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Review on Development of UAM Research Through Bibliometric Knowledge Mapping

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Abstract: With growing urban congestion, urban air mobility (UAM), which brings urban mobility into a third dimension for more efficient urban travel, has become a global research focus today. To provide a detailed summary of the development status and critical issues for UAM, this paper conducts bibliometric analyses on relevant publications in the Web of Science database from 1993 to 2024 using visualization software, such as VOSviewer and CiteSpace. This study covers publication output, country collaboration networks, core institutions, co-citation analysis, high-frequency keywords, and thematic mapping. Together, these indicators outline the core scholarly development of the UAM field. The findings aim to help readers gain a clearer understanding of the current research landscape and identify promising directions for future exploration.

Key words: advanced air mobility; urban air mobility (UAM); research landscape; visualization analysis

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0 Introduction

Due to the rapid urbanization process, the global urban population has experienced significant growth. The demand for urban transportation increases accordingly, leading to more severe traffic congestion. Cities worldwide confront persistent traffic congestion issues, entailing substantial costs, environmental pollution, sustainable development challenges, and societal conflicts[1]. This has made cities explore new transportation technologies to overcome these challenges. Urban air mobility (UAM) is one of such solutions. UAM takes advantage of low-utilized low-altitude urban airspace and provides efficient, point-to-point travel, which has enormous potential to reduce congestion in cities[2].

Over the recent years, significant progress in automation, electric propulsion, and related technologies has created strong potential for the development of air mobility. Various sectors have put a lot of effort into advancing UAM. Regulatory agencies in the United States, China, Europe, and other countries have already developed frameworks governing UAM operations[3-5]. Simultaneously, Major aerospace companies such as Airbus, Boeing, Embraer, Bell, and EHang have been actively manufacturing UAM aircraft[6-9]. In the meantime, Honda and Uber, as well as other companies, have participated in UAM programs[4].

Due to ongoing industrial advancements, academic interest in UAM has grown significantly. Much work has been conducted. Particularly, several articles have offered overviews of existing studies. Straubinger et al.[10] provided an in-depth analysis of UAM research published up to 2020, offering a framework that covers the key technological, regulatory, and societal aspects. Rajendran et al.[11] focused on the operations of air taxis, addressing factors such as demand forecasting, network design, pricing, fleet maintenance, and pilot scheduling.

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Garrow et al.[12] presented a comparison between the studies on UAM, electric vehicles, and autonomous vehicles, using data from the American Institute of Aeronautics and Astronautics database (2015—2020). Cohen et al.[13] summarized the main benefits and challenges of UAM, such as efficiency improvement, better accessibility, regulation, safety, and public acceptance. Schweiger et al.[14] reviewed 49 papers on UAM ground infrastructure published between 2016 and 2021. Mazur et al.[3] assessed European and international regulations, identifying gaps in vehicle certification, airspace integration, and vertiport operations, and proposing harmonized guidelines for scalable and interoperable UAM systems. Wang et al.[15] discussed the mechanisms, applications, and challenges of UAM, discussing its potential to improve mobility and resolve issues with airspace management, communication, and regulation. Long et al.[16] reviewed UAM demand studies from 2017 to 2022, evaluating estimation approaches such as stated preference surveys, discrete choice models, and simulations. They identified cost, time, income, and public acceptance as major demand drivers and emphasized the importance of data-driven models for planning and policy development. Pak et al.[17] describes ongoing research at the German Aerospace Center known as DLR, involving simulation, traffic management, and vertiport planning. Nonetheless, conventional literature review methods are increasingly inefficient given the rapid expanding of the literature, which makes the review process time-consuming and prone to subjectivity.

For this reason, and in an attempt to analyze UAM research more comprehensively, this paper applies bibliometric methods using tools such as VOSviewer and CiteSpace. Data are collected from the Web of Science Core Collection, a widely recognized database of scholarly publications. Based on this dataset, we attempt to identify the intellectual structure, stage characteristics, and thematic hotspots within the UAM field.

This paper is organized as follows: In Section 2, we outline the process of data extraction and describe the analytical approach. It also includes a preliminary analysis of co-citation networks. Section 3 introduces the major research themes in the UAM field. Section 4 summarizes the key findings, concluding the paper.

1 Concept and History of UAM

1.1 Definitions of UAM

The National Aeronautics and Space Administration (NASA) has introduced a new concept known as advanced air mobility (AAM). It represents a new mode of transportation with the potential to transform passenger and cargo air travel. AAM aims to create a safe, efficient, and highly automated air transport network serving both urban and rural areas. The concept covers a wide array of emerging technologies, ranging from small unmanned aerial systems to automated airspace management, smart air traffic management (ATM) systems, and next-generation navigation solutions. One of the key aspects of AAM is UAM, which represents a significant leap forward in the field[18-19].

UAM involves the reliable operation of manned and unmanned aircraft in urban environments, primarily to provide short-range, on-demand passenger and cargo transportation[2,20]. It consists of three key elements: (1) The aerial vehicle, typically an electric vertical take-off and landing (eVTOL) aircraft, forms the core of the system. (2) The infrastructure, which mainly includes vertiports, designated areas on the ground or elevated platforