UAM operations will most likely occur at lower flight levels and closer to residential neighborhoods than traditional airline operations, and thereby increase the likelihood of community opposition to the development of urban airspace. Studies suggest that UAM might be constrained by social factors such as the perception of safety, security, privacy, ownership, liability, regulation [73], noise, visual pollution, air pollution, and equity [74]. The final definition of airspace structures will mostly depend on noise, visual pollution, and privacy concerns.

地方社区日益影响其在管辖范围内的航空公司和机场的运营 [71]。在低空进行的航班可能会使个人暴露于负外部性，如空气污染、噪音、生活环境的退化或财产价值的降低 [72]。城市空中交通 (UAM) 的运营很可能在比传统航空运营更低的飞行高度和更靠近住宅区的位置进行，从而增加了社区对城市空域开发反对的可能性。研究表明，UAM 可能会受到社会因素的影响，如对安全、安保、隐私、所有权、责任、监管 [73] 的认知，以及噪音、视觉污染、空气污染和不公平 [74] 等。

3.2.1. Noise

3.2.1. 噪音

Several studies have highlighted noise as the key constraint to the implementation of UAM [15,74-76]. The International Civil Aviation Organization (ICAO) has concluded that UAM noise will cause a significant level of annoyance [77]. Noise can interfere with daily activities and sleep, which causes stress-related symptoms [78]. Sleep disturbance reduces the quality of life and causes health issues [79-81]. Community opposition to noise is already a significant consideration for airports and airlines [82,83]. The FAA imposes noise limits for various types of aircraft, but it is anticipated that stricter standards will be required for urban aviation [84, 85] . Adverse effects of noise in a community can be reduced by manufacturing quieter air vehicles or setting up flying routes that reduce noise exposure.

多项研究强调噪音是实施 UAM 的主要限制因素 [15,74-76]。国际民用航空组织 (ICAO) 得出结论，UAM 的噪音将引起显著的烦躁水平 [77]。噪音可能会干扰日常生活和睡眠，导致与压力相关的症状 [78]。睡眠障碍会降低生活质量并引发健康问题 [79-81]。社区对噪音的反对已经是机场和航空公司需要考虑的一个重要因素 [82,83]。美国联邦航空管理局 (FAA) 对各种类型的飞机设定了噪音限制，但预计城市航空将需要更严格的标准 [84, 85] 。通过制造更安静的航空器或设立减少噪音暴露的飞行路线，可以降低社区中噪音的负面影响。

Reducing UAM noise will not be simple [86]. The volume and the frequency of a sound primarily depend on its source, which in the case of drones are motors, propellers, and airframes [87,88]. Although an electric engine in a modern multi-copter has significantly lower engine noise than a helicopter, the propellers create a high-frequency sound that cannot be easily eliminated [89,90]. The initial tests by NASA [91] show that, even at the same decibel levels, drones generate sound that is more annoying to the listeners than the sound generated by a car. Another study by NASA suggests that the listener’s annoyance may increase with the number of propellers [92] since a human ear is sensitive not only to volume but also to the frequency of sound. These results indicate that high-frequency noise produced by drone propellers might generate pushback even if the sound volume (in decibels) is within acceptable limits.

降低无人航空器系统 (UAM) 的噪音并非易事 [86]。声音的音量和频率主要取决于其来源，在无人机的案例中，来源是电机、螺旋桨和机身 [87,88]。尽管现代多旋翼无人机中的电动引擎的噪音显著低于直升机，但螺旋桨产生的无法轻易消除的高频声音 [89,90]。NASA 的初步测试 [91] 显示，即使在相同的分贝水平下，无人机产生的声音比汽车产生的声音更让听众感到烦恼。NASA 的另一个研究表明，听众的不快感可能会随着螺旋桨数量的增加而增加 [92]，因为人耳不仅对音量敏感，也对声音的频率敏感。这些结果表明，即使声音的音量 (以分贝为单位) 在可接受范围内，由无人机螺旋桨产生的高频噪音也可能引起反对。

The volume and frequency of sound also depend on the listener’s distance from the source. Propeller sound decreases by about 6 dB with every doubling of distance from the source [87], which means that the level of noise exposure can be controlled by defining flight paths closer or farther away from the residential areas. Rather than relying solely on quieter engines to reduce community noise, operators will need to adjust flying paths to minimize the exposure to sound [93]. The adjustment of flying routes may be made proactively by designing airspace to reduce noise exposure or reactively in response to landowners’ lawsuits and community opposition.

声音的音量和频率还取决于听众距离声源的远近。螺旋桨的声音在距离声源翻倍时大约减少 6 dB [87]，这意味着可以通过定义靠近或远离居民区的飞行路径来控制噪音暴露水平。运营商不仅需要依赖更安静的引擎来减少社区噪音，还需要调整飞行路径以最小化声音暴露 [93]。飞行路线的调整可以是主动的，通过设计减少噪音暴露的空域，也可以是反应性的，响应土地所有者的诉讼和社区反对。

3.2.2. Visual pollution

3.2.2. 视觉污染

Visual disturbances in residential neighborhoods are likely to create localized pushback as low-level flights might be visually undesirable [94]. In one of the few articles on the subject [95], the authors conducted a text-mining semantic analysis to investigate a general sentiment toward drones and found that the public will likely be annoyed by small aircraft because they clutter the visual field and create shadows. A survey by Airbus found that 45% of respondents are concerned about visual pollution [96]. The way to combat it would be to create routes that fly over less-populated areas or water. A whitepaper by Uber [15] points out that visual pollution concerns can be addressed via trip route modifications to avoid particularly sensitive vistas or by consolidating traffic to existing transportation corridors such as above highways. Social scientists argue that drones can be viewed as usurpers taking over people's right to the city and air [97]. In popular literature and media, dystopian urban environments are usually presented as spaces cluttered with small aircraft (Fig. 5), which might influence real-world public sentiment and UAM acceptance.

居住区的视觉干扰可能会导致局部抵制，因为低空飞行在视觉上可能不受欢迎 [94]。在少数关于这个主题的文章之一 [95] 中，作者进行了一项文本挖掘语义分析，以调查对无人机的普遍情绪，并发现公众可能会因为小型飞行器杂乱地占据视觉领域并产生阴影而感到烦恼。空客的一项调查发现 45% 的受访者对视觉污染感到担忧 [96]。对抗这种情况的方法是创建飞越人口较少地区或水域的航线。Uber 的一份白皮书 [15] 指出，可以通过修改行程路线来避免特别敏感的景观，或者将交通集中到现有的交通走廊上方，比如高速公路上方，来解决视觉污染问题。社会科学家认为，无人机可以被看作是篡夺人们城市和空中权利的入侵者 [97]。在流行文学和媒体中，反乌托邦的城市环境通常被描绘为小型飞行器充斥的空间 (图 5)，这可能会影响现实世界中公众的情绪和对城市空中交通 (UAM) 的接受度。

Fig. 5. Dronepolis: a dystopian view of UAM [98].
图 5. 无人机城市: 对城市空中交通的反乌托邦观点 [98]。

3.2.3. Privacy

3.2.3. 隐私

Issues of privacy are exacerbated in residential and business areas. A successful airspace concept should ensure that air vehicles do not create a sense of intrusion on the human environment [99, 100] . In a democracy, a person does not have to justify the desire for privacy, the state must justify its violation. Legal scholars agree that the argument that "no privacy problem exists if a person has nothing to hide" is not valid [101]. Saying you do not care about privacy because you have nothing to hide is to say you do not care about freedom of speech because you have nothing to say [102]. It is to assume that no one has anything to conceal, including political and religious beliefs, immigration status, or health records. In addition to recognizing the importance of privacy, it is important to understand that there are multiple types of privacies that should be safeguarded: privacy of the person, of behavior and action, of communication, of data and image, of thoughts and feelings, location and space, of association [103]. The specific privacy type associated with UAM is difficult to define, given drones' diverse capabilities and applications. For example, aircraft equipped with cameras can capture images that can provide information about people's location, behavior, and activity patterns [103].

住宅和商业区的隐私问题被放大。一个成功的空域概念应确保航空器不对人类环境产生侵入感 [99, 100] 。在民主社会中，个人无需为追求隐私的愿望辩护，而是国家必须为其侵犯隐私辩护。法学学者

们同意，“如果一个人没有隐藏之事，就不存在隐私问题”的观点是无效的 [101]。说你不在乎隐私，因为你没有什么可隐藏的，就像说你不关心言论自由，因为你没有什么可说的 [102]。这是假设没有人有任何需要隐藏的东西，包括政治和宗教信仰、移民身份或健康记录。除了认识到隐私的重要性之外，了解存在多种应受保护的隐私类型也很重要: 个人隐私、行为和行动隐私、通信隐私、数据和图像隐私、思想和情感隐私、位置和空间隐私、以及结社隐私 [103]。与城市空中出行 (UAM) 相关的特定隐私类型难以定义，因为无人机的功能和用途多种多样。例如，配备相机的飞机可以捕捉图像，提供关于人们位置、行为和活动模式的信息 [103]。

The arguments for safeguarding privacy might sound outdated. After all, people relinquished privacy when they bought a smartphone. However, the issue of UAM acceptance is less about the ownership of private data and more about the perception of privacy. UAM operations, which occur in low altitude airspace, may accentuate annoyance over the proximity of the flights and the perceived privacy loss [104]. And experience from airport development shows just how powerful annoyed citizens can be. The main two factors expected to affect the perception of privacy are the number of flights and their altitude. These factors are nearly entirely dependent on the decisions about the design of airspace.

保护隐私的论点可能听起来有些过时。毕竟，人们在购买智能手机时就已经放弃了隐私。然而，城市空中出行 (UAM) 的接受问题，与其说是关于私人数据的所有权，不如说是关于隐私感知。在低空空域进行的 UAM 运营可能会加剧对航班近距离的烦恼以及对隐私丧失的感知 [104]。机场开发的经验表明，烦恼的公民的力量有多么强大。预计将影响隐私感知的两个主要因素是航班数量和飞行高度。这些因素几乎完全取决于关于空域设计的决策。

3.3. Operational factors - system

3.3. 运营因素 - 系统

The scalability of air traffic control is one of the critical constraints for the operation of UAM [17]. The FAA estimates that there are 1.7 million drones in the US at the end of 2020 [105], seven times larger than combined airline and general aviation fleets. Accommodating such traffic requires new and innovative system-wide solutions in air traffic management, communication, navigation, and surveillance.

空中交通管制系统的可扩展性是影响城市空中交通 (UAM) 运行的关键约束之一 [17]。美国联邦航空局 (FAA) 估计，到 2020 年底美国有 170 万架无人机 [105]，这是航空公司和通用航空机队总和的七倍。要容纳这样的交通量，需要在空中交通管理、通信、导航和监视方面提出新的、创新的系统性解决方案。

3.3.1.Air traffic management system

3.3.1. 空中交通管理系统

The main challenges in air traffic management are airspace integration, separation, contingency management, capacity, traffic flow management, and scheduling [106]. If aircraft in urban airspace can freely select their routes, speed, and altitude, the air traffic management system needs to be technologically advanced to facilitate that selection.

空中交通管理中的主要挑战包括空域整合、分离、应急管理等，以及容量、交通流管理和调度 [106]。如果城市空域中的飞机可以自由选择其航线、速度和高度，那么空中交通管理系统需要技术上先进，以促进这种选择。

There are two approaches to thinking about managing urban air traffic. The first, proposed by the FAA and NASA [1,2], argues that the air traffic management system should be centralized and technologically able to accommodate aircraft of all levels of performance. The second approach, promoted mainly by the industry, argues that aircraft should select their preferred routes while maintaining safety with onboard technology, such as sense-and-avoid. It follows that aircraft with inadequate technological capabilities would not be able to enter the airspace. The advantages of one approach over the other depend on, among others, the maturity of the system. NASA proposed stages of the development of UAM, called NASA's UAM Maturity Levels [107], presented in Table 1. In the early stages, when both aircraft and management systems' technological capabilities are limited, it is reasonable to expect limited operations constrained to selected regions [108]. A government aviation agency (such as the FAA in the US) will maintain its regulatory authority, but the operations will not be managed by air traffic control. As technology advances, higher integration between the operator and management system could be achieved.

对于管理城市空中交通，有两种思考方法。第一种，由 FAA 和 NASA [1,2] 提出，认为空中交通管理系统应该是集中式的，并且在技术上能够适应所有性能级别的飞机。第二种方法，主要由行业推动，认

为飞机应选择它们偏好的航线，同时利用机载技术，如感知与避让，来保持安全。因此，技术能力不足的飞机将无法进入空域。一种方法相对于另一种方法的优势取决于系统的成熟度等因素。NASA 提出了 UAM 发展的阶段，称为 NASA 的 UAM 成熟度等级 [107]，在表 1 中展示。在早期阶段，当飞机和管理系统的技术能力都有限时，可以合理预期操作受限，仅限于选定的区域 [108]。政府航空机构 (如美国的 FAA) 将保持其监管权限，但操作将不由空中交通管制管理。随着技术的进步，操作者和管理系统之间可能实现更高程度的整合。

3.3.2. Communication, navigation, and surveillance

3.3.2. 通信、导航和监视

Significant technological improvements are required in all three aspects of the communication, navigation, and surveillance (CNS) system. The existing UAVs mainly rely on simple point-to-point communication over the unlicensed band, which is unreliable, insecure, and can only operate over a very limited range. Technologies currently not used in traditional aviation, such as LTE and 5G-and-beyond cellular services, as well as satellite links will be required to facilitate communication between aircraft and traffic control. However, wireless communication face many challenges, including availability, latency, use-of-power, and security issues. Further developments are needed to enable safe UAM operations. For a detailed review of the emerging communication technologies in UAM, see Refs. [109,110].

通信、导航和监视 (CNS) 系统的所有三个方面都需要显著的技术改进。现有的无人机主要依赖未经许可频段的简单点对点通信，这种通信方式不可靠、不安全，且只能在小范围内运行。为了实现飞机与交通管制之间的通信，需要使用目前在传统航空中未使用的技术，如 LTE 和 5G 及更先进的蜂窝服务，以及卫星链路。然而，无线通信面临许多挑战，包括可用性、延迟、功耗和安全性问题。需要进一步发展以实现安全的城市空中交通 (UAM) 运行。关于 UAM 中新兴通信技术的详细回顾，请参见参考文献 [109,110]。

The availability and accuracy of GPS can also be a problem. In the urban environment, buildings can block satellites from direct line of site to the GPS receiver, which can cause errors in navigation or completely block the signal. Moreover, atmospheric conditions can cause a variation in the precision of GPS positioning. An experiment [111] measuring a flight path precision of a drone in an urban environment showed that the drone deviated up to 2 m from the expected flight path. However, in a few situations, the drone deviated 5 m or more. Other studies on GPS accuracy found that in city canyons the positioning drift can be over 20 m due to signal blockage [112]. While there are no official FAA standards on the maximum allowable difference between the estimated position and the true position of a drone, some authors argue that the error should not exceed 3 m [113], which indicates that either GPS needs to be improved, or new technologies need to be developed to sustain higher technical capability levels of UAM.

GPS 的可用性和准确性也可能存在问题。在城市环境中，建筑物可能会阻挡卫星与 GPS 接收器的直接视线，这可能导致导航错误或完全阻挡信号。此外，大气条件可能导致 GPS 定位精度的变化。一项实验 [111] 测量了无人机在城市环境中的飞行路径精度，结果显示无人机偏离了预期飞行路径高达 2 m 。然而，在某些情况下，无人机的偏离达到了 5 m 或更多。其他关于 GPS 准确性的研究发现，在城市峡谷中，由于信号阻挡，定位漂移可能超过 20 m [112]。虽然 FAA 没有关于无人机估计位置与真实位置之间最大允许差异的官方标准，但一些作者认为误差不应超过 3 m [113]，这表明需要改进 GPS 或开发新技术，以维持 UAM 更高技术水平的需求。

Higher positional accuracy could be achieved by using an image-based navigation system, cooperative navigation, or signals and additional ground infrastructure. For example, a combination of GPS and cellular networks can reduce error down to 15 cm [114], or in some cases, even down to 2 cm [112]. Only experiments and experience will show which level of navigational precision is required for safe UAM. Reducing error from 5 m to 1 m will undoubtedly improve the safety of the system. However, even the most precise GPS systems are for naught if the signal is not available. The improvements in accuracy should be followed by improvements in availability.

更高的位置精度可以通过使用基于图像的导航系统、合作导航或信号及额外的地面基础设施来实现。例如，GPS 和蜂窝网络的组合可以将误差降低到 15 cm [114]，在某些情况下，甚至可以降低到 2 cm [112]。只有实验和经验才能显示，为确保城市空中出行 (UAM) 安全所需的导航精度水平。将误差从 5 m 降低到 1 m 无疑将提高系统的安全性。然而，如果信号不可用，即使是最精确的 GPS 系统也无济于事。精度提高之后，还应提高可用性。

Table 1

表 1

NASA's UAM maturity levels (UML) [107].

美国国家航空航天局 (NASA) 的城市空中出行成熟度级别 (UML)[107]。

State	UML	Description
Initial	1	Early operation exploration and demonstrations in limited environments.
	2	Low-density and low-complexity commercial operations with assistive automation.
Intermediate	3	Low-density, medium-complexity operations with comprehensive safety assurance automation.
	4	Medium-density operations with collaborative automated systems.
Mature	5	High density and complexity operations with highly- integrated automated networks.
	6	Ubiquitous UAM operations with system-wide automated optimization.

状态	UML	描述
初始	1	在有限环境中的早期运营探索和演示。
	2	低密度和低复杂度的商业运营，采用辅助自动化。
中级	3	低密度、中等复杂度的运营，采用全面的安全保障自动化。
	4	中等密度的运营，采用协作自动化系统。
成熟	5	高密度和高复杂度的运营，采用高度集成的自动化网络。
	6	普遍存在的城市空中交通 (UAM) 运营，实现系统范围内的自动化优化。

Traditional radars are inadequate for the surveillance of low-altitude UAM operations. Some operators propose the use of automatic dependent surveillance-broadcast (ADS-B); however, in high-density environments, the ADS-B frequency band will likely be oversaturated [115]. Advanced surveillance systems that overcome ADS-B limitations should be developed [116]. Higher freedom of flight will require more sophisticated CNS technology, and organizations that present new concepts for urban air traffic need to explicitly address the shortcomings of current technologies.

传统雷达无法满足对低空 UAM 运行的监控需求。一些运营商提议使用自动依赖监视广播 (ADS-B)；然而，在高密度环境中，ADS-B 频段可能会过度饱和 [115]。应开发能够克服 ADS-B 限制的高级监控系统 [116]。更高的飞行自由度将需要更先进的通信、导航和监视 (CNS) 技术，提出城市空中交通新概念的组织需要明确指出当前技术的不足。

3.3.3. Capacity

3.3.3. 容量

Government agencies agree that airspace should be able to accommodate all air vehicles, regardless of their capabilities and sizes [1,2, 117]. Decisions and projections about capacity will determine the design of airspace. These decisions include the layout of airspace geometries, air traffic control, traffic mix, and separation. The consequences of inadequate capacity are ground delay, airborne delay, increased cost of entering the airspace as well as a possible prioritization of airspace for specific classes. However, capacity is constrained by safety, as well as other factors presented here, and should be determined as one of the many variables in a multivariant optimization.

政府机构同意，空域应能够容纳所有航空器，无论其能力和大小 [1,2, 117]。关于容量的决策和预测将决定空域的设计。这些决策包括空域几何布局、空中交通管制、交通混合和间隔。容量不足的后果包括地面延误、空中延误、进入空域的成本增加，以及可能对特定类别空域的优先分配。然而，容量受到安全性等因素的限制，并应作为多变量优化中的众多变量之一来确定。

3.4. Operational factors - vehicles

3.4. 运营因素 - 航空器

The design of airspace depends on the characteristics of aircraft that use airspace. These aircraft differ in size, speed, maneuverability, autonomy, and CNS capabilities. The resulting airspace will need to reconcile these differences.

空域的设计取决于使用空域的飞机的特性。这些飞机在大小、速度、机动性、自主性和 CNS 能力方面各不相同。所设计的空域需要调和这些差异。

3.4.1. Aircraft type and aircraft mix

3.4.1. 飞机类型和飞机混合

In traditional aviation, the size and maneuverability of an aircraft are important factors in airport planning. They set the dimensional requirements of airport infrastructure and flying procedures. Similar to traditional aviation, the design of landing and take-off pads and airspace structures depends on the type of aircraft. Characteristics such as weight, wingspan, speed, range, materials, maximum altitude, and endurance provide a basis for classification and identification [8,118]. As the new air vehicles emerge, it is crucial to identify their differences and similarities with the existing aircraft and to determine how the mix of these vehicles impacts the constraints of airspace. As the industry of aircraft manufacturing advances, airspace needs to be flexible to accommodate and integrate new types of vehicles.

在传统航空中，飞机的大小和机动性是机场规划中的重要因素。它们决定了机场基础设施和飞行程序的空间尺寸要求。与传统航空类似，着陆和起飞垫以及空域结构的设计取决于飞机的类型。诸如重量、翼展、速度、航程、材料、最大高度和续航能力等特性为分类和识别提供了基础 [8,118]。随着新型航空器的出现，识别它们与现有飞机的差异和相似之处至关重要，同时还需要确定这些航空器的混合使用如何影响空域的限制。随着飞机制造业的进步，空域需要具有灵活性，以适应和整合新型航空器。

3.4.2. Level of autonomy

3.4.2. 自主级别

Automation could overcome some of the deficiencies of the air traffic management system or CNS system and could increase the robustness of the system against interference. As the level of autonomy increases, it is expected that urban airspace will be able to accommodate an increasing number of aircraft. However, there are multiple definitions of levels of autonomy. For example, DroneII [119] proposed six levels (Table 2), The North Atlantic Treaty Organization (NATO) [120] defined four levels (Table 3), The National Institute of Standards and Technology [121,122] proposed a framework of five levels (Table 4), and Air Force Research Laboratory [123] proposed ten levels of autonomy (Table 5).

自动化可以克服空中交通管理系统或 CNS 系统的某些缺陷，并可以提高系统对干扰的鲁棒性。随着自主级别的提高，预计城市空域将能够容纳越来越多的飞机。然而，关于自主级别的定义有多种。例如，DroneII [119] 提出了六个级别 (表 2)，北大西洋公约组织 (NATO)[120] 定义了四个级别 (表 3)，美国国家标准与技术研究院 [121,122] 提出了一个包含五个级别的框架 (表 4)，而空军研究实验室 [123] 提出了十个自主级别 (表 5)。

The first step in creating a single UAM airspace would be to adopt a single classification for aircraft autonomy and, based on it, create procedures and rules of flying. Despite many classifications and levels, the common features that define the level of autonomy are control, perception (situational awareness), decision-making, and communication/cooperation [123]. These features could be a start in defining a single classification system. There will likely be a transitional period where the airspace will accept both manned and unmanned aircraft of different levels of autonomy. To accommodate this traffic, the controllers or the designers of the system will need to separate their operations.

创建单一 UAM 空域的第一步将是采用单一的飞机自主性分类，并在此基础上创建飞行程序和规则。尽管有许多分类和级别，但定义自主性级别的共同特征是控制、感知 (态势感知)、决策和通信/合作 [123]。这些特征可以作为定义单一分类系统的起点。可能存在一个过渡期，在此期间空域将接受不同自主级别的有人和无人飞机。为了适应这种交通流量，控制器或系统设计者将需要分离他们的操作。

Table 2
表格 2
Levels of autonomy by DroneII [119].
DroneII 的自主级别 [119]。

LEVEL	DESCRIPTION	CONTROL	USE
0	No automation	Pilot in full control.	Recreational drones
1	Pilot assistance	Pilot in control, drone controls at least one vital function.	Inspection and maintenance, photography, monitoring
2	Partial Automation	Pilot is responsible, drone controls heading, altitude and speed.	Mapping, surveying, spaying and seeding in agriculture
3	Conditional Automation	Pilot is a backup; drone performs all functions given a set of conditions.	Mapping, surveying
4	High Automation	Drone in control under a fixed set of rules. Human may not be needed.	Photography, filming, delivery
5	Full Automation	Drone in control, no expectation of human intervention.	Passenger transport

等级	描述	控制	使用
0	无自动化	飞行员完全控制。	娱乐无人机
1	飞行员辅助	飞行员控制，无人机至少控制一个关键功能。	检查与维护、摄影、监控
2	部分自动化	飞行员负责，无人机控制航向、高度和速度。	地图绘制、测量、农业中的喷洒和播种
3	有条件自动化	飞行员作为备份；在给定一组条件下，无人机执行所有功能。	映射，测量
4	高自动化	无人机在固定的规则集下控制。可能不需要人类。	摄影，摄像，送货
5	完全自动化	无人机控制，不期望人类干预。	客运

Table 3
表格 3
Levels of autonomy by NATO [120].
北约的自主级别 [120]。

LEVEL	DESCRIPTION	CAPABILITY
1	Remotely controlled system	Actions depend on operator input.
2	Automated system	Actions depend on fixed built-in functionality (preprogrammed).
3	Autonomous non-learning system	Actions depend upon a fixed set of rules.
4	Autonomous learning system with the ability to modify rules	Actions depend upon a set of rules that can be modified for continuously improving goal directed reactions.

等级	描述	能力
1	遥控系统	行为依赖于操作员的输入。
2	自动化系统	行为依赖于固定的内置功能 (预编程)。
3	自主非学习系统	行为依赖于一套固定的规则。
4	具有修改规则能力的自主学习系统	行为依赖于一套可以修改以实现持续改进目标导向反应的规则。

Table 4
表格 4
Levels of autonomy by National Institute of Standards and Technology [121,
美国国家标准与技术研究院的自主级别 [121]，122].

LEVEL	DESCRIPTION	CAPABILITY
1	Remote control	No tactical behavior.
2	High-level human input	Low-level tactical behavior in simple environment.
3	Mid-level human input	Multi-functional missions in moderate environment.
4	Low-level human input	Collaborative, high-complexity missions in difficult environment.
5	No human input	All missions in extreme environments.

等级	描述	能力
1	遥控	没有战术行为。
2	高级别的人类输入	在简单环境中的低级别战术行为。
3	中级别的人类输入	在适中环境中的多功能任务。
4	低级别的人类输入	在困难环境中的协作、高复杂性任务。
5	没有人类输入	在极端环境中的所有任务。

3.4.3. Energy efficiency

3.4.3. 能源效率

The endurance of batteries imposes severe constraints on the operational time of an electric UAM aircraft. Several solutions have been proposed, including a more efficient rotor configuration [124], the use of novel lightweight materials [125], and dumping exhausted battery modules out of the aircraft in flight [126]. A most realistic option, however, is to select trajectories that minimize energy consumption [12, 127-129]. In Ref. [127], the authors proposed an energy-efficient path-planning strategy for a hexacopter. The authors found that the best results are achieved by flying at lower altitudes and by flying a shallower descent. Another study found that cruise efficiency drops with an increase in cruise altitude [12].

电池的续航能力对电动 UAM 飞机的运行时间造成了严重限制。已经提出了几种解决方案，包括更高效的旋翼配置 [124]、使用新型轻质材料 [125]，以及在飞行中抛掉耗尽的电池模块 [126]。然而，最现实的选择是选择最小化能耗的轨迹 [12, 127-129]。在文献 [127] 中，作者提出了一种针对六旋翼无人机的节能路径规划策略。作者发现，在较低高度飞行和进行较浅的下降可以获得最佳结果。另一项研究发现，巡航效率随着巡航高度的增加而下降 [12]。

What is evident is that the operators and individual aircraft will look to optimize their paths to minimize energy consumption. Given the findings that energy efficiency drops with cruise altitude, the goal of minimizing energy consumption conflicts with other goals of reducing noise exposure or increasing capacity. A common theme emerges: optimizing for a single factor might provide a sub-optimal system solution. Therefore, the design of airspace structures and routes should carefully consider energy consumption in the context of efficiency, but also other critical factors, such as safety and community acceptance.

显然，操作员和单架飞机将寻求优化其航线以最小化能耗。考虑到巡航高度上能源效率下降的发现，最小化能耗的目标与其他目标，如减少噪声暴露或提高容量相冲突。一个共同的主题出现了: 仅针对单一因素进行优化可能会提供次优的系统解决方案。因此，在设计空域结构和航线时，应仔细考虑在效率背景下能耗的问题，同时也要考虑其他关键因素，如安全和社区接受度。

Table 5

表 5

Levels of autonomy by Air Force Research Laboratory [123].

美国空军研究实验室的自主级别 [123]。

LEVEL	DESCRIPTION	CAPABILITY	SEPARATION
0	Remotely piloted vehicle	Altitude sensing.	Several miles
1	Execute preplanned missions	Flight control and navigation sensing. All actions are preplanned.	Several miles
2	Pre-loaded alternative plans	Automatic trajectory execution. External commands.	Several miles
3	Limited response to real time events	Automatic trajectory execution. Ability to compensate for limited failures.	Several miles
4	Robust response to anticipated events	Automatic trajectory execution. Ability to compensate for most failures.	Hundreds of yards
5	Event adaptive vehicle	On-board derived vehicle trajectory. Ability to compensate for most failures. Ability to predict onset of failures.	<100 yards
6	Real time multi- vehicle coordination	Detection of other aircraft in local airspace. On-board collision avoidance.	<100 yards
7	Real time multi- vehicle cooperation	Continuous flight path evaluation. Trajectory optimization. On-board collision avoidance. Off-board data sources for deconfliction & tracking	Not required
8	Multi-vehicle mission performance optimization	Detection & tracking of other air vehicles within local airspace. Operation in controlled airspace without external control. On-board deconfliction & collision avoidance.	Not required
9	Multi-vehicle tactical performance optimization	Detection & tracking of other air vehicles within airspace. Full decision making capability on-board. Full independence.	Not required

等级	描述	能力	分离
0	遥控驾驶车辆	高度感知。	几英里
1	执行预先计划的任务	飞行控制和导航感知。所有行动都是预先计划的。	几英里
2	预加载的替代计划	自动轨迹执行。外部命令。	几英里
3	对实时事件反应有限	自动轨迹执行。能够补偿有限的故障。	几英里
4	对预期事件的鲁棒响应	自动轨迹执行。能够补偿大多数故障。	数百码
5	事件自适应车辆	车载推导的车辆轨迹。能够补偿大多数故障。能够预测故障的起始。	<100 码
6	实时多车辆协调	检测局部空域中的其他飞机。车载避撞。	<100 码
7	实时多车辆合作	连续飞行路径评估。轨迹优化。车载避撞。利用外部数据源进行冲突解除和跟踪	不需要
8	多车辆任务性能优化	在本地空域内检测和跟踪其他航空器。在受控空域内无需外部控制进行操作。机上冲突解除与避碰。	不需要
9	多车辆战术性能优化	在空域内检测和跟踪其他航空器。完全的机上决策能力。完全独立。	不需要

The list of the studies presented in this chapter can be found in Table 6, grouped by the relevant factors. These factors are used to assess the airspace concepts presented in Section 4.

本章呈现的研究列表可以在表 6 中找到，按相关因素分组。这些因素用于评估第 4 节中提出的空域概念。

Table 6

表 6

List of relevant studies grouped by the factors that impact airspace design.

按影响空域设计的因素分组的相关研究列表。

Group	Factor		Studies
Safety	Object avoidance	Separation	[32-36,130]
		Sense-and-avoid	[39-41]
		Aircraft avoidance	[30,35,43]
		Static Geofence	[25,34,45,131-135]
		Dynamic Geofence	[25,34,38,132,135]
	Wind gusts		[51,52,59,60]
	Weather		[67-70]
Social	Noise		[15,74–76,84–86]
	Privacy		[25,103,104,137]
	Visual pollution		[94-97]
System	Air Traffic Management		[21,106–108]
	Communication, Navigation, and Surveillance		[109–114]
	Capacity		[1,18,22,117]
Vehicle	Aircraft type		[8,118]
	Autonomy		[119-123]
	Energy efficiency		[12,127-129]

群体	因素		研究
安全	避障	分离	[32-36,130]
		感知与避让	[39-41]
		飞机避障	[30,35,43]
		静态地理围栏	[25,34,45,131-135]
		动态地理围栏	[25,34,38,132,135]
	阵风		[51,52,59,60]
	天气		[67-70]
社会因素	噪音		[15,74–76,84–86]
	隐私		[25,103,104,137]
	视觉污染		[94-97]
系统	空中交通管理		[21,106–108]
	通信、导航与监视		[109–114]
	容量		[1,18,22,117]
航空器	飞机类型		[8,118]
	自主性		[119-123]
	能源效率		[12,127-129]

4. Review of urban airspace design concepts

4. 城市空域设计概念的回顾

This section assesses the most important government- and industry-led urban airspace design initiatives around the world, and then summarizes and evaluates the most relevant factors, which are classified into four groups: safety, social, system, and vehicle factors.

本节评估了全球范围内政府主导和行业主导的最重要的城市空域设计倡议，然后总结和评估了最相关的因素，这些因素被分为四组: 安全因素、社会因素、系统因素和车辆因素。

4.1. Government-led initiatives

4.1. 政府主导的倡议

4.1.1. FAA-NASA UAS traffic management (UTM)

4.1.1. FAA-NASA 无人机交通管理 (UTM)

The UAS Traffic Management (UTM) [1,138,139] is a project by NASA that aims to enable small, unmanned drones to access low-altitude airspace beyond visual line of sight (BVLOS) with minimal impact to the existing aviation system (Fig. 6). The low-altitude airspace is defined as airspace below 400ft , where the UTM operations are segregated from other airspace users. The development of UTM is sequenced in four Technical Capability Levels (Table 7), with the simple, remote, and rural operations in the first phase, and dense urban operations in the fourth phase [139]. In the initial stages, the existing technology and separation procedures will be used to facilitate operations, while the improvement of technologies such as detect-and-avoid, in-flight separation service, and contingency procedures will enable future phases.

无人机交通管理 (UTM)[1,138,139] 是美国国家航空航天局 (NASA) 的一个项目，旨在使小型无人驾驶无人机能够在不影响现有航空系统的情况下，进入低空空域进行超视距飞行 (BVLOS)(图 6)。低空空域定义为 400ft 以下的空域，UTM 操作与其他空域用户隔离。UTM 的开发分为四个技术能力等级 (表 7)，第一阶段是简单、远程和农村地区的操作，第四阶段是密集城市的操作 [139]。在最初阶段，将使用现有的技术和分离程序来促进操作，而探测与避让、飞行中分离服务以及应急程序的改进将使得未来阶段成为可能。

Although UTM is envisioned as a low-altitude region in uncontrolled (Class G airspace), NASA does plan to integrate UAS operations in other airspace classes [140]. In the controlled airspace, UAS are segregated from controlled air traffic by creating transition tunnels, or blocks of airspace reserved for UAS operations. Alternatively, UAS operations can be integrated into the controlled air traffic flows where they will behave the same as traditional aviation [140].

尽管 UTM 被设想为不受控制的低空区域 (G 类空域)，但 NASA 计划将无人机系统 (UAS) 的操作集成到其他空域类别中 [140]。在受控空域中，通过创建过渡隧道或为 UAS 操作保留的空域块，将 UAS 与受控航空交通隔离开。或者，UAS 操作可以集成到受控航空交通流中，它们的行为将与传统航空相同 [140]。

The operators (drone pilots) are responsible for submitting a flight plan and for maintaining separation from other aircraft. The plan contains information about the airspace volume, times, and locations of the operation. While UTM provides advisories, weather information, and other observations, the operator is responsible for the planning and execution of the safe flight, identification of unexpected operational conditions, or hazards that may affect their operation. The stage-four UTM will provide authentication, geofencing, capacity management, airspace corridors, weather integration, trajectory management, contingency management, and the dynamic adjustments of the system. The FAA will maintain the link between UTM and NAS and create real-time airspace constraints for UAS Operators [140].

操作员 (无人机驾驶员) 负责提交飞行计划，并与其他航空器保持分离。计划包含有关空域体积、操作时间和地点的信息。虽然 UTM 提供咨询、气象信息和其他观测数据，但操作员负责安全飞行的规划和执行、识别可能影响其操作的非预期操作条件或危险。第四阶段的 UTM 将提供身份验证、地理围栏、容量管理、空域走廊、气象整合、轨迹管理、应急管理和系统的动态调整。联邦航空管理局 (FAA) 将保持 UTM 与国家空域系统 (NAS) 之间的联系，并为无人机操作员创建实时空域约束 [140]。

The existing technologies used currently for NAS and in the initial phases of UTM for surveillance and navigation are ADS-B and GPS. Although the initial tests showed that these technologies could be used for UTM, experiments by NASA show that ADS-B can be used for surveillance only in a limited scope, at very low power, low traffic, and short distances. At higher traffic densities, the use of ADS-B will adversely affect manned aviation surveillance [141]. Despite these limitations, the goal for initial UTM implementation is to minimize development time by utilizing existing technologies [142].

现有技术目前用于 NAS 和 UTM 的初始阶段进行监控和导航的是 ADS-B 和 GPS。尽管最初的测试表明这些技术可以用于 UTM，但 NASA 的实验表明，ADS-B 只能在有限的范围内、在非常低的功率、低流量和短距离内用于监控。在更高的流量密度下，使用 ADS-B 将对有人驾驶航空监控产生不利影响 [141]。尽管存在这些限制，初始 UTM 实施的目标是通过利用现有技术来最小化开发时间 [142]。

In the initial phases, UTM will not provide much airspace structure, as aircraft will fly on user-selected pre-approved routes. While the UTM project does raise concerns about social factors, the selection of routes is currently not constrained by social factors.

在初始阶段，UTM 不会提供太多的空域结构，因为飞机将在用户选择的预先批准的路线上飞行。虽然 UTM 项目确实引起了对社会因素的关注，但目前路线的选择并未受到社会因素的制约。

4.1.2.FAA urban air mobility (UAM) concept of operations

4.1.2.FAA 城市空中出行 (UAM) 操作概念

The FAA forecasts increased demand for alternative modes of air transportation enabled by the progress in electric aircraft technology and vertical take-off and landing capabilities. New vehicles can be incorporated into airspace by creating new airspace structures. Fig. 7 illustrates the FAA's approach to the relationship between UAM, UTM, and ATM operations within different airspace classes.

FAA 预测，随着电动飞机技术的进步和垂直起降能力的实现，对替代航空运输模式的需求将会增加。新车辆可以通过创建新的空域结构融入空域。图 7 说明了 FAA 在 UTM、UAM 和不同空域类别中的 ATM 操作之间关系的方法。

Under the FAA's proposal, UAM operations are conducted in UAM Corridors without ATC separation services. The corridors are the mechanism of separation between UAM and other operations. Within the corridors, separation is maintained by UAM operators, which in the initial phases of UAM operation, includes pilot on board. Each corridor will have performance requirements (such as maneuverability or sense-and-avoid capabilities) to ensure more efficient operations. Different corridors may have different requirements. Initially, the corridors will connect two UAM aerodromes to support point-to-point operations. In the later stages, the FAA expects the development of more complex and efficient networks that move away from point-to-point operations.

根据 FAA 的提案，UAM 操作在没有 ATC 分离服务的 UAM 走廊内进行。走廊是 UAM 与其他操作之间的分离机制。在走廊内，分离由 UAM 运营商维持，在 UAM 操作的初始阶段，包括在机上的飞行员。每个走廊都将有性能要求 (如机动性或感知-避让能力)，以确保更高效的操作。不同的走廊可能有不同的要求。最初，走廊将连接两个 UAM 机场，以支持点对点操作。在后期阶段，FAA 预计将开发更复杂和高效的网络，这些网络将摆脱点对点操作。

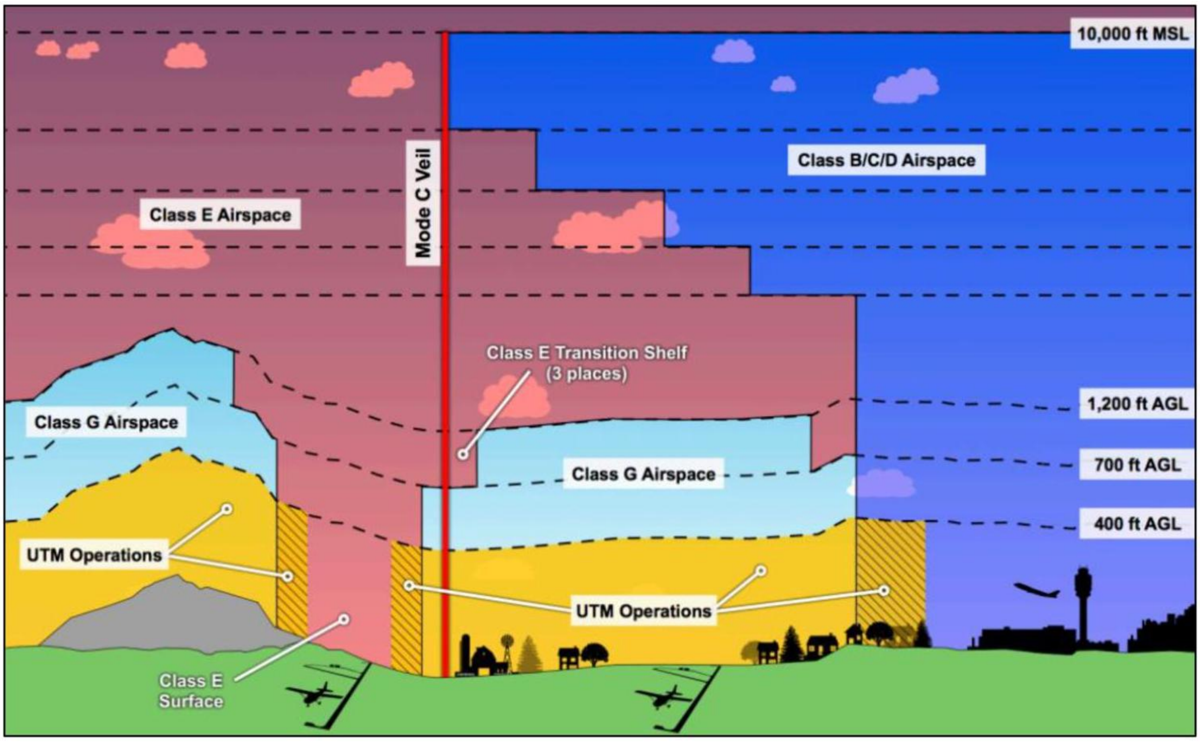


Fig. 6. NASA's UTM system would integrate UAS operations in the airspace above buildings and below traditional aviation operations [139].

图 6. 美国国家航空航天局 (NASA) 的无人机交通管理系统 (UTM) 将把无人机系统 (UAS) 的操作集成到建筑物上空和传统航空作业以下的空域 [139]。

Table 7

表 7

NASA's Technical Capability Levels [139].

美国国家航空航天局 (NASA) 的技术能力等级 [139]。

Technical Capability Levels (TLC)				
	TCL 1	TCL 2	TCL 3	TCL 4
Population	Remote	Sparse	Moderate	Dense
Traffic density	Low	Low	Moderate	High
Application	Rural	Industrial	Suburban	Urban
Other	Notification based operation	Tracking procedures	V2V communication	Large-scale contingency management

技术能力水平 (TLC)				
	TLC 1	TCL 2	TCL 3	TCL 4
人口	遥远的	稀疏的	中等的	稠密的
交通密度	低	低	中等的	高
应用	乡村	工业	郊区	城市
其他	基于通知的操作	跟踪程序	车与车通信 (V2V)	大规模应急事务管理

The FAA posits that corridor design criteria should include 1) Minimal impact on the existing NAS operations, 2) Public interest considerations, such as noise, safety, and security, and 3) Customer needs. Within the corridor, additional structure - ”tracks” may exist. The ”tracks” enable additional separation of aircraft with different technological capabilities (Fig. 8).

美国联邦航空局 (FAA) 提出，走廊设计标准应包括:1) 对现有国家空域系统 (NAS) 操作的最小影响，2) 公共利益考虑，如噪音、安全和保安，以及 3) 客户需求。在走廊内，可能存在额外的结构 - ” 轨道”。这些” 轨道” 使得不同技术能力的飞机之间有额外的分离 (图 8)。

Centralized air traffic management services provide weather, terrain, and obstacle data. UAM operators are also responsible for constantly monitoring weather and winds prior to and throughout the flight. If the performance of aircraft is inadequate to maintain safety in the forecasted weather, the flight should be postponed.

集中的空中交通管理服务提供天气、地形和障碍物数据。城市空中交通 (UAM) 运营商还有责任在飞行前和整个飞行过程中不断监控天气和风速。如果飞机的性能不足以在预报的天气中保持安全，则应推迟飞行。

4.1.3. NASA UAS traffic flow control (UTFC) in urban areas

4.1.3. 美国国家航空航天局 (NASA) 在城市区域的无人机交通流量控制 (UTFC)

In another concept proposed by NASA [22], the urban airspace is divided into multiple layers (Fig. 9). Each layer contains an airspace structure located above a street, which creates multi-level networks between densely located tall buildings (Fig. 10). Three types of airspace structures are considered: sky-lane, sky-tube, and sky-corridor. Each structure provides a different number of degrees of freedom. Sky-lanes are the most restrictive in terms of altitude, heading, speed, and position, whereas sky-corridor allows the most freedom. The UAS traffic flow control (UTFC) controls density and throughput, supervises directional flows of traffic, provides traffic information, identifies unauthorized flights, and sends safety advisories.

在 NASA 提出的另一个概念中 [22]，城市空域被划分为多个层次 (图 9)。每一层都包含位于街道上方的空域结构，这在大楼密集地区之间创建了多层网络 (图 10)。考虑了三种类型的空域结构: 天空巷道、天空管道和天空走廊。每种结构提供了不同数量的自由度。天空巷道在高度、航向、速度和位置方面最为限制，而天空走廊允许最大的自由度。无人机交通流量控制 (UTFC) 控制密度和吞吐量，监管交通的方向流动，提供交通信息，识别未经授权的飞行，并发送安全通告。

The structures are designed to assure the level of safety while minimizing investments in infrastructure and technology. More structure provides more predictable operations and thus requires less technical support. Additionally, with more structure, it is easier to segregate aircraft based on their capabilities, which increases safety and reduces the number of potential conflicts. Finally, more structure provides robustness to system failure and scalability [22].

这些结构被设计来在最小化基础设施和技术投资的同时确保安全水平。更多的结构提供了更可预测的运行，因此需要较少的技术支持。此外，结构越多，越容易根据飞机的能力对它们进行分离，这提高了安全性并减少了潜在的冲突数量。最后，更多的结构为系统故障提供了鲁棒性，并且具有可扩展性 [22]。

The same study [22] tested different structures, and the results show that more structure (sky-lanes) provides a safer and simpler environment. However, more complexity reduces capacity and increases delays. The corridors provide less structure which increases capacity but also increases the probability of loss of separation. The comparison of these structures is presented in Table 8.

同一项研究 [22] 测试了不同的结构，结果显示更多的结构 (天路) 提供了一个更安全、更简单的环境。然而，更多的复杂性会降低容量并增加延迟。走廊提供了较少的结构，这增加了容量，但也增加了失去间隔的可能性。这些结构的比较在表 8 中呈现。

In this concept, each vehicle is responsible for maintaining separation and avoiding collision within the lane or while changing lanes, turning, or exiting the lane. The authors do not include considerations about social factors, or the technologies needed for the concept to work.

在这个概念中，每个车辆负责在车道内或变更车道、转弯或离开车道时保持间隔和避免碰撞。作者没有包括关于社会因素或实现该概念所需技术的考虑。

4.1.4. MITRE

4.1.4. MITRE

MITRE proposed a concept of augmented Visual Flight Rules operations [143], which enables UAM aircraft to operate in Class G airspace under the existing Visual Flight Rules by using detect-and-avoid capabilities. If the aircraft needs to enter controlled airspace, the Dynamic Delegated Corridors are created. The Dynamic Corridor allows UAM aircraft to fly in busy airspace by defining specific tunnels in NAS and segregating traffic (Fig. 11).

MITRE 提出了一个增强视觉飞行规则操作的概念 [143]，这使得城市空中交通 (UAM) 飞机能够通过使用检测和避让能力，在现有的视觉飞行规则下在 G 类空域中运行。如果飞机需要进入受控空域，将创建动态委托走廊。动态走廊允许 UAM 飞机通过在空管系统 (NAS) 中定义特定的隧道并分离流量，在繁忙空域中飞行 (图 11)。

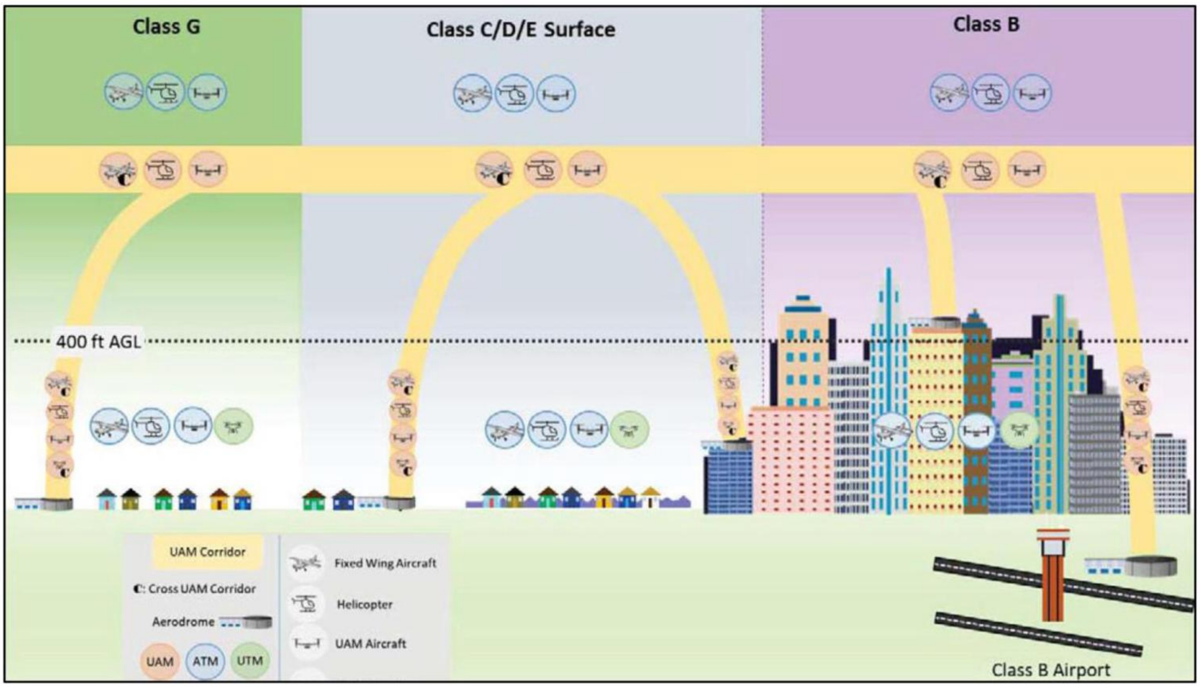


Fig. 7. UAM, UTM and ATM Operating Environments [1].
图 7. UAM、UTM 和 ATM 运行环境 [1]。

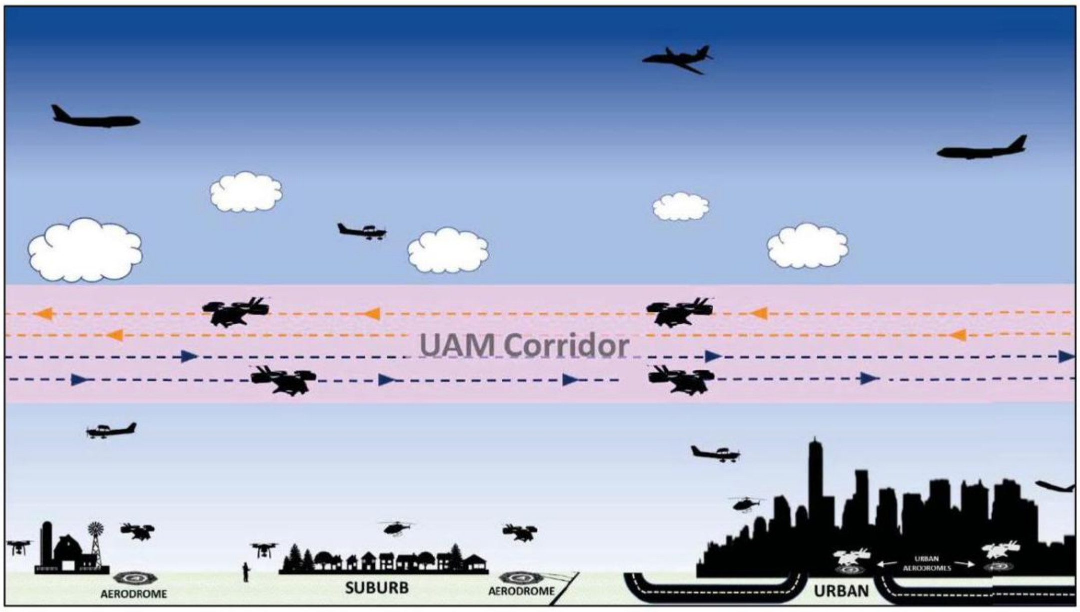


Fig. 8. FAA's UAM Corridors with tracks [1].
图 8. FAA 的 UAM 走廊及轨迹 [1]。

Aircraft will need to be equipped and supported by a wide variety of decision support tools, as the onboard technology will be responsible for maintaining separation and conducting avoidance maneuvers. Additionally, these tools will provide information such as traffic conditions, corridor position and heading, weather advisories, and airspace flight rules. The air traffic management system and architecture will be similar to UTM, with more stringent safety standards.

飞机将需要配备和支持各种决策支持工具，因为机载技术将负责保持间隔和执行避障机动。此外，这些工具还将提供诸如交通状况、走廊位置和航向、天气警告以及空域飞行规则等信息。空中交通管理系统和架构将与 UTM 相似，但将采用更为严格的安全标准。

The priority will be given to aircraft with better technology, such as advanced detect-and-avoid, noise reduction capabilities, navigation precision technology, and vehicle-to-vehicle (V2V) communication technology. More capable aircraft will be able to fly the most efficient preferred routes. The hope is that under this approach, the operators will have an incentive to improve capabilities which would increase airspace capacity and safety. However, the impacts of mixed-equipage operations on the system should be carefully investigated and understood.

优先权将赋予拥有更好技术的飞机，例如先进的检测与避障能力、降噪能力、导航精度技术以及车对车 (V2V) 通信技术。能力更强的飞机将能够飞行最高效的偏好航线。希望在这种方法下，运营商将会有改进能力的激励，这将提高空域容量和安全。然而，应当仔细调查和理解混合装备操作对系统的影响。

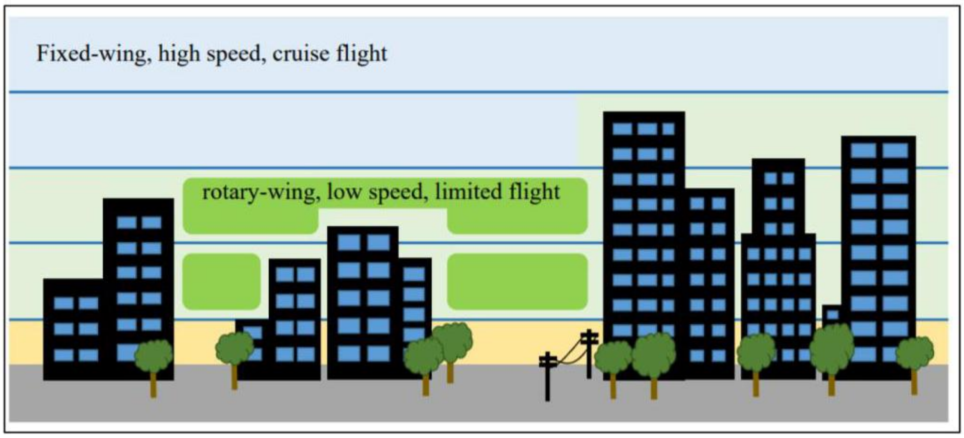


Fig. 9. NASA UAS traffic flow control: Vertical layers of the airspace in urban areas.

图 9. 美国宇航局 UAS 交通流量控制: 城市区域空域的垂直层次。

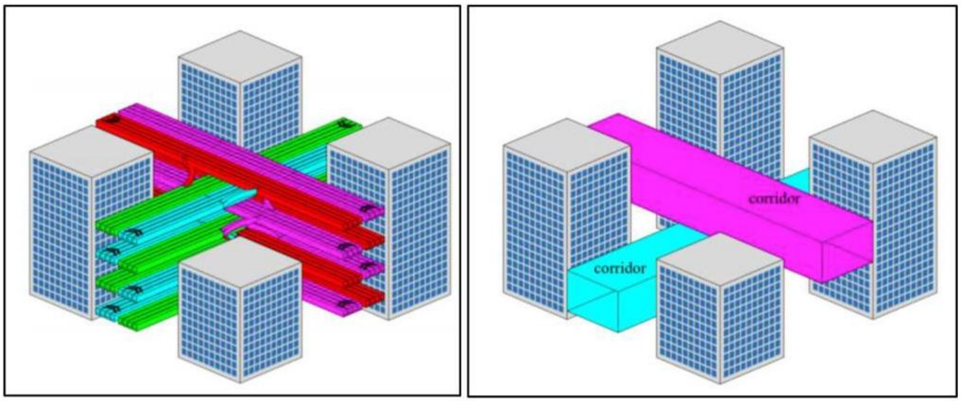


Fig. 10. NASA UAS traffic flow control: Composition of airspace structures: sky-lanes (left) and corridors (right) [22].

图 10. 美国宇航局 UAS 交通流量控制: 空域结构的组成: 天路 (左) 和走廊 (右)[22]。

Table 8

表 8

Comparison of airspace structures in UTFC [22].

UTFC 中空域结构的比较 [22]。

Structure	Advantage	Disadvantage
Sky-lane	Reduces traffic complexity, similar to roads on the ground.	Increases delay; Vulnerable to a wind gust; Requires traffic control signals, low capacity.
Sky-tube	Simple, flexible flight.	Requires traffic flow control.
Corridor	Flexible flight, high capacity.	Requires rules for separation assurance and collision avoidance.

结构	优点	缺点
天空通道	降低交通复杂性，类似于地面上的道路。	增加延迟；容易受到阵风影响；需要交通控制信号，容量低。
天空管道	简单，灵活的飞行。	需要交通流量控制。
走廊	灵活的飞行，高容量。	需要制定分离保证和避碰规则。

4.1.5. SESAR U-SPACE

4.1.5. SESAR U-SPACE

U-space is a project initiated by the European Commission to allow drones to operate in low-level airspace, at an altitude of up to 150 m [144]. U-space provides a framework to support routine drone operations and creates rules for interactions with manned aviation. Initially, flights will be allowed to operate only in small parts of reserved airspace. However, as technology improves, the operations will spread to other parts of airspace in four stages:

U 空间是由欧盟委员会发起的一个项目，旨在允许无人机在低空空域内，在高达 150 m [144] 的海拔高度上运行。U 空间提供了一个框架，以支持常规无人机操作，并制定了与有人驾驶航空互动的规则。最初，飞行仅允许在预留空域的小部分内进行。然而，随着技术的改进，操作将在四个阶段扩展到空域的其他部分:

- The first stage provides basic services such as identity (ID) registration and static geofencing to identify drones and inform operators about restricted areas. The majority of operations will happen in low-density regions. However, some visual line of sight (VLOS) operations in the urban environment are allowed.
- 第一阶段提供基本服务，如身份 (ID) 注册和静态地理围栏，以识别无人机并告知操作员受限区域。大多数操作将在低密度区域进行。然而，城市环境中的一些视距内操作 (VLOS) 是被允许的。
- The second stage connects drones to the ATC and manned aviation. Where appropriate, the existing infrastructure will be used, but new technologies, such as 5 G , and mix of 5 G and ADS-B, will also be implemented. The range of VLOS operations in uncontrolled and controlled airspace will be increased. Operations will be approved automatically, and some beyond the visual line of sight (BVLOS) will be allowed.
- 第二阶段将无人机与空中交通管制 (ATC) 和有人驾驶航空连接起来。在适当的情况下，将使用现有的基础设施，但也会实施新技术，如 5 G ，以及 5 G 与 ADS-B 的混合。在不受控和受控空域中，VLOS 操作的范围将增加。操作将自动获得批准，某些超视距 (BVLOS) 操作将被允许。
- The third stage introduces operations in high-density and high-complexity areas. Detect-and-avoid, as well as reliable means of communication, will enable an increase of operations in all environments. Interactions with ATM/ATC and manned aviation will become routine. New operations, such as urban air mobility, are expected to occur.
- 第三阶段引入在高度密集和高度复杂区域内的操作。探测与避让，以及可靠的通信手段，将使得所有环境中的操作数量增加。与空中交通管理 (ATM)/空中交通管制 (ATC) 和有人驾驶航空的互动将成为常规。预计将出现新的操作，如城市空中出行。
- The fourth stage fully integrates unmanned with ATM/ATC and manned aviation by leveraging high levels of automation.
- 第四阶段通过利用高度自动化，将无人机完全与空中交通管理 (ATM)/空中交通管制 (ATC) 和有人驾驶航空集成。

In addition to stages, airspace is partitioned in X, Y , and Z airspace (Fig. 12). Airspace X is low-risk airspace with few basic requirements from the operator. The pilot remains responsible for collision avoidance, and only visual-line-of-sight operations are allowed. In Airspace Y , an approved flight plan is needed, the pilot needs to be trained for Y operations, and BVLOS operations are allowed. Airspace Z also requires a pre-approved flight plan, provides centralized capacity management and coordination between aircraft.

除了阶段之外，空域被划分为 X, Y 和 Z 空域 (图 12)。空域 X 是低风险空域，对操作员的基本要求很少。飞行员仍负责避碰，只允许视距内操作。在空域 Y 中，需要批准的飞行计划，飞行员需要接受 Y 操作的培训，并允许 BVLOS 操作。空域 Z 还需要一个预先批准的飞行计划，提供集中化的容量管理和飞机之间的协调。

Under U-Space rules, social acceptance indicators such as noise, privacy, and visual impact must be considered. For example, under U-Space rules, the aircraft will be issued noise certificates that attest compliance with noise regulation. However, the airspace is not designed in a way that can address these issues.

在 U-Space 规则下，必须考虑社会接受度指标，如噪音、隐私和视觉影响。例如，在 U-Space 规则下，飞机将被颁发噪音证书，证明符合噪音规定。然而，空域的设计并未以一种能够解决这些问题的方式进行。

4.1.6.DLR U-SPACE

4.1.6.DLR U-SPACE

The concept proposed by The German Aerospace Center - Deutsches Zentrum für Luft-und Raumfahrt (DLR) [146] integrates new airspace users, such as UAS and air taxis into uncontrolled airspace (Class G). The airspace is segmented into regions (”cells”) for users of similar characteristics. Characteristics such as aircraft level of autonomy and equipage, availability of U-space traffic control, and occurrence of VFR-traffic are considered, and airspace is segmented so that vehicles of similar characteristics are flying in the same cell. Within a cell, each aircraft is modeled by an ellipsoid based on its performance parameters, such as automation, navigation, communication, and surveillance capabilities (Fig. 13). The lower the capabilities, the larger the safety ellipsoid around the aircraft. As a result, a cell capacity might be reached with only a few air vehicles with a large ellipsoid, or by more aircraft with smaller ellipsoids. Vehicle operators must maintain the separation between two air vehicles. The air traffic management system creates geofences, which can be static, such as terrain and ground obstacles and permanent no-fly zones, or dynamic, such as temporary closure of airspace due to weather or special event. While the U-Space concept does not explicitly mention wind gusts, it does leave the possibility to create a dynamic geofence in the case of severe weather events, such as heavy winds or rains.

德国航空航天中心 - 德意志航空和航天中心 (DLR)[146] 提出的概念将新的空域用户，如无人机系统 (UAS) 和空中出租车集成到不受控制的空域 (G 类)。空域被划分为具有相似特征的用户区域 (” 单元”)。考虑到飞机的自主等级和装备水平、U-space 交通控制的可用性以及目视飞行规则 (VFR) 交通的出现，空域被划分，以便具有相似特征的车辆在同一单元中飞行。在单元内，每架飞机根据其性能参数 (如图 13 所示)，如自动化、导航、通信和监视能力，用一个椭球体建模。能力越低，飞机周围的安全椭球体越大。因此，一个单元的容量可能只由少数带有大椭球体的航空器达到，或者由更多带有小椭球体的飞机达到。航空器运营商必须保持两架航空器之间的分离。空中交通管理系统创建地理围栏，可以是静态的，如地形和地面障碍物以及永久禁飞区，也可以是动态的，如因天气或特殊事件而临时关闭空域。虽然 U-Space 概念没有明确提及阵风，但它确实为在严重天气事件 (如强风或大雨) 的情况下创建动态地理围栏留下了可能性。

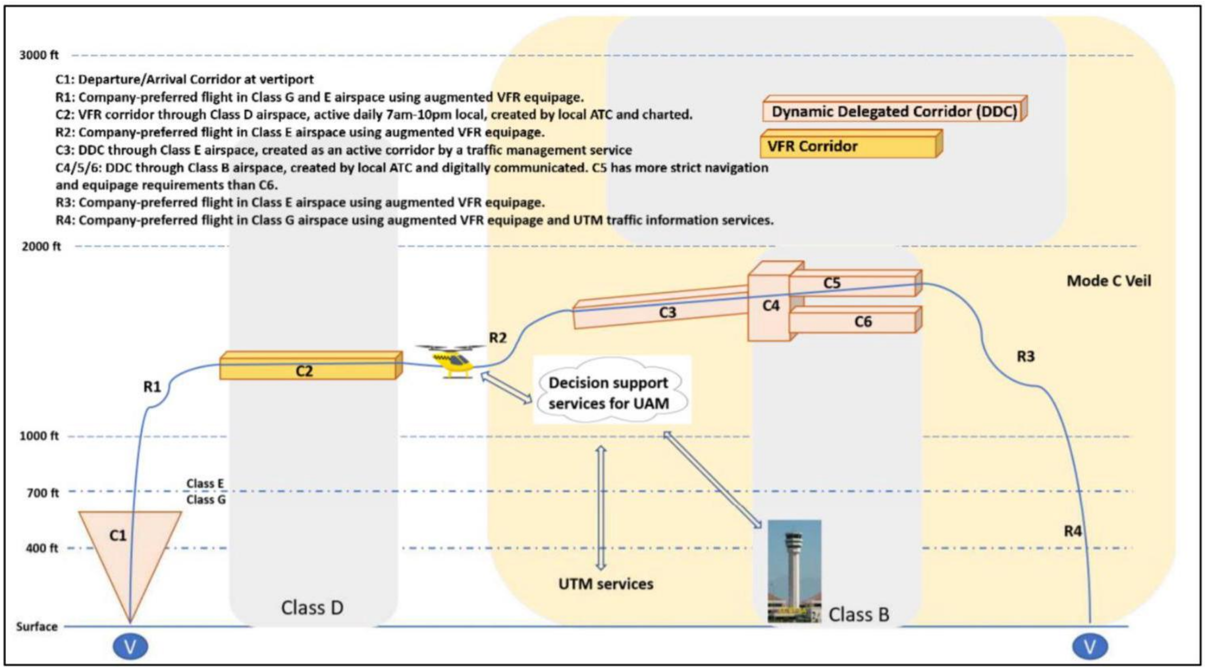


Fig. 11. Airspace integration concept by MITRE [143].

图 11. MITRE [143] 的空域集成概念。

The role of the traffic management system is to segment the airspace, set up the geofences, and approve flight paths within predefined time slots in a first-come-first-serve fashion. On the tactical level, ATC monitors position, altitude, and heading of aircraft and sends traffic, geo-fence, or weather advisories to aircraft. The surveillance is achieved by ADS-B and through the LTE network. Communication to the aircraft could be conducted through LTE, Open Glider Network, or very high frequency (VHF) data link, depending on the aircraft’s capabilities and equipage. A special segment of airspace is dedicated to VFR flights with limited communication abilities.

交通管理系统的角色是分割空域，建立地理围栏，并按照先来先服务的原则在预定义的时间槽内批准飞行路径。在战术层面，空中交通管制 (ATC) 监控飞机的位置、高度和航向，并向飞机发送交通、地理围栏或天气咨询。监控是通过自动相关监视广播 (ADS-B) 和通过 LTE 网络实现的。与飞机的通信可以通过 LTE、开放滑翔机网络或甚高频 (VHF) 数据链进行，这取决于飞机的能力和装备。空域的一个特殊部分被指定用于具有有限通信能力的目视飞行规则 (VFR) 飞行。

From the user perspective, the advantage of the proposed concept is that it opens the airspace equally for aircraft with low and high technical capabilities and provides safety by segregating them. This approach minimizes complexity, but it also reduces the capacity of overall airspace since some cells might be underutilized. At low density, air vehicles have a lot of freedom in terms of route selection, but at high densities, they are required to follow predefined trajectories. The management system monitors the airspace requirements and the planned aircraft missions and updates the segments accordingly over time.

从用户的角度来看，所提出概念的优势在于它平等地为技术能力高低不同的飞机开放空域，并通过分离它们来提供安全。这种方法降低了复杂性，但也减少了整体空域的容量，因为某些单元可能会未被充分利用。在低密度情况下，航空器在航线选择上有很大的自由度，但在高密度情况下，它们需要遵循预定义的轨迹。管理系统监控空域需求和计划中的飞机任务，并相应地随时间更新单元。

The concept of cells does not explicitly consider social factors, such as noise, or privacy, as social factors do not explicitly constrain the position or size of the cell. This issue could be solved by creating a geofence.

单元的概念没有明确考虑社会因素，如噪音或隐私，因为社会因素并没有明确限制单元的位置或大小。这个问题可以通过创建地理围栏来解决。

4.1.7. METROPOLIS

4.1.7. 大都市

The authors of the project Metropolis [24,147] proposed four different types of urban airspace for unmanned aerial vehicles (UAVs) and personal air vehicles (PAV): full mix, layers, zones, and tubes. The minimum cruise altitude for all four concepts is 300ft above ground and 100 ft (UAVs)/500 ft (PAVs) above the highest building. Flying between buildings is prohibited due to noise and privacy concerns. The maximum altitude is 6500ft to prevent mixing with traditional aviation.

项目“大都市”的作者们 [24,147] 提出了四种用于无人航空器 (UAVs) 和个人航空器 (PAV) 的城市空域类型: 完全混合、分层、区域和管道。所有四种概念的最小巡航高度为 300ft 地面以上，并且比最高建筑物高出 100 英尺 (UAVs)/500 英尺 (PAVs)。由于噪音和隐私问题，禁止在建筑物之间飞行。最大高度为 6500ft 以防止与传统航空混合。

Safety is achieved by maintaining minimum separation and equipping aircraft with sense-and-avoid capabilities. The minimum separation corresponds to a $1-\min$ spacing, which for PAVs equals $250 \mathrm{~m}$. Vertical separation is proposed to be $50 \mathrm{~m}$. Aircraft are autonomous, and human pilots may only be needed in emergency situations. Additionally, aircraft are equipped with ADS-B, which reports location to surrounding aircraft. The operational factors, such as capacity and efficiency, depending on the type of airspace, are:

安全是通过保持最小间隔并装备飞机具有感知和避让能力来实现的。最小间隔对应于 $1-\min$ 间距，对于 PAVs 等于 $250 \mathrm{~m}$ 。建议垂直间隔为 $50 \mathrm{~m}$ 。飞机是自主的，人类飞行员可能在紧急情况下才需要。此外，飞机配备了 ADS-B，向周围的飞机报告位置。操作性因素，如容量和效率，取决于空域的类型，包括:

- Full Mix (free flight) - All air vehicles share the airspace and move without barriers. Air Traffic Control does not require flight plans; it only manages the capacity of the airspace and sets up the geofences, while tactical collision avoidance tasks are delegated to each aircraft. The difficulty in resolving conflicts is the highest in the Full Mix concept since aircraft have four degrees of freedom: speed, altitude, and X and Y coordinates. On the other hand, this freedom reduces distances traveled by aircraft, thus reducing associated trip costs. The path planning algorithm determines the optimal trajectory and executes it. If a conflict arises, priority is given to the aircraft with poorer maneuverability, and cruise is prioritized over climb or descent.

- 完全混合 (自由飞行)- 所有航空器共享空域并无需障碍物移动。空中交通管制不需要飞行计划；它只管理空域的容量并设置地理围栏，而战术避撞任务则分配给每架飞机。在完全混合概念中解决冲突的难度最高，因为飞机具有四个自由度: 速度、高度以及 X 和 Y 坐标。另一方面，这种自由度减少了飞机的飞行距离，从而降低了相关的行程成本。路径规划算法确定最佳轨迹并执行。如果出现冲突，优先考虑机动性较差的飞机，巡航优先于爬升或下降。

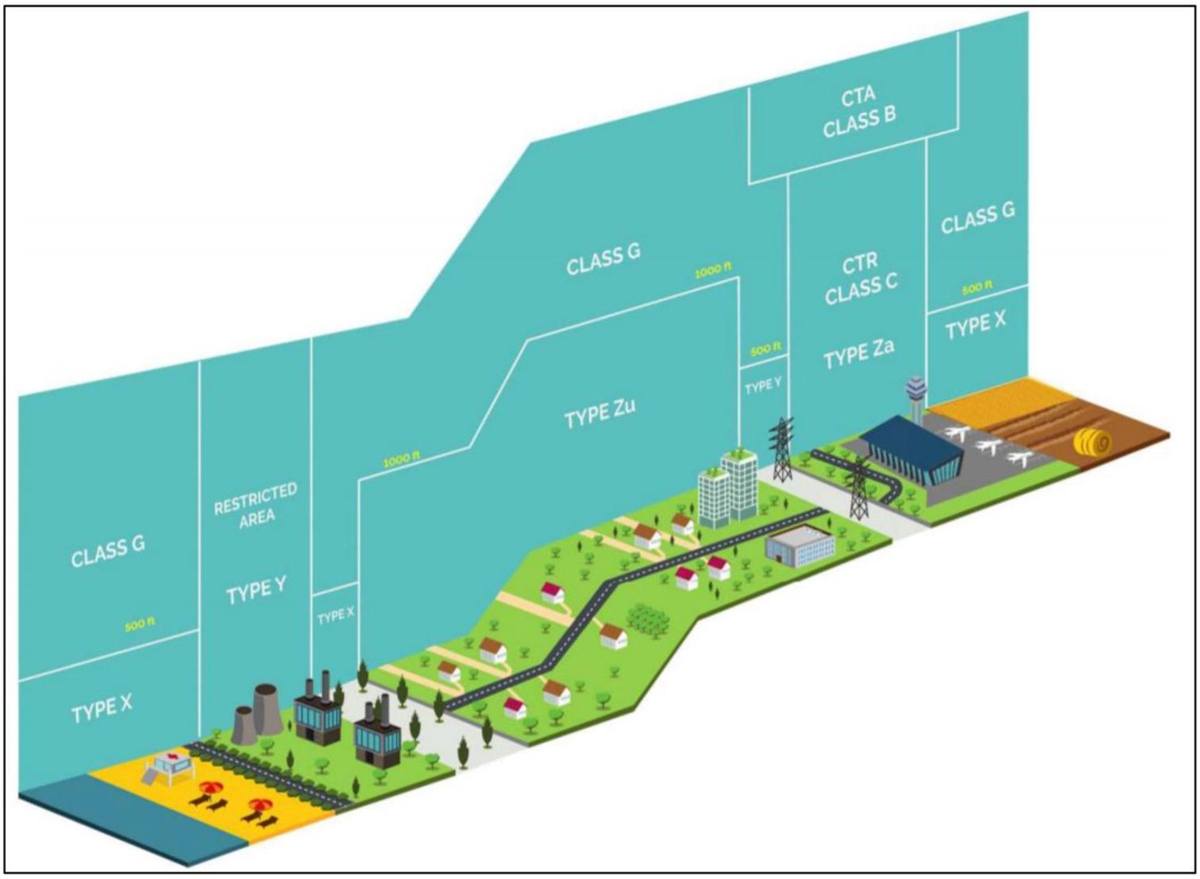


Fig. 12. SESAR's U-Space airspace concept [145]. X - low risk, Y - medium risk, Z - highest risk.
图 12. SESAR 的 U-Space 空域概念 [145]。X - 低风险，Y - 中等风险，Z - 最高风险。

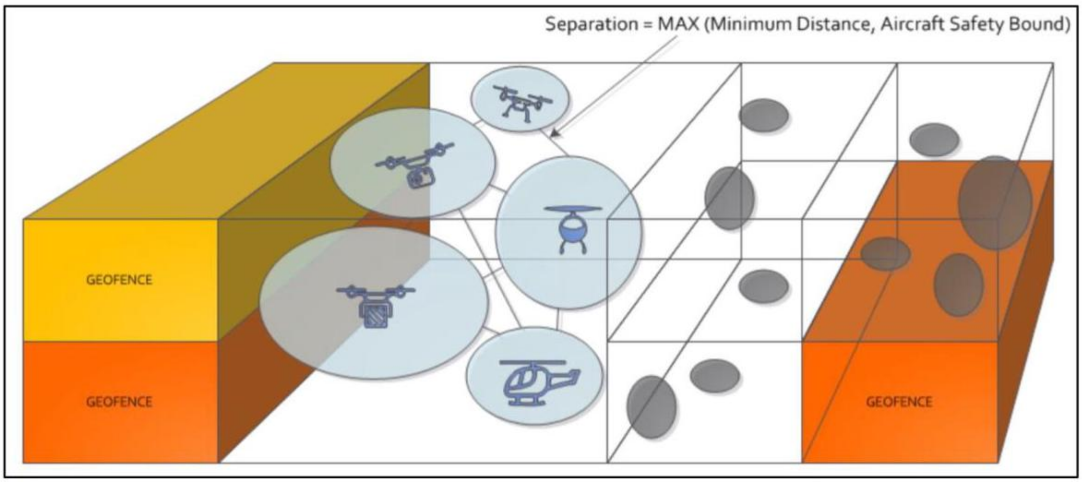


Fig. 13. DLR's airspace concept with cells [146]. The lower aircraft performance - the larger the ellipsoid.
图 13. DLR 的空域概念，包含单元 [146]。飞机性能越低 - 椭圆体越大。

- Layers - Airspace is divided into layers where every altitude band corresponds to a heading range (Fig. 14). Layered airspace aims to facilitate separation and increase safety. The airspace is portioned into the feeder layer, UAV layer, and PAV layer. The feeder layer is the lowest layer, and it is used for climbs and descents. Above it is a layer reserved for small unmanned drones, followed by a separation layer and a PAV level layer system (see Fig. 15).

• 分层 - 空域被划分为多层，每个高度带对应一个航向范围 (图 14)。分层空域旨在便于分离并提高安全性。空域被划分为馈送层、无人机层和飞行器层。馈送层是最低层，用于爬升和下降。其上方是预留用于小型无人机的层，接着是分离层和飞行器层系统 (见图 15)。

The altitude thresholds will depend on the height of the buildings in the city. Since PAVs have to accelerate to a certain speed to enter the PAV layer, take-off procedures will not completely be vertical. These

高度阈值将取决于城市中建筑的高度。由于飞行器必须加速到一定速度才能进入飞行器层，起飞程序将不会完全垂直。这些

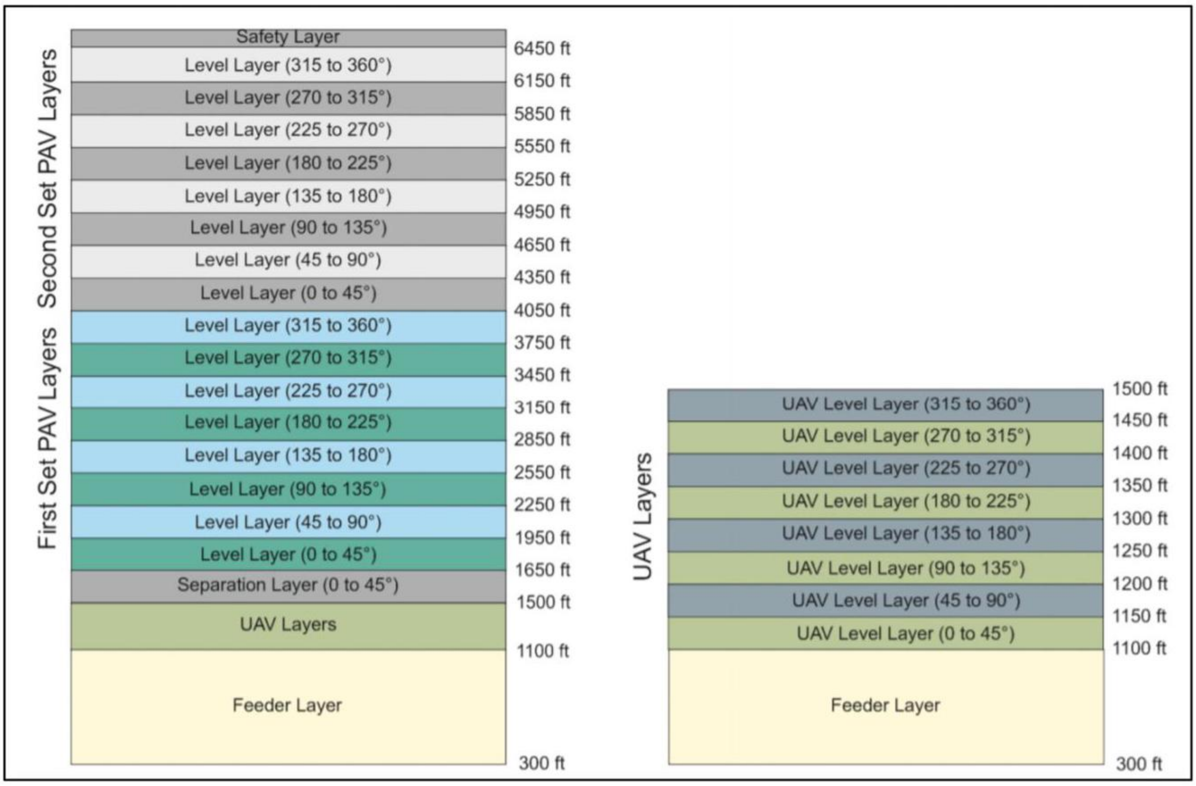


Fig. 14. Flight levels in layered airspace [24].

图 14. 分层空域中的飞行高度 [24]。

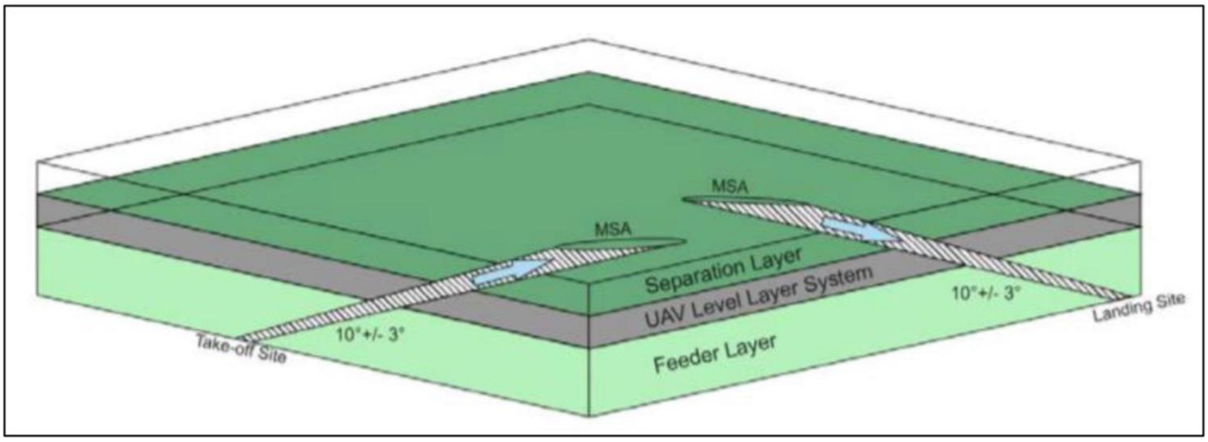


Fig. 15. Take-off and landing cones for Personal Air Vehicles in layered airspace [24].

图 15. 分层空域中个人飞行器的起飞和降落锥体 [24]。

”cones” are implemented only to pass the UAV layer system safely. It represents a protected zone that is prohibited for UAVs. ATC is in charge of collecting flight plans and creating cones.

” 锥体” 仅用于安全地通过无人机层系统。它代表了一个禁止无人机进入的保护区域。空中交通管制负责收集飞行计划并创建锥体。

- Zones - Airspace is partitioned into zones for different types of vehicles, based on their characteristics, such as speed, maneuverability, level of autonomy, as well as global directions to aid separation between vehicles. Two types of structures can be discerned: circular and radial zones (see Fig. 16). The circular zones are used similarly to ring roads, while the radial zones serve as connections between concentric zones. There is no vertical segmentation. Instead, altitude is selected flexibly, based on the planned flight distance between origin and destination.

- 区域 - 根据车辆的特性，如速度、机动性、自主级别以及用于车辆分离的全局方向，将空域划分为不同类型的区域。可以区分出两种结构: 圆形区域和辐射区域 (见图 16)。圆形区域的使用类似于环形道路，而辐射区域则作为同心区域之间的连接。没有垂直分割。相反，高度根据计划起飞点与目的地之间的飞行距离灵活选择。

- Tubes provide a fixed route structure presented in Fig. 17. Aircraft can only follow the tubes and maintain an equal speed as the other aircraft in the airspace, which offers the advantage of channeling traffic in a safely separated manner. By creating multiple layers of tubes, it is possible to segregate aircraft based on their speed, heading, and size. This increases the throughput and safety of the system. Short flights utilize a dense grid at the lower levels, while longer flights benefit from long straight tubes in the upper layers of the topology, allowing them to travel longer distances at higher speeds.

管道提供了一种固定的路线结构，如图 17 所示。飞机只能沿着管道飞行，并保持与空域中其他飞机相同的速度，这有助于以安全分隔的方式引导交通。通过创建多层次的管道，可以根据飞机的速度、航向和大小对其进行分离。这提高了系统的吞吐量和安全性。短途飞行利用低层密集的网格，而长途飞行则从顶层拓扑结构中的长直管道中受益，使它们能够在较高速度下行驶更长的距离。

The study also created simulations and compared the performance of different airspace topologies. The summary is presented in Table 9. Based on the results of the simulations, the study found that Free flight increases robustness by distributing conflict resolution tasks, increases flight efficiency with direct routing, and reduces the probability of conflict. However, there are some concerns over the uncertainties of aircraft positions and their impact on safety. In terms of the number of UAV-PAV conflicts, the best performing structure is Layers, while Tubes yield the highest number and severity of conflicts. The tube creates the highest delays and the longest flights, concluded that the best structure in terms of safety versus capacity is the layered airspace [24]. Additionally, the study concluded that pre-planning and prevention of conflict routes are difficult to perform and that at least some airspace structure is needed to provide separation. A trade-off to structure is capacity, as more structure reduces capacity.

该研究还创建了模拟，并比较了不同空域拓扑结构的性能。总结呈现在表 9 中。基于模拟结果，研究发现自由飞行通过分配冲突解决任务提高了鲁棒性，通过直接路由提高了飞行效率，并降低了冲突的可能性。然而，对于飞机位置的确定性和它们对安全性的影响存在一些担忧。在无人机-有人机冲突数量方面，表现最好的结构是分层结构，而管道产生的冲突数量和严重程度最高。管道造成了最高的延误和最长的飞行时间，结论是就安全与容量的最佳结构而言，分层空域是最佳选择。此外，研究还得出结论，预先规划和预防冲突航线是难以执行的，至少需要一些空域结构来提供分离。结构的权衡是容量，因为更多的结构会减少容量。

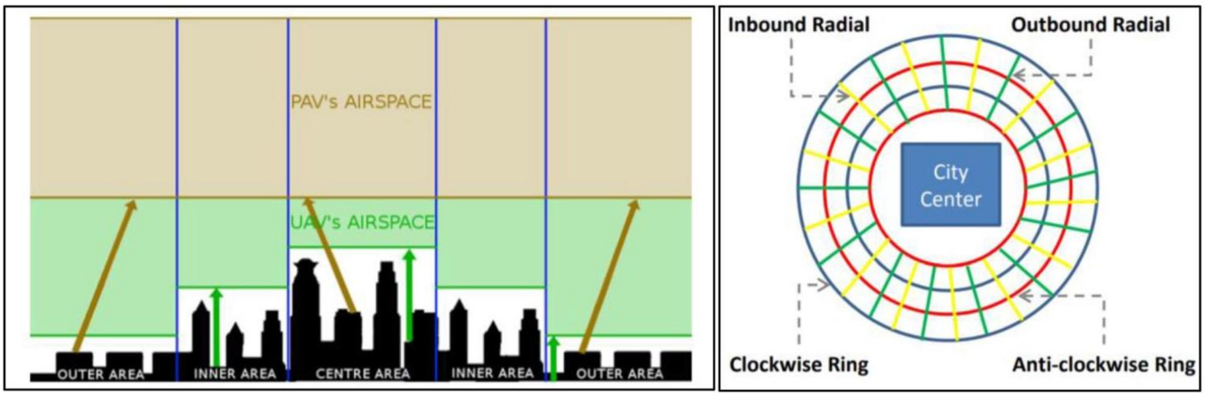


Fig. 16. Zones: vertical (left) and top-down (right) view [24].
图 16。区域: 垂直视图 (左) 和俯视图 (右)[24]。

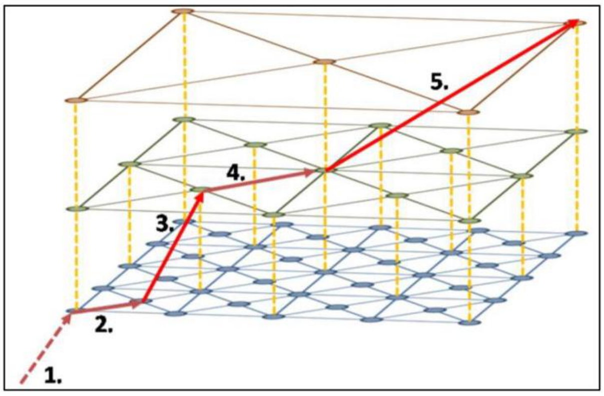


Fig. 17. An air vehicle taking-off and climbing to the appropriate tube [24].
图 17。一架航空器起飞并爬升到适当的管道中 [24]。

4.1.8. ONERA's low-level Remotely Piloted Aircraft System (RPAS) traffic management system (LLRTM)

4.1.8. ONERA 的低空遥控飞行器系统 (RPAS) 交通管理系统 (LLRTM)

French research agency ONERA proposed a Low-level Remotely Piloted Aircraft System (RPAS) Traffic Management System (LLRTM) [148] to monitor piloted drone traffic, manage it in uncontrolled airspace below 500ft , coordinate it with ATC in controlled airspace, and provide ground-based detect-and-avoid functions. The service is based on the network of ground receivers and onboard ID and tracking devices. The resulting system performs traffic detection and conflict resolution [149]. The main goal of LLRTM is to reduce the risk of collision between two drones, as well as collisions between drones and traditional aircraft.

法国研究机构 ONERA 提出了一种低级别遥控飞行器系统 (RPAS) 交通管理系统 (LLRTM)[148]，用于监控有人驾驶的无人机交通，在 500ft 以下的未控空域中管理无人机，与管制空域中的空中交通管制 (ATC) 协调，并提供基于地面的检测与避让功能。该服务基于地面接收器网络和机载识别与跟踪设备。该系统执行交通检测和冲突解决 [149]。LLRTM 的主要目标是降低两架无人机之间以及无人机与传统飞机之间碰撞的风险。

The airspace is segmented in vertical layers separated by buffer zones. The heights of layers are defined by the aircraft cylinders. A cylinder is a 500 feet wide horizontal and 200 feet wide vertical region around the aircraft used for maintaining separation, as shown in Fig. 18.

空域被划分为垂直层次，层次之间设有缓冲区。层次的垂直高度由飞机的圆柱体定义。圆柱体是围绕飞机的 500 英尺宽的水平区域和 200 英尺宽的垂直区域，用于保持间隔，如图 18 所示。

All aircraft must have electronic identification and tracking technology. Although ADS-B is commonly used by commercial aviation, its operating frequency does not have a sufficient capacity to be used by drones. Instead, the authors propose FLARM (Flight Alarm) transceivers, which broadcast the ID, position, altitude, heading, and speed every second. The next stages of the development of this concept will include 4D trajectories, automation, and the best-equipped/best-served approach.

所有飞机都必须具备电子识别和跟踪技术。尽管 ADS-B 被商业航空广泛使用，但其工作频率的容量不足以供无人机使用。因此，作者提出使用 FLARM(飞行警报) 接收器，每秒广播 ID、位置、高度、航向和速度。这一概念的下一步发展将包括 4D 轨迹、自动化和最佳装备/最佳服务方法。

4.1.9. Singapore Nanyang Technological University's UTM concept

4.1.9. 新加坡南洋理工大学的无人机交通管理 (UTM) 概念

The Nanyang Technological University from Singapore proposed a concept of managing urban air operations [150] by defining two-way traffic lanes that are horizontally and vertically separated (Fig. 19). The lanes are placed so that they avoid areas with dense populations to minimize risk. In the initial phases of the airspace development, the lanes are positioned above ground infrastructure - railways and roads. The operations are restricted based on time, such as non-peak hours. Certain rooftops will be designated for take-off and landing, while the air in the vicinity of these rooftops is reserved for the climb and descend.

新加坡南洋理工大学提出了一种管理城市空中运行的概念 [150]，通过定义水平方向和垂直方向分离的双向航路 (见图 19)。这些航路被布置在避开人口密集区域的上方，以最小化风险。在空域开发的初期阶段，航路被设置在地面上方的基础设施之上 - 铁路和道路。这些运行根据时间受到限制，例如非高峰时段。某些屋顶将被指定用于起飞和降落，而靠近这些屋顶的空域则保留用于爬升和下降。

Table 9

表 9

Comparison of airspace structures by ranked characteristics 1-best, 4-worst.

根据排名特征比较空域结构 1-最佳，4-最差。

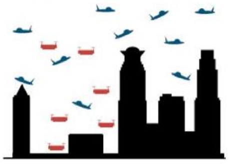
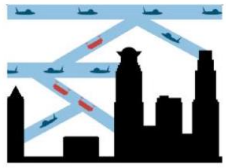
	Full Mix	Layers	Zones	Tubes
				
Safety	2	1	3	4
Third party risk	2	1	3	4
Capacity	1	2	3	4
Efficiency	1	2	3	4
Noise	2	1	4	3

Fig. 18. Separation guidance under LLRTM proposal [148].

图 18. LLRTM 提案下的分离引导 [148]。

Additionally, airspace is divided into zones, as presented in Fig. 20: no flying zone (NFZ), business zone (BZ), and residential zone (RZ). The goal of zones is to create constrained airspace where a single UAS control station manages flights within the zone. The authors envision travel and delivery operations from one rooftop within the zone to another within the same zone. Flying to another zone is possible, but the control needs to be transferred to another air traffic control, similar to the airspace-based operations in today's airspace.

此外，空域被划分为几个区域，如图 20 所示: 禁飞区 (NFZ)、商业区 (BZ) 和住宅区 (RZ)。区域的目的是创建受限制的空域，其中单个无人机控制站管理该区域内的飞行。作者设想在区域内的一个屋顶到另一个屋顶之间的旅行和送货运行。飞往另一个区域是可能的，但需要将控制权转移给另一个空中交通管制，类似于当今空域中的基于空域的运行。

Within a zone, aircraft can also use the predetermined flight tubes to simplify the complexity of managing the traffic and create a more predictable environment. Every aircraft is equipped with advanced detect-and-avoid technology. The technological requirements for aircraft in this airspace include detect-and-avoid capabilities, vehicle-to-vehicle and vehicle-to-ground communication links, GPS localization, and remote piloting.

在一个区域内，飞机还可以使用预设的飞行管道来简化管理交通的复杂性，并创建一个更加可预测的环境。每架飞机都配备了先进的检测和避让技术。在这种空域中飞机的技术要求包括检测和避让能力、车对车和车对地通信链路、GPS 定位和远程驾驶。

The authors argue that social factors, such as privacy, should not be limiting factors, but should be included in the broader assessment of costs and benefits of the technology. If the benefits of the technology outweigh the privacy and noise concerns, the operations should be allowed [150].

作者认为，社会因素，如隐私，不应成为限制因素，而应包含在技术的成本和收益的更广泛评估中。如果技术的收益超过了隐私和噪音的担忧，则应允许这些运行 [150]。

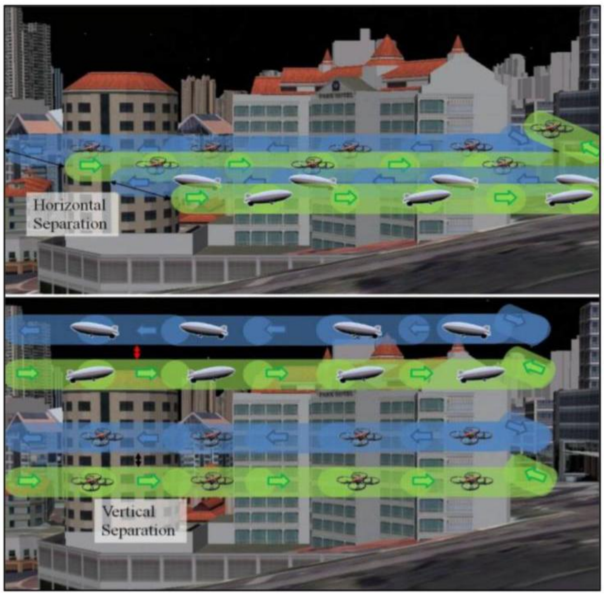


Fig. 19. Horizontally and vertically separated flight lanes in Singapore [150].
图 19. 在新加坡水平与垂直分离的飞行航道 [150]。

4.1.10. China's civil UAS Aviation Operation Management System (UOMS)

4.1.10. 中国民用无人机航空运行管理系统 (UOMS)

UAS Aviation Operation Management System (UOMS) [151] is an air traffic management system that enables drone operations in low-level airspace. UOMS provides static geofencing, dynamic geofencing, flight plan approval, traffic capacity and flow management, and flight surveillance and warning system. UOMS segregates aircraft into different flight levels based on their characteristics (Fig. 21).

无人机航空运行管理系统 (UOMS)[151] 是一种空中交通管理系统，能够实现在低空空域中的无人机运行。UOMS 提供静态地理围栏、动态地理围栏、飞行计划审批、交通容量与流量管理以及飞行监视与警告系统。UOMS 根据飞机的特性将飞机划分为不同的飞行高度层 (图 21)。

In China, general aviation has its own management system, called General Aviation Flight Service (GAFS). It is intended that both UOMS and GAFS operate in the same area. UAS flights and general aviation are not segregated, and UOMS and GAFS share all information.

在中国，通用航空拥有自己的管理系统，称为通用航空飞行服务 (GAFS)。预计 UOMS 和 GAFS 将在同一区域内运行。无人机飞行和通用航空并未分离，UOMS 和 GAFS 共享所有信息。

All drones in UOMS airspace are connected to the cellular network. Tests on communication networks show that the 4 G network provides coverage below 300 m , and 5 G network can support flights up to heights of 1000 m . The precision of location reporting is enhanced by using communication networks since GPS has reliability issues [151].

UOMS 空域中的所有无人机都连接到蜂窝网络。通信网络的测试显示，4 G 网络提供了低于 300 m 的覆盖范围，而 5 G 网络能够支持飞行至 1000 m 的高度。由于 GPS 的可靠性问题 [151]，使用通信网络增强了位置报告的精度。

4.1.11. JAXA UAS traffic management

4.1.11. JAXA 无人机交通管理

Japan Aerospace Exploration Agency (JAXA) proposed a concept of the UAS traffic management (UTM) system for traffic management of UAS operations [152]. UTM collects flight plans of all manned and unmanned flights, sets geofences, and provides information on traffic, weather, and geofenced areas. Individual traffic management service providers coordinate with central airspace management service, coordinate with it, and ensure the safety of operations by separating drones in their control from drones of other providers (Fig. 22).

日本宇宙探索机构 (JAXA) 提出了无人机交通管理 (UTM) 系统的概念，用于无人机运行交通管理 [152]。UTM 收集所有有人和无人飞行的飞行计划，设置地理围栏，并提供关于交通、天气和地理围栏区域的信息。各个交通管理服务提供商与中央空域管理服务协调，与之协调，并通过将其控制的无人机与其他提供商的无人机分离来确保操作的安全性 (图 22)。

The development of UTM is sequenced in four stages, starting from the remotely piloted VLOS operations in the first stage, to the automated BVLOS operations in urban areas. In-flight traffic management functions are transmitted using a mobile communication network (LTE) over the air [153].

无人机交通管理系统 (UTM) 的发展分为四个阶段，从第一阶段远程操控的视距内 (VLOS) 操作开始，到第四阶段的自动化城市视距外 (BVLOS) 操作。飞行交通管理功能通过移动通信网络 (LTE) 在空中传输 [153]。

4.2. Industry-led initiatives

4.2. 行业主导的倡议

4.2.1. Amazon

4.2.1. 亚马逊

In a proposal by Amazon [154] airspace below 500 feet is segregated into layers (Fig. 23). Four layers are suggested:

在亚马逊的一份提案 [154] 中，500 英尺以下的空域被划分为多个层级 (见图 23)。建议分为四个层级:

- Low-Speed, Localized Traffic - area below 200 feet is reserved for applications such as recreation, surveying, inspection, surveillance, and videography, as well as low-tech aircraft without detect-and-avoid technology.

- 低速、局部交通 - 200 英尺以下的区域预留用于娱乐、测量、检查、监控和摄影等应用，以及没有检测与避障技术的低技术飞行器。

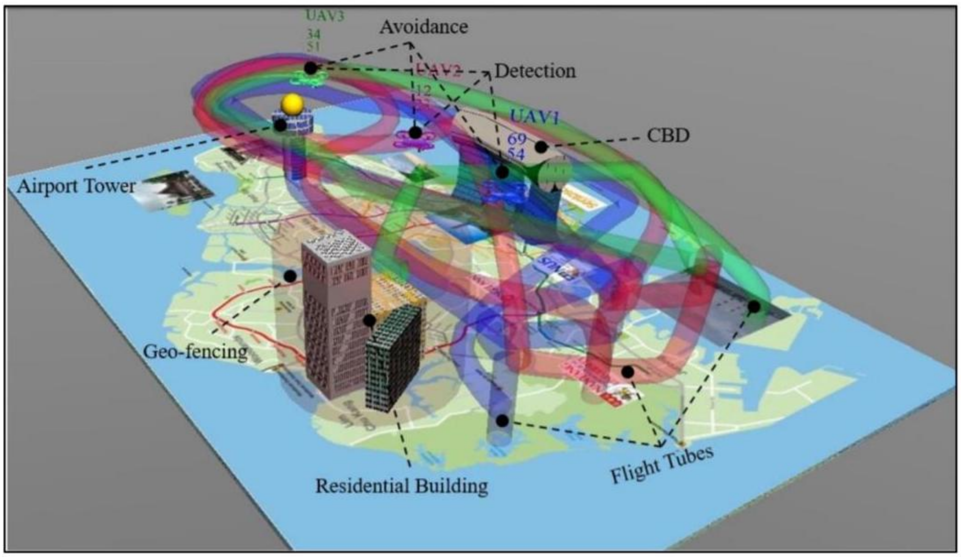


Fig. 20. Airspace in Singapore [150].
图 20. 新加坡的空域 [150]。

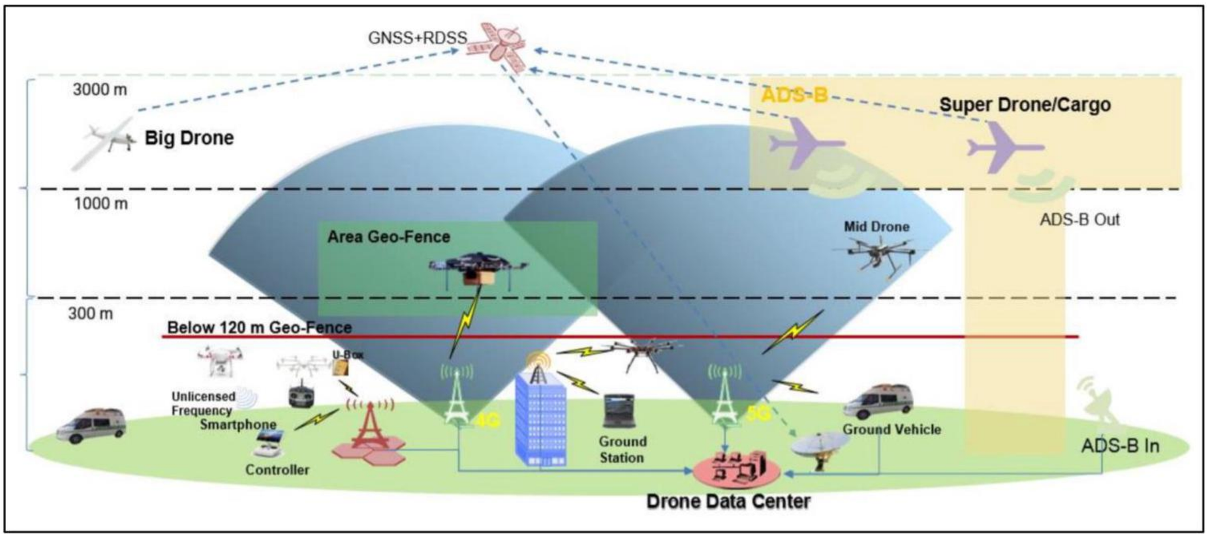


Fig. 21. UOMS in China [151].
图 21. 中国的无人机操作系统 (UOMS)[151]。

- High-speed transit - includes levels between 200 and 400 feet, and is reserved for well-equipped autonomous aircraft vehicles that operate beyond the line of sight. Technological capabilities required for this layer include detect-and-avoid capabilities, vehicle-to-vehicle (V2V) communication, and collision avoidance.

- 高速通行 - 包括 200 至 400 英尺之间的层级，预留用于装备精良、能进行视距外操作的自主飞行器。这一层级所需的技术能力包括检测与避障能力、车与车之间的通信 (V2V) 和避碰能力。

- No Fly Zone - is the area between 400 and 500 feet, and,

- 禁飞区 - 介于 400 至 500 英尺之间的区域，

Predefined Low-Risk Locations - area established by aviation authorities.
预设低风险位置 - 由航空当局设立的区域。

The vehicle would be able to access different layers of airspace based on equipage and capabilities. Operators with a lesser-equipped vehicle may fly safely in a remote area. However, the only aircraft with sophisticated technology will be able to operate in an urban or dense environment. The equipage levels and access are presented in Table 10.

飞行器能够根据其设备和能力访问不同层级的空域。设备较少的运营商可以在偏远地区安全飞行。然而，只有配备先进技术的飞机才能在城市或密集环境中运行。设备级别和访问权限在表 10 中展示。

A central management entity controls off-line coordination and performs auditing; however, the majority of traffic management is performed by operators in a federated fashion. Those operators would coordinate by following established protocols, using vehicle-to-vehicle, vehicle-to-operator, and operator-to-operator communication. This approach will entail a distributed network comprised of local/regional air operations centers and remote vehicle operators. This new system is essential given the highly automated nature of future UAS.

一个中心管理实体控制离线协调并执行审计；然而，大多数交通管理是由操作员以联邦方式进行的。这些操作员将遵循既定协议进行协调，使用车辆间、车辆与操作员间以及操作员之间的通信。这种方法将包含一个由本地/区域空中运行中心和远程车辆操作员组成的分布式网络。鉴于未来无人机系统 (UAS) 高度自动化的特性，这个新系统至关重要。

Highly equipped UAS will be capable of navigation, merging and sequencing, communication, maintaining safe self-separation, collision avoidance, and deconfliction in congested airspace without operator assistance. Collision avoidance must be achieved with both collaborative and non-collaborative objects. Collaborative detect-and-avoid collision avoidance is enabled by vehicle-to-vehicle communication. On the other hand, non-collaborative collision avoidance is enabled by sensors, which recognize non-collaborative entities such as manned aircraft, birds, and balloons.

高度装备的无人机将能够在没有操作员协助的情况下进行导航、合并和排序、通信、保持安全自我分离、避障以及在拥挤空域中进行冲突解除。避障必须针对合作和非合作目标实现。合作的检测-避障是通过车辆间的通信实现的。另一方面，非合作的避障是通过传感器实现的，这些传感器能够识别非合作实体，如有人驾驶飞机、鸟类和气球。

4.2.2. Airbus

4.2.2. 空中客车

Airbus proposed four concepts (Fig. 24) of designing airspace: Basic Flight, Free Routes, Corridors, and Fixed Routes [156]. In Basic Flight, both manned and unmanned aircraft are responsible for self-separation and must maintain it at all times. If all aircraft select a direct route without coordination, the safety decreases as the number of conflicts increases. In the Free Route, aircraft can fly any path as long as the path is pre-approved, deconflicted from other routes, and approved by a traffic manager. This approach provides flexibility while maintaining an acceptable level of safety. The trajectories are less-than-optimal since the flight plan can be rejected. Corridors are predefined volumes in space, used in high-demand situations. This concept is similar to the waypoint procedures used in traditional aviation. Fixed Routes are used to ensure safety when there is a mix of aircraft capabilities and high traffic density. These routes are constructed and modified dynamically based on risk, traffic, and weather.

空中客车提出了四种设计空域的概念 (图 24): 基本飞行、自由航线、走廊和固定航线 [156]。在基本飞行中，有人驾驶和无人驾驶飞机均负责自行保持间隔，并且必须始终维持这种间隔。如果所有飞机未经协调选择直飞路线，随着冲突数量的增加，安全性将降低。在自由航线中，飞机可以飞行任何预先批准、与其他航线无冲突并由交通管理员批准的路径。这种方法在保持可接受的安全水平的同时提供了灵活性。由于飞行计划可能会被拒绝，所以轨迹不是最优的。走廊是空间中预定义的体积，用于高需求情况。这个概念与传统航空中使用的航点程序类似。固定航线用于确保在飞机能力和交通密度混合时安全。这些航线根据风险、交通和天气动态构建和修改。

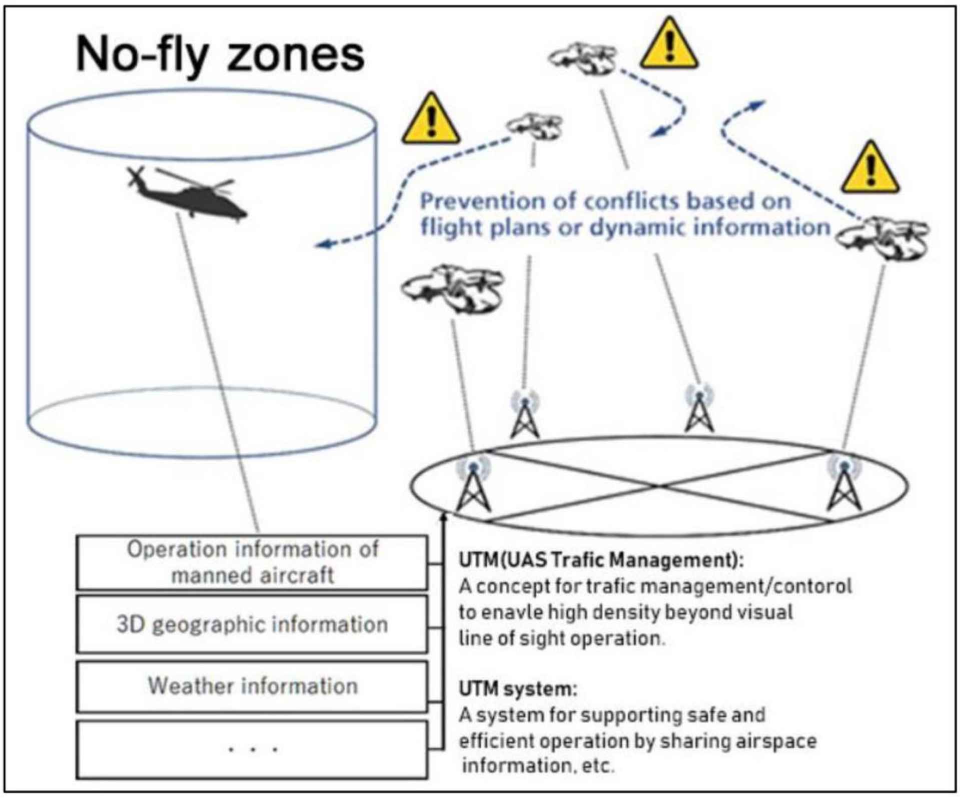


Fig. 22. Japanese UTM [152].
图 22. 日本无人机交通管理系统 (UTM)[152]。

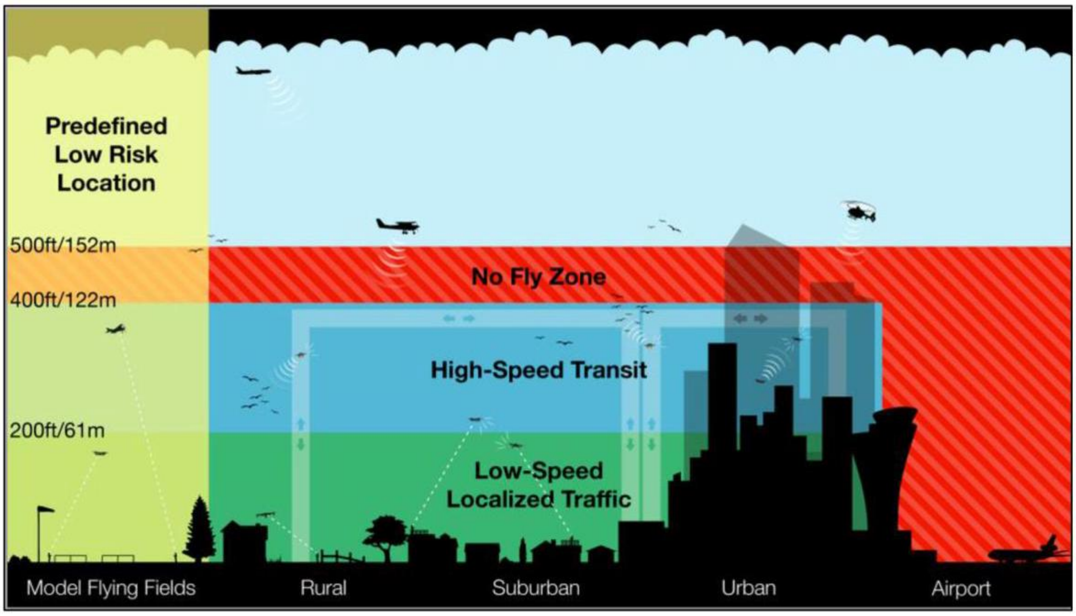


Fig. 23. Urban airspace concept by Amazon [154].
图 23. 亚马逊提出的城市空域概念 [154]。

Airbus proposes new flight rules that would accommodate unmanned operations. For example, Basic Flight Rules (BFR) would cover manned flights that operate independently. They would be responsible for maintaining separation, routing, and safety. On the other hand, Managed Flight Rules (MFR) would cover operations that coordinate their path with a traffic management system and follow its separation guidance.

空中客车提出了新的飞行规则，以适应无人驾驶操作。例如，基本飞行规则 (BFR) 将涵盖独立运行的有人驾驶飞行。它们将负责保持间隔、航线和安全。另一方面，受控飞行规则 (MFR) 将涵盖与交通管理系统协调路径并遵循其间隔指导的操作。

Table 10
表 10
Equipage and airspace access under best-equipped, best-served model proposed by Amazon [155].
亚马逊提出的最佳装备、最佳服务模型下的机组人员和空域接入 [155]。

Class	Equipage	Airspace Access
Basic	Radio Control	Line of sight flight in predefined low-risk locations.
Good	Transmission of ID and location via V2V, ability to receive air traffic and weather data, internet connection via ground infrastructure, GPS and Wifi capabilities, geospatial data.	Operations below 200 feet in rural areas.
Better	Avoidance based on collaborative V2V, onboard internet connection, ADS-B Out.	Operations below 200 feet in suburban operating areas.
Best	Non-collaborative detect-and-avoid, onboard internet connection, ADS-B In/ Out, 4D trajectory planning and management, alternate landing execution.	BVLOS operations below 400 feet in all areas, in all conditions.

类别	装备	空域准入
基础	无线电控制	在预定的低风险地点进行视距内飞行。
良好	通过车对车 (V2V) 传输识别和位置信息，能够接收空中交通和气象数据，通过地面基础设施连接互联网，GPS 和 Wifi 功能，地理空间数据。	在乡村地区 200 英尺以下的飞行作业。
更好	基于协作车对车 (V2V) 的避障，机上互联网连接，ADS-B Out。	在郊区操作区域 200 英尺以下的作业。
最佳	非协作检测与避让，机上互联网连接，ADS-B 接收/发送，4D 航迹规划与管理，备选着陆执行。	在所有区域、所有条件下 400 英尺以下的视距外 (BVLOS) 作业。

Real-time two-way communications report position and status so that traffic managers can coordinate with their aircraft. Around airports, ATM and UTM services work together. For example, they coordinate the direction of local traffic flows between fixed-wing aircraft and unmanned drones at local airports based on weather conditions. Traffic management services provide basic information to pilots and autopilots about conditions in the airspace, regulation, and nearby traffic. Managed aircraft use this information as input for tactical self-separation and collision avoidance.

实时双向通信报告位置和状态，以便交通管理人员能够与他们的飞机协调。在机场周围，空中交通管理 (ATM) 和无人交通管理 (UTM) 服务共同工作。例如，他们根据天气条件协调本地机场的固定翼飞机和无人机的本地交通流向。交通管理服务向飞行员和自动驾驶系统提供有关空域状况、规定和附近交通的基本信息。受管理的飞机将此信息作为战术自我分离和避障的输入。

Aircraft will also need to meet navigation performance standards. Navigation may be assisted by GPS, ground-based beacons, or other technology (see Table 11). Aircraft may need to maintain precise navigation in areas like urban canyons, where multipath effects degrade traditional navigation accuracy. With traffic management services maintaining separation for managed drones, detect and avoid is a backup. Simulations show that it works well in low-density regions, while strategic and tactical management works better at higher densities.

飞机还需要满足导航性能标准。导航可能由 GPS、地面信标或其他技术 (见表 11) 辅助。飞机可能需要在城市峡谷等区域保持精确导航，在这些区域多径效应降低了传统导航的准确性。在交通管理服务为

管理的无人机保持分离的情况下，检测与避让是一种备用手段。模拟显示，在低密度区域这种方法效果良好，而在高密度区域，战略和战术管理效果更好。

4.2.3. Boeing

4.2.3. 波音

Boeing proposed a concept of free-flight, performance-based routes for low altitude trajectory operations [157]. These routes would be managed by a 4D trajectory-based separation management system that would maintain safety, including during approach and departure for operations around hubs and terminal locations.

波音提出了一个基于性能的低空轨迹运行的自由飞行概念 [157]。这些航线将由一个基于 4D 轨迹的分离管理系统进行管理，该系统将保持安全，包括在枢纽和终端位置附近的进近和起飞过程中。

The technological requirements include onboard algorithms for real-time flight planning and in dense traffic environments. Traffic, weather, and other operational restrictions will be shared in real-time, and the aircraft will dynamically adjust its flight plan and route. Advanced detect-and-avoid systems will provide safety assurance and collision avoidance during the flight.

技术要求包括机上算法用于实时飞行规划以及在高密度交通环境中的运行。交通、天气和其他运行限制将实时共享，飞机将动态调整其飞行计划和航线。先进的检测与避让系统将在飞行中提供安全保证和避障。

4.2.4. Embraer-X

4.2.4. Embraer-X

Embraer-X proposed a concept called Urban Air Traffic Management (UATM) [158]. The UATM airspace is positioned between lower-level airspace reserved for small UAS (sUAS) operations, and traditional ATM airspace (Fig. 25). Within the UATM airspace, the aircraft use routes and corridors. Routes are linear trajectories defined by waypoints that accommodate a single vehicle, while corridors accommodate multiple vehicles. Given the complex mix of aircraft capabilities, routes and corridors are critical for managing traffic efficiently. Different rules apply to different structures and access to some corridors or routes may be restricted. The combination of layers and structures provides access to aircraft of different capability levels while maintaining safety.

Embraer-X 提出了一个名为城市空中交通管理 (UATM) 的概念 [158]。UATM 空域位于保留给小型无人机系统 (sUAS) 的低空空域和传统空中交通管理 (ATM) 空域之间 (图 25)。在 UATM 空域内，飞机使用航线和走廊。航线是由航点定义的线性轨迹，仅供单一飞行器使用，而走廊则可供多个飞行器使用。鉴于飞行器能力的复杂混合，航线和走廊对于有效管理交通至关重要。不同的结构适用于不同的规则，某些走廊或航线的访问可能受到限制。层次和结构的组合为不同能力的飞行器提供了访问权限，同时保持安全。

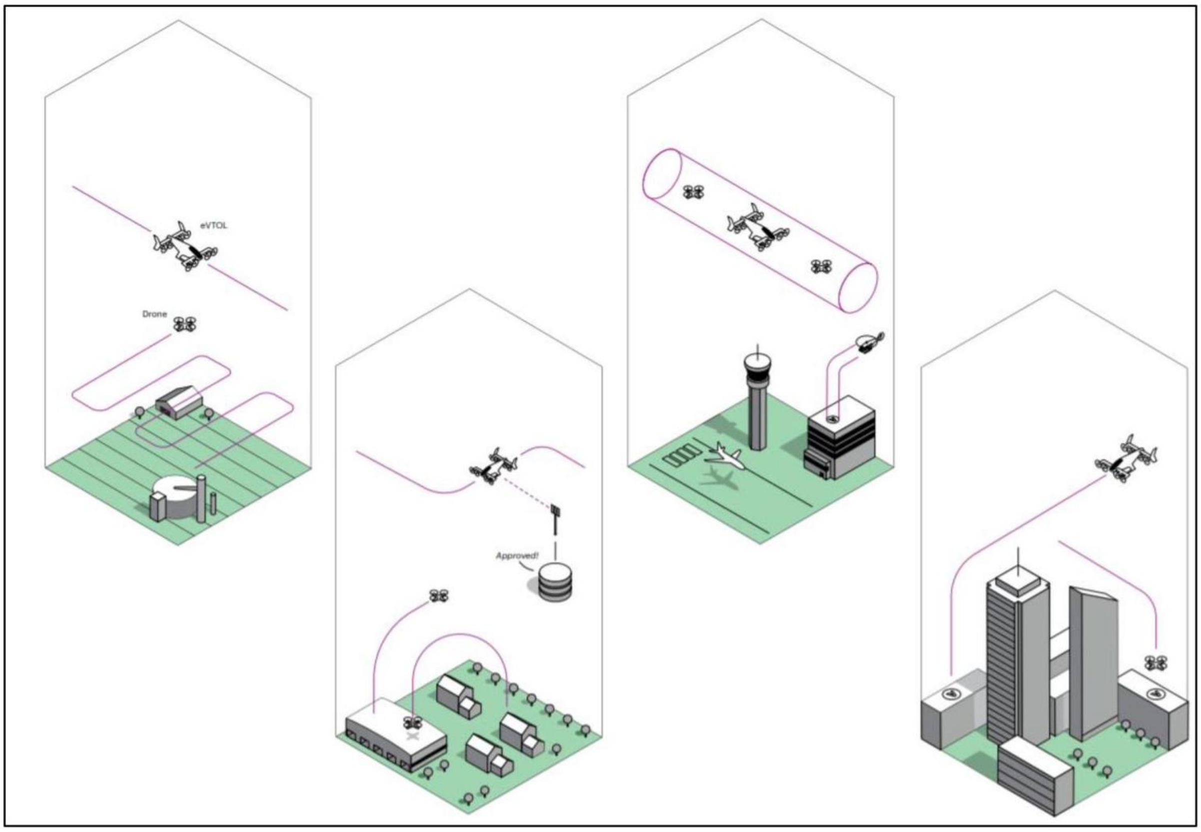


Fig. 24. Airspace structures by Airbus (left to right): Basic Flight, Free Route, Corridors, and Fixed Route [156].

图 24. 空域结构 (由空中客车公司提供，从左至右): 基本飞行、自由航线、走廊和固定航线 [156]。

Table 11

表 11

Services offered based on the level of automation in Airbus proposal.

根据空中客车提案中自动化程度提供的服务。

Automation	Level 1	Level 2	Level 3	Level 4	Level 5
Operations	VLOS	Autonomous BVLOS in low- density airspace	Integration of BVLOS in controlled airspace	Fleet operations	On-demand autonomous operations in high-density airspace
Airspace	VFR corridors, altitude restrictions, automated geofencing	UAS tracking, automated approvals	Unmanned procedures, corridor configurations	High-density controlled airspace	Dynamic and performance-based rules for access to airspace
Services	SWIM System-Wide Information Management	Network manager	ATM-UTM coordination, digital traffic manager	Specialized traffic management	ATM integration, congestion avoidance

自动化	一级	二级	三级	四级	五级
操作	视距外 (VLOS)	自主视距外 (BVLOS) 在低密度空域	在控制空域中集成视距外 (BVLOS)	机队运营	在高密度空域的按需自主作业
空域	VFR 走廊、高度限制、自动地理围栏	无人机系统 (UAS) 追踪、自动审批	无人飞行程序、走廊配置	高密度控制空域	访问空域的动态和基于性能的规则
服务	SWIM 系统级信息管理	网络管理器	ATM-UTM 协调，数字流量管理器	专用流量管理	ATM 集成，避免拥塞

The operator files a flight plan to the central traffic management authority that authorizes the 4-D trajectory and ensures it is decon-flicted, and that the requested routes, corridors, and airspace will be available at the designated time slot. The traffic management system dynamically manages routes, corridors, and geofences based on traffic, weather conditions, emergencies, or other restrictions. Additionally, the system ensures that flights conform to the flight authorizations and assigned routes.

运营商向中央交通管理当局提交飞行计划，该当局批准 4-D 轨迹，确保其无冲突，并确保在指定的时间段内所需的航线、走廊和空域可用。交通管理系统根据交通、天气条件、紧急情况或其他限制动态管理航线、走廊和地理围栏。此外，系统确保航班符合飞行授权和指定的航线。

To develop UATM, Embraer-X relies on the development of new technologies. For example, the report indicates that the foundation for surveillance will be GPS supported by a new technology that would serve as a redundancy in case of a GPS failure. However, as shown by NASA, GPS failure is not as big of a problem as GPS accuracy, which can be off by as much as 5 m [136]. Additionally, tracking will also depend on ADS-B-like devices that will have its benefits, and communication will be conducted on the 5G LTE network.

为了开发 UATM，Embraer-X 依赖于新技术的开发。例如，报告指出，监视的基础将是 GPS，由一种新技术作为备份，以防 GPS 失败。然而，正如 NASA 所示，GPS 失败并不是一个大问题，GPS 精确度的问题更大，其误差可能高达 5 m [136]。此外，跟踪还将依赖于类似 ADS-B 的设备，这将有其优势，通信将在 5G LTE 网络上进行。

The report indicates that the positioning of routes and the design process must consider communities that will be affected by the negative externalities of air traffic. Well-designed airspace structures will reduce risks, maintain efficient traffic flow, and ensure community acceptance when traffic reaches high volumes, which is the reason why all stake-holders should be included in the design process as soon as possible

报告指出，在确定航线位置和设计过程中，必须考虑将受到空中交通负面影响影响的社区。设计良好的空域结构将降低风险，保持交通流的效率，并在交通量达到高峰时确保社区接受，这就是为什么所有利益相关者应尽可能早地被纳入设计过程中的原因。[158].

4.2.5. Uber elevate

4.2.5. Uber elevate

Uber took a more modest approach of integrating its on-demand VTOL operations into the existing framework of air traffic management. They don't directly specify airspace structure but listed the recommendations for the successful operations of their on-demand VTOLs [15]. Although Uber's proposal relies on the existing technologies and NASA UTM proposal, it does present a discussion about the principles of designing urban airspace, especially in terms of social acceptance, which is not odd given that Uber's success relies on the positive acceptance of its users.

Uber 采取了一种更为谨慎的方法，将其按需 VTOL 运营整合到现有的空中交通管理框架中。他们没有直接指定空域结构，但列出了确保其按需 VTOL 成功运营的建议 [15]。尽管 Uber 的提案依赖于现有技术和 NASA UTM 提案，但它确实提出了关于设计城市空域原则的讨论，特别是在社会接受度方面，这并不奇怪，因为 Uber 的成功依赖于用户的积极接受。

The proposed safety level is twice that of driving a car based on the number of fatalities per passenger-mile. Using Part 135 operations as a proxy, Uber argues that the current safety level in air-taxi aviation is worse than driving (about 0.15 deaths per 100 million passenger miles).

提出的安全水平是基于每乘客英里死亡人数的两倍于驾驶汽车。使用 Part 135 运营作为代理，Uber 认为目前的空中出租车航空安全水平低于驾驶 (大约每 1 亿乘客英里 0.15 人死亡)。

In the initial phases, the existing technologies such as ADS-B and radio-based voice communication will be used for operations of VTOLs with a human pilot onboard. However, to achieve a higher density of operations, new technologies, specifically developed for low-level airspace, will need to be developed. The whitepaper calls for the extension of NASA's UTM above 500 feet to accommodate intended VTOL operations and create seamless integration with airports and terminal areas. Additional technologies needed are 1) digital air traffic control communication, 2) a UTM system expanded to higher altitudes that can manage a mix of VTOLs and General Aviation aircraft, and 3) traffic management system that can integrate VTOLs and airline approaches and departures near airports.

在初始阶段，将使用现有技术，如 ADS-B 和基于无线电的语音通信，用于载有人的 VTOL 运营。然而，为了实现更高密度的运营，需要开发专门针对低空空域的新技术。白皮书呼吁将 NASA 的 NASA UTM 扩展到 500 英尺以上，以适应计划的 VTOL 运营，并与机场和终端区域实现无缝集成。需要的额外技术包括 1) 数字空中交通控制通信，2) 扩展到更高空域的 UTM 系统，能够管理 VTOL 和通用航空飞机的混合，以及 3) 能够整合 VTOL 和机场附近航线进近和起飞的交通管理系统。

Fig. 25. UATM concept by Embraer-X [158].
图 25. Embraer-X 提出的 UATM 概念 [158]。

Uber argues that stringent standards for reducing noise should be adopted, including noise objectives for vehicles, long-term and short-term annoyance. Using these metrics, and real-time tracking of site noise as inputs, the minimum-noise flight path should be selected.

Uber 认为应该采用严格的减噪标准，包括车辆噪音目标、长期和短期的烦躁度。使用这些指标以及实时跟踪现场噪音作为输入，应选择最小噪音飞行路径。

4.3. Assessment of urban airspace concepts

4.3. 城市空域概念的评估

The summary of the proposed concepts is presented in Table 12 and Table 13. Each concept is evaluated according to the dimensions presented in Section 3: safety, social, system, and vehicle factors. Most concepts focused on the limited notion of safety, which includes avoidance of physical objects, but less on safety impacts of weather or wind. The most frequent, sometimes unstated assumption is that the technology required to support UAM operations exists and is ready for implementation. However, technologies such as detect-and-avoid, advanced communication, navigation, and surveillance are still inadequate to facilitate safe operations.

所提出概念的总结呈现在表 12 和表 13 中。每个概念都根据第 3 节中提出的维度进行评估: 安全性、社会性、系统因素和车辆因素。大多数概念都集中在有限的安全观念上，包括避免物理障碍物，但很少考虑天气或风速对安全的影响。最常见的是，有时没有明确提出的假设是支持城市空中出行 (UAM) 操作所需的技术已经存在且准备实施。然而，诸如探测与避让、高级通信、导航和监视等技术仍然不足以促进安全运行。

Social factors are largely ignored, which is not uncommon in the initial phases of developing new engineering solutions. While the abstraction of the physical nature of a city into a mathematical network is a useful tool for the ideation of possible solutions, the customer (i.e., the public) should be introduced into the process sooner rather than later.

社会因素在很大程度上被忽视了，这在开发新工程解决方案的初期阶段并不少见。虽然将城市的物理本质抽象成一个数学网络是构思可能的解决方案的有用工具，但应尽早将客户 (即公众) 纳入这一过程。

It is noticeable that private companies are promoting airspace concepts that do not require centralized air traffic control or management system. While this approach might seem quicker, it increases complexity, which might ultimately reduce the trust and safety of air mobility.

translation: 可以注意到，私人公司正在推广不需要集中空中交通控制或管理系统的空域概念。虽然这种方法可能看起来更快，但它增加了复杂性，最终可能会降低空中出行的信任度和安全性。

Overall, the proposed concepts can roughly be divided into three groups. The first group includes the most realistic proposals that rely on the existing technologies, and that could be implemented today. These are the proposals by NASA, FAA, SESAR U-Space and to a measure, DLR U-Space. Under these proposals, drones fly in G Class airspace, below the altitude of 400ft and leverage the existing air traffic management system, which provides identity registration, as well as weather and obstacle (geofence) data. The pilots are required to fly the drones in the line of sight and maintain separation from the other traffic according to the existing airspace rules. The operations are kept separate from the controlled airspace. If there is a need to go through controlled airspace, UAV operator can use segregated corridors with the permission of air traffic control. Although future phases require more advanced technologies, the first phase could be implemented today.

总的来说，所提出的概念大致可以分为三组。第一组包括最现实的建议，这些建议依赖于现有技术，并且今天就可以实施。这些建议包括 NASA、FAA、SESAR U-Space 以及在一定程度上 DLR U-Space 的建议。在这些提议下，无人机在 G 类空域飞行，飞行高度低于 400ft 并利用现有的空中交通管理系统，该系统提供身份注册以及天气和障碍物 (地理围栏) 数据。飞行员需要保持视线内飞行无人机，并根据现有的空域规则与其他交通保持分离。这些操作与受控空域保持分离。如果需要穿越受控空域，无人机操作员可以使用经空管许可的隔离走廊。尽管未来阶段需要更先进的技术，但第一阶段今天就可以实施。

The second group of airspace concepts proposes dedicated UAM traffic control and the creation of airspace structures, such as layers, tubes, lanes, etc. This group includes the majority of proposals, including UTFC, MITRE, METROPOLIS, ONERA, Singapore UTM, Airbus, and Embraer-X. To properly function, these concepts require improvement of several technologies, most importantly, improvement in high-capacity communication networks, and improvement in the precision of surveillance systems which would enable remote path planning and conflict resolution. These concepts propose static separation requirements and may or may not be complemented by advanced sense and avoid systems.

第二组空域概念建议设立专用的 UAM 交通控制并创建空域结构，如层次、管道、通道等。这组包括大多数提议，包括 UTFC、MITRE、METROPOLIS、ONERA、新加坡 UTM、空客和 Embraer-X。为了正常运行，这些概念需要改进几项技术，最重要的是，提高大容量通信网络的能力，以及提高监控系统的精度，这将使得远程路径规划和冲突解决成为可能。这些概念提出了静态分离要求，并可能辅以先进的感知与避让系统。

The third group of concepts, such as those from Amazon and Boeing, rely on the development of technologies that would enable UAVs to be highly independent of any air traffic control. The vehicles are expected to carry high-quality cameras, LIDAR, and some version of RADAR, and

第三组概念，如亚马逊和波音公司的概念，依赖于技术的发展，这些技术将使无人机在无需任何空中交通控制的情况下高度独立。预计这些车辆将配备高质量的摄像头、LIDAR 和某种版本的雷达，

Table 12
表 12
Review of airspace concepts.
空域概念综述。

Concept			v1.0	NASA UTM	NASA UTFC	MITRE	SESAR U-Space	DLR U-Space	Metropolis-a	Metropolis-b	Metropolis-c	Metropolis-d
Country/Region			USA	USA	USA	USA	EU	Germany	Netherlands	Netherlands	Netherlands	Netherlands
Structure			Corridors	Preapproved Trajectories	Skylanes	Preapproved Trajectories	Preapproved Trajectories	Cells	Full mix	Layers	Zones	Tubes
Safety	Object avoidance	Static Geofence	✓	✓	✓	✓	✓	✓	✓	✓	3	✓
		Dynamic Geofence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Sense and avoid	Not required	Not required	Required	Required	Not required	Not required	Required	Not required	Not required	Not required
		Separation	Static	Static	Static	Static	Static	Dynamic	Static	Static	Static	Static
	Wind gusts		3	X	x			3	X	X	X	X
	Weather		/	3		3	3	/	3	3	/	3
Social	Noise								X		X	
	Privacy		X	X	X	X			X	X	X	X
	Visual pollution		X	X	X				X	X	X	X
System	Airspace Management		Centralized	Centralized	Centralized	Centralized	Centralized	Centralized	Centralized	Centralized	Centralized	Centralized
	CNS		Not specified	GPS, ADS-B	Not specified	Not specified	LTE, FLARM, ADS-B	LTE, FLARM. ADS-B	LTE, FLARM. ADS-B	LTE. FLARM. ADS-B	LTE, FLARM. ADS-B	LTE, FLARM. ADS-B
	Capacity		Medium	High	Low	High	High	High	High	High	Medium	Low
Vehicle	Automation	Manned	3	X	X	I	3	J	S	/	/	/
		Unmanned	X	/	J	/	3	/	/	/	/	/
	Critical aircraft		Various	sUAS	sUAS	Various	Various	Various	Various	Various	Various	Various
	Energy-efficient paths		X	3	X	✓	3		3	X	X	x

概念			v1.0	美国宇航局 UTM(无人机交通管理系统)	美国宇航局 UTFC(无人机交通飞行中心)	MITRE(美国一家从事科研工作的非营利组织)	SESAR U-Space(欧洲单一欧洲天空高级空中交通管理系统)	DLR U-Space	大都市-a	大都市-b	大都市-c	大都市-d
国家/地区			美国	美国	美国	美国	欧盟	德国	荷兰	荷兰	荷兰	荷兰
结构			走廊	预批准轨迹	天空通道	预批准轨迹	预批准轨迹	单元	完全混合	层次	区域	管道
安全	避障	静态地理围栏	✓	✓	✓	✓	✓	✓	✓	✓	3	✓
		动态地理围栏	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		感知与避让	不需要	不需要	需要	需要	不需要	不需要	需要	不需要	不需要	不需要
		分离	静态	静态	静态	静态	静态	动态	静态	静态	静态	静态
	阵风		3	X	x			3	X	X	X	X
	天气		/	3		3	3	/	3	3	/	3
社交	噪音								X		X	
	隐私		X	X	X	X			X	X	X	X
	视觉污染		X	X	X				X	X	X	X
系统	空域管理		集中化	集中化	集中化	集中化	集中化	集中化	集中化	集中化	集中化	集中化
	民航通信导航监视系统 (CNS)		未指定	全球定位系统 (GPS)、广播式自动相关监视 (ADS-B)	未指定	未指定	长期演进技术 (LTE)、飞行器避让系统 (FLARM)、广播式自动相关监视 (ADS-B)	长期演进技术 (LTE)、飞行器避让系统 (FLARM)、广播式自动相关监视 (ADS-B)	长期演进技术 (LTE)、飞行器避让系统 (FLARM)、广播式自动相关监视 (ADS-B)	长期演进技术 (LTE)、飞行器避让系统 (FLARM)、广播式自动相关监视 (ADS-B)	长期演进技术 (LTE)、飞行器避让系统 (FLARM)、广播式自动相关监视 (ADS-B)	长期演进技术 (LTE)、飞行器避让系统 (FLARM)、广播式自动相关监视 (ADS-B)
	容量		中等	高	低	高	高	高	高	高	中等	低
车辆	自动化	有人驾驶	3	X	X	I	3	J	S	/	/	/
		无人驾驶	X	/	J	/	3	/	/	/	/	/
	关键飞机		各种	小型无人航空系统 (sUAS)	小型无人航空系统 (sUAS)	各种	各种	各种	各种	各种	各种	各种
	节能路径		X	3	X	✓	3		3	X	X	x

Table 13
表 13
Review of airspace concepts (continued).
空域概念综述 (续)。

Concept			ONERA	Singapore	UOMS	JAXA	Amazon	Airbus	Boeing/Aurora	Embraer-X	Uber Elevate
Country/Region			France	Singapore	China	Japan	USA	EU	USA	USA	USA
Structure			Layers	Lanes	Layers	Corridors	Layers	Basic flight, Free routes, Corridors, Fixed routes	Tubes	Layers with routes and corridors	Preapproved Trajectories
Safety	Object avoidance	Static Geofence	✓	✓	✓	✓	✓	3	✓	✓	3
		Dynamic Geofence	**X**	X	✓	x	x	✓	✓	✓	✓
		Sense and	Not required	Required	Not required	Required	Required	Not required	Required	Required	Not Required
		Separation	Static	Static	Static	Static	Dynamic	Static	Dynamic	Static	Static
	Wind gusts		X	3	X		X	X	X	X	3
	Weather		X	X	/	X	X	/	/	/	3
Social	Noise		X		X	X	x	X	X	3	3
	Privacy		X		x	x	X	3	3	3	3
	Visual pollution		X		X	X	X	X	X	3	3
System	Airspace Management		Centralized	Decentralized	Decentralized	Centralized	Decentralized	Centralized	Decentralized	Centralized	Decentralized
	CNS		FLARM, LTE, ADS-B	GPS, V2V Comm	4G/5G LTE	Precision mapping, RADAR, GPS	WiFi, ADS-B. V2V	ADS-B, V2V Comm	ADS-B, Internet, Blockchain	Next generation GPS and ADS-B	Next generation technologies
	Capacity		Medium	Low	High	High	Medium	Varies	Medium	High	Not specified
Vehicle		Manned	3		/			3			3
		Unmanned		3				3			
	Critical aircraft		Various	UAS	Various	Various	Various	Various	Various	Various	VTOL
	Energy-efficient paths		X	X	X	X	X	3	✓	x	x

概念			ONERA(法国国家航空航天研究机构)	新加坡	UOMS(未知，可能是一个组织或系统名称)	JAXA(日本宇宙航空研究开发机构)	亚马逊	空中客车	波音/奥罗拉	Embraer-X(巴西航空工业公司的子公司)	Uber Elevate(Uber 的飞行汽车项目)
国家/地区			法国	新加坡	中国	日本	美国	欧盟	美国	美国	美国
结构			层级	车道	层级	走廊	层级	基本飞行，自由航线，走廊，固定航线	管道	带有路线和走廊的层	预批准的轨迹
安全性	物体避让	静态地理围栏	✓	✓	✓	✓	✓	3	✓	✓	3
		动态地理围栏	**X**	X	✓	x	x	✓	✓	✓	✓
		感知与	不需要	需要	不需要	需要	需要	不需要	需要	需要	不需要
		分离	静态	静态	静态	静态	动态	静态	动态	静态	静态
	风暴		X	3	X		X	X	X	X	3
	天气		X	X	/	X	X	/	/	/	3
社会性	噪音		X		X	X	x	X	X	3	3
	隐私		X		x	x	X	3	3	3	3
	视觉污染		X		X	X	X	X	X	3	3
系统	空域管理		集中式	分布式	分布式	集中式	分布式	集中式	分布式	集中式	分布式
	中枢神经系统 (CNS)		FLARM, LTE, ADS-B	GPS, 车对车通信 (V2V Comm)	4G/5G LTE	精确映射，雷达，GPS	WiFi, ADS-B, 车对车通信 (V2V)	ADS-B, 车对车通信 (V2V Comm)	ADS-B, 互联网，区块链	下一代 GPS 和 ADS-B	下一代技术
	容量		中等	低	高	高	中等	可变	中等	高	未指定
车辆		有人的	3		/			3			3
		无人的		3				3			
	关键飞机		各种	无人机系统 (UAS)	各种	各种	各种	各种	各种	各种	垂直起降 (VTOL)
	节能路径		X	X	X	X	X	3	✓	x	x

have the potential to collect, process, and transmit large volumes of data. The UAVs will have the capability to sustain this heavy payload while not jeopardizing endurance and range, which implies improvement in battery technology. The concepts rely on advanced sense-and-avoid systems.

具有收集、处理和传输大量数据潜力。无人机将具备在不妨碍续航和航程的情况下维持这一重负载的能力，这意味着电池技术的改进。这些概念依赖于先进的感知与避让系统。

5. Discussion

5. 讨论

The first step in the process of designing airspace is to determine its structure. Air vehicles in less structured airspace have more degrees of freedom and can freely choose their position, altitude, heading, and speed, which allows them to fly cost-effective routes. However, these concepts, although least prohibitive, require high technological capabilities, including advanced detect-and-avoid systems, vehicle-to-vehicle communication, and more advanced ADS-B and GPS services. On the other side of the spectrum (Fig. 26), concepts with the most structure can accommodate various levels of equipage but require strict rules and route following to ensure safety.

设计空域的第一步是确定其结构。在结构较为松散的空域中，航空器拥有更多的自由度，可以自由选择其位置、高度、航向和速度，这使得它们能够飞行成本效益较高的航线。然而，尽管这些概念限制最少，但它们需要高技术能力，包括先进的检测与避让系统、车与车之间的通信以及更先进的 ADS-B 和 GPS 服务。在另一端 (图 26)，结构最为严密的概念能够适应不同级别的设备，但需要严格遵守规则和航线以保障安全。

Less structured airspace has been shown to allow for higher traffic densities by reducing traffic flow constraints and structure. Here, aircraft can fly user-preferred (often direct) routes, while separation responsibility is delegated to individual aircraft using onboard conflict resolution technologies [24,157]. Energy consumption is lower due to more efficient routes. However, free flight is possible only if vehicles are autonomous, and the concept is not inclusive of aircraft with lesser technological capabilities. Free flight concepts usually do not consider social factors in selecting their routes, as this would require higher levels of coordination and structure. The collision risk is high since the detect-and-avoid system is the only barrier that prevents an accident, and flights can have multiple collision points along their trajectories. Third-party risk is also high since user-selected routes might be located above high-density neighborhoods. These findings are supported by the Metropolis study (Table 9) and the Altiscope study that showed that increasing disorder in airspace leads to lower safety levels [159]. The concept of free flight is popular as it does not require a centralized traffic management system; it is achievable solely by developing higher-level autonomy. However, it can only be implemented in limited, constrained geographic areas where there is little chance of contact with other aircraft or objects. The performance of these different factors for free flight, as well as for the other more complex structures, is qualitatively presented in Fig. 27.

结构较为松散的空域已被证明能够通过减少流量约束和结构来允许更高的交通密度。在这里，飞机可以飞行用户偏好的 (通常是直飞的) 航线，而分离责任则委派给使用机载冲突解决技术的各架飞机 [24,157]。由于航线更加高效，能源消耗降低。然而，只有在车辆具备自主性时才可能实现自由飞行，而且这一概念并不包含技术能力较低的飞机。自由飞行概念在选择航线时通常不考虑社会因素，因为这需要更高水平的协调和结构。碰撞风险很高，因为检测和避障系统是防止事故的唯一屏障，而且航班在其轨迹上可能有多个碰撞点。第三方的风险也很高，因为用户选择的航线可能位于高密度社区上方。这些发现得到了大都市研究 (表 9) 和 Altiscope 研究的支持，后者表明空中交通秩序的增加会导致安全水平降低 [159]。自由飞行的概念很受欢迎，因为它不需要集中式的交通管理系统；它仅通过发展更高水平的自主性就能实现。然而，它只能在有限的、受限制的地理区域内实施，在那里与其他飞机或物体的接触机会很小。这些不同因素对自由飞行的表现，以及对于其他更复杂结构的性能，以定性的方式呈现在图 27 中。

Other concepts aim at changing the airspace structure specifically for integrating small UAS, for example, by introducing specialized UAS traffic management (UTM). One step further is to segregate aircraft of different capabilities into different layers. The study [160] has shown that layers reduce the probability of a collision in three ways: by creating vertical separation between operations, by segregating flights according to the direction and speed, which reduces the number of conflict points, and by separating according to the aircraft capabilities. The concept of layers also performs well in terms of capacity [160], third-party risk [147], and inclusivity [156].

其他概念旨在专门改变空域结构，以便整合小型无人机系统 (UAS)，例如，通过引入专门的无人机交通管理 (UTM)。更进一步的是，将不同能力的飞机分离到不同的层次。研究 [160] 表明，层次可以通过以下三种方式减少碰撞的概率: 通过在操作之间创建垂直间隔，通过根据飞行方向和速度分离飞行，这减少了冲突点的数量，以及根据飞机的能力进行分离。层次的概念在容量 [160]、第三方风险 [147] 和包容性 [156] 方面也表现出色。

Some structures can be beneficial in terms of traffic separation, but too much structure only reduces performance. As flight paths become constrained, capacity, efficiency, and safety decrease. Since multiple aircraft are guided to the pre-set waypoints or structures, the number of potential conflicts increases, compared even with free flight [147]. Highly structured airspace has an advantage in that it can accept aircraft of different technological capabilities, i.e., it is inclusive.

一些结构在交通分离方面可能是有益的，但过多的结构只会降低性能。随着飞行路径变得受限，容量、效率和安全性都会降低。由于多架飞机被引导到预设的航点或结构，潜在的冲突数量增加，甚至与自由飞行 [147] 相比也是如此。高度结构化的空域的优势在于它可以接受不同技术能力的飞机，即它是包容的。

The structure comes from the need to separate operations without imposing too many technological requirements. Rotorcraft wake vortex propagates downward and does not create the same issues as wake vortices in traditional aviation [22]. Therefore, the horizontal separation for rotary-wing UASs is only influenced by the need to avoid conflict, which means that the separation standards mainly depend on a vehicle's speed, maneuverability, sensor system technology, and autonomous decision-making capability.

这种结构来源于需要在不对技术要求施加过多限制的情况下分离操作。旋翼机的尾涡向下传播，不会产生传统航空中尾涡的同样问题 [22]。因此，旋翼无人机系统的水平间隔仅受避免冲突的需求影响，这意味着分离标准主要取决于飞机的速度、机动性、传感器系统技术和自主决策能力。

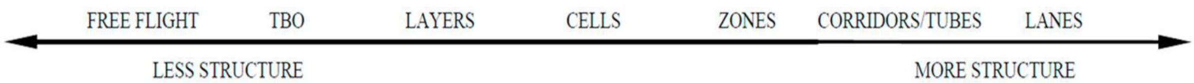


Fig. 26. Airspace structure and design concepts.

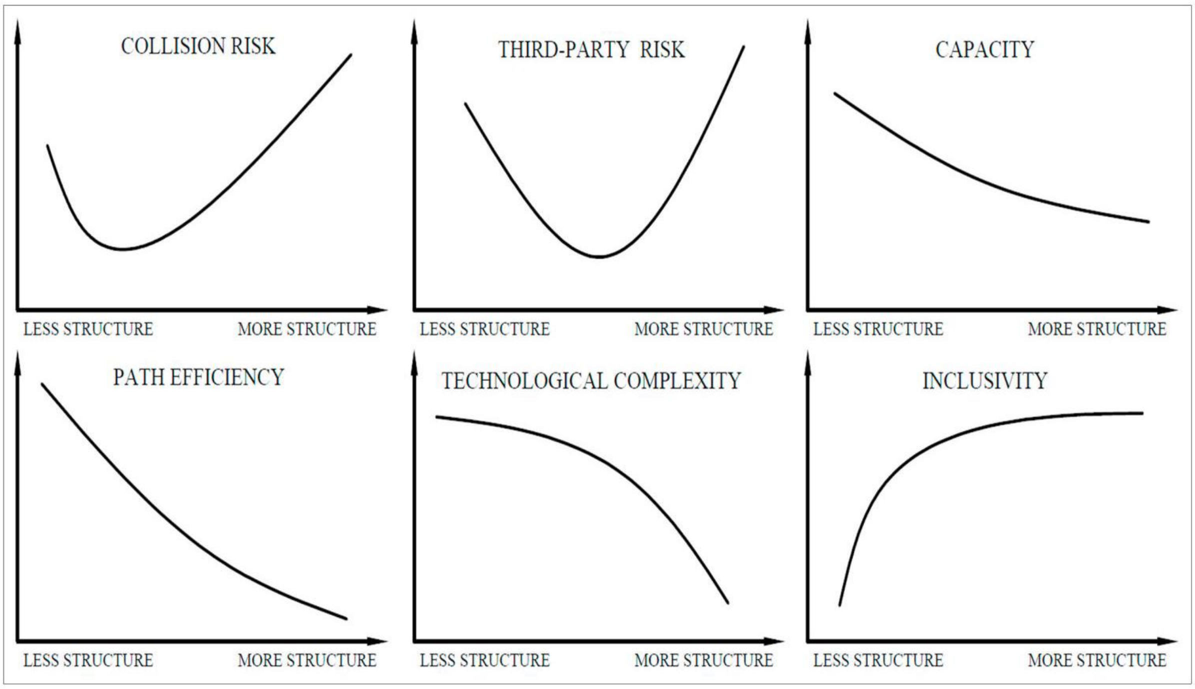


Fig. 27. Performance vs. Airspace structure.

图 27. 性能与空域结构。

The technology required to provide such capabilities is still not sophisticated enough. For example, although advances in detect-and-avoid systems have been made, it cannot be relied upon for safety assurance [161]. The GPS can provide accuracy up to 5 m , which is not adequate for high-precision navigation in unstructured airspace [111]. ADS-B, required for tracking and surveillance, lacks frequency bandwidth to support high-density UAM traffic [115] and should be replaced with more advanced surveillance systems [116]. For these reasons, it is reasonable to predict that in the short- and mid-term, more segregated airspace will be developed.

提供此类功能所需的技术仍不够成熟。例如，尽管在检测和避让系统方面取得了进展，但它不能依赖于确保安全 [161]。GPS 可以提供高达 5 m 的精度，这对于在非结构化空域中的高精度导航是不够的 [111]。用于跟踪和监视的 ADS-B 缺乏频率带宽来支持高密度的城市空中交通 [115]，并且应该被更先进的监视系统所取代 [116]。出于这些原因，可以合理预测，在短期内和中期内，将开发更多的隔离空域。

Finally, the collection of these concepts shows that social factors usually come as an afterthought, which is a mistake since noise is one of the most severe capacity-limiting factors [162]. The focus of the research efforts presented in this article is placed on the trade-off between safety and capacity. However, the assumptions for these concepts are based on an abstract network, with a particular emphasis on efficiency over other outcomes. Idealized networks usually ignore risks such as bird strikes and realities on the ground.

最后，这些概念的集合表明社会因素通常是在事后才考虑到的，这是一个错误，因为噪音是最严重的容量限制因素之一 [162]。本文呈现的研究努力的焦点是放在安全与容量之间的权衡。然而，这些概念的假设是基于一个抽象网络，特别强调效率而非其他结果。理想化的网络通常会忽略诸如鸟击和地面现实等风险。

Urban air mobility, as a new mode of transportation, is there to serve the public. But currently, there is a little public debate over what UAM should look like, and the average city resident seems to be unfamiliar with the concept of UAM. Urban air has been seen as a common good, with a little contestation over rights to it. However, as the privatization of the air proceeds, it is naïve to expect that it will simply be appropriated by the aviation industry without pushback from state and local legislatures, private citizens, communities, and other interests. Traditionally, areas around airports were the only areas affected, and the wider population had no contact with air traffic operations, mainly because air transportation networks do not have physical manifestation on the ground. Aviation and the cities were able to coexist without much contact. However, urban aviation is manifesting itself on the ground, by physically changing the built environment and altering the living environment, which impacts the interests of communities, real-estate developers, politicians, citizens, and interest groups.

城市空中出行，作为一种新的交通模式，其存在是为了服务公众。但目前，关于 UAM 应该是什么样子，公众讨论较少，普通城市居民似乎对 UAM 的概念不太熟悉。城市空间一直被视为公共财产，对其权利的争夺较少。然而，随着空气私有化的进行，期望它会被航空业简单地占有，而不受到国家、地方立法机构、私人公民、社区和其他利益的抵制，这是天真的。传统上，只有机场周边地区受到影响，更广泛的人群与空中交通运作没有接触，主要是因为航空运输网络在地面没有物理表现。航空与城市能够在没有太多接触的情况下共存。然而，城市航空正在通过改变建筑环境和影响生活环境，在地面显现出来，这影响了社区、房地产开发商、政治家、公民和利益团体的利益。

Even a policy taken for granted by researchers, such as drone identification, poses challenges when implemented in the real world. Remote Identification of Unmanned Aircraft Systems Rule [163] is a proposed rule that would require all drones to have remote identification capabilities. However, the proposal has faced an uproar by the hobby model aviation community, claiming that the new rules would effectively wipe out the community and the supporting $1 billion industry. A simple piece of legislation is facing serious opposition. The issues such as air rights, land appropriation, land use, and zoning will be much harder to solve.

即使是被研究人员视为理所当然的政策，如无人机识别，在现实世界中实施时也面临着挑战。无人机远程识别规则 [163] 是一项提议规则，要求所有无人机具备远程识别能力。然而，这一提议遭到了业余模型航空社区的强烈反对，他们声称新规则将有效地消灭这个社区以及支持的 $1 十亿美元产业。一项简单的立法正面临严重的反对。诸如空气权利、土地征用、土地使用和分区等问题将更难解决。

The UAM is in the ”honeymoon” phase, similar to where autonomous vehicles were in the early 2010s. New aircraft prototypes are here, and the industry is enthusiastic. However, there is still a long way to go in terms of technology, regulation, and public conversation. The ramifications of rolling out too quickly, especially in passenger transportation, are severe. By rushing to start UAM passenger transport, the unexpected safety issues and public opposition might stop the UAM development and force cities to ban UAM. Traditional aviation has been dealing with public opposition for over five decades, mainly due to aircraft noise imposed on communities near airports. However, most commercial airports are currently located in the suburbs, whereas vertiports will mostly be located in more densely populated areas. Since commercial airports developed mechanisms for dealing with public concerns in suburban environments, these same mechanisms may not fully apply to vertiport and city environments.

UAM 目前处于“蜜月期”，类似于自动驾驶汽车在 2010 年代初期的阶段。新型飞机原型已经问世，行

业充满热情。然而，在技术、法规和公众对话方面仍有很长的路要走。特别是在客运领域，过早推广的后果是严重的。如果急于启动 UAM 客运，意外的安全问题以及公众的反对可能会停止 UAM 的发展，迫使城市禁止 UAM。传统航空业已经处理了超过五十年的公众反对，主要是因为机场附近的社区受到飞机噪音的影响。然而，大多数商业机场目前位于郊区，而垂直机场将主要位于人口更为密集的地区。由于商业机场已经在郊区环境中建立了处理公众关注的机制，这些机制可能不完全适用于垂直机场和城市环境。

The aviation agencies around the world will likely have more difficulties in enacting their solutions in the space where there are so many stakeholders and will need to reach out to a wider audience than today.

全世界的航空机构很可能在有许多利益相关者的领域中实施其解决方案时遇到更多困难，并将需要比今天接触更广泛的受众。

6. Conclusion

6. 结论

This study presents a review of urban airspace design concepts and creates a framework that can be used to assess the proposed concepts. We define four groups of factors that impact the physical structure of airspace: safety, social, system, and vehicle factors and then analyze airspace proposals based on these factors. The analysis shows that most proposals 1) focus on the limited notion of safety, 2) rely on technologies that are still not available, and 3) do not address social factors adequately.

本研究对城市空域设计概念进行了综述，并创建了一个用于评估提议概念的框架。我们定义了影响空域物理结构的四组因素: 安全因素、社会因素、系统因素和车辆因素，然后基于这些因素分析空域提议。分析表明，大多数提议 1) 专注于有限的安全概念，2) 依赖尚未可用的技术，以及 3) 没有充分解决社会因素。

Additionally, we find that the structure and restrictiveness of airspace can influence capacity, safety, and efficiency. Less structured airspace, such as the concept of Free flight, allows greater capacity and route efficiency but requires greater technological capabilities and reduces safety. On the other hand, more restrictive structures, such as tubes and lanes, enable the operations of less-equipped aircraft but increase delays.

此外，我们发现空域的结构和限制性可以影响容量、安全和效率。结构较少的空域，如自由飞行概念，允许更大的容量和航线效率，但需要更高的技术能力并降低安全性。另一方面，更具限制性的结构，如管道和通道，使得装备较少的飞机能够运行，但会增加延误。

Recommendations for further research on the topic of urban airspace include:

关于城市空域研究的一些建议包括:

- Research of risk, including accident scenario planning, bird strike risk, loss of control, and risk due to wind gusts.
- 对风险的研究，包括事故场景规划、鸟击风险、失控风险以及因阵风造成的风险。
- Research and discussion about data usage, rights, anonymization, and de-identification of data collected by aircraft in the urban environment.
- 关于数据使用、权利、数据匿名化和去标识化的研究和讨论，这些数据是由在城市环境中飞行的飞机收集的。
- Research on new technologies, especially ADS-B, detect-and-avoid, technology for taking over control if the geofence is breached, and a safety protocol under which new tech can be inspected.
- 对新技术的研究，特别是 ADS-B、检测与避让技术、如果地理围栏被突破时接管控制权的技术，以及新技术的安全协议。
- Research into psychoacoustic effects of drone noise on humans and airspace concept development that has noise at the core of its design.
- 对无人机噪音对人类心理声学效应的研究以及将噪音作为设计核心的空域概念开发。
- Research of community input and design, including visual pollution and privacy concerns.
- 对社区投入与设计的研究，包括视觉污染和隐私问题。
- Research on the impact of ground infrastructure on urban planning, including landing and take-off sites, real estate, zoning, planning issues, inequalities, and air rights.
- 对地面基础设施对城市规划影响的研究，包括起降场地、房地产、分区规划问题、不平等和空权。

Declaration of competing interest

竞争利益声明

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

作者声明，他们没有已知的可能影响本文报告工作的财务利益或个人关系。

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ADS-B: Automatic dependent surveillance-broadcast

ADS-B: 自动依赖监视-广播

ATC: Air Traffic Control

ATC: 空中交通管制

BFR: Basic Flight Rules

BFR: 基本飞行规则

A. Bauranov and J. Rakas

A. Bauranov 和 J. Rakas

BVLOS: Beyond visual line of sight

BVLOS: 超视距

BZ : Business zone

BZ : 商业区

CNS: Communication, Navigation and Surveillance

CNS: 通信、导航和监视

EUROCAE: European Organization for Civil Aviation Equipment

EUROCAE: 欧洲民用航空设备组织

FAA: Federal Aviation Administration

FAA: 联邦航空管理局

FLARM: Flight Alarm

FLARM: 飞行警报

GAFS: General Aviation Flight System

GAFS: 通用航空飞行系统

GPS: Global Positioning System

GPS: 全球定位系统

ICAO: The International Civil Aviation Organization

ICAO: 国际民用航空组织

ID: Identity
ID: 身份
JAXA: Japan Aerospace Exploration Agency
JAXA: 日本宇宙探索机构
LTE: Long-Term Evolution
LTE: 长期演进技术
MFR: Managed Flight Rules
MFR: 管理飞行规则
NAS: National Airspace System
NAS: 国家空域系统
NASA: National Aeronautics and Space Administration, The
NASA: 美国国家航空航天局
NATO: North Atlantic Treaty Organization, The
NATO: 北大西洋公约组织
NFZ: No Flying Zone Progress in Aerospace Sciences 125 (2021) 100726
NFZ: 禁飞区航空航天科学进展 125(2021)100726
ONERA: The Office National d'Etudes et de Recherches Aérospatiales
ONERA: 国家航空航天研究局
PAV: Personal Air Vehicles
PAV: 个人飞行器
RPAS: Remotely Piloted Aircraft System
RPAS: 遥控飞行器系统
sUAS: small UAS
sUAS: 小型无人机系统
SWIM: System Wide Information Management
SWIM: 系统-wide 信息管理
TLC: Technical Capability Levels
TLC: 技术能力水平
UAM: Urban Air Mobility
UAM: 城市空中出行
UAS: Unmanned Aerial Systems
UAS: 无人航空系统
UATM: Urban Air Traffic Management
UATM: 城市空中交通管理
UAV: Unmanned Aerial Vehicle
UAV: 无人航空器
UML: Urban Air Mobility (UAM) Maturity Levels
UML: 城市空中出行 (UAM) 成熟度等级
UTM: Unmanned Aerial Systems (UAS) Traffic Management
UTM: 无人航空系统 (UAS) 交通管理
V2V: Vehicle-to-vehicle
V2V: 车与车之间的通信
VDL: Very High Frequency (VHF) Data Link
VDL: 甚高频 (VHF) 数据链
VLOS: Visual-line-of-sight
VLOS: 目视直线视距
VTOL: Vertical Take-off and Landing
VTOL: 垂直起降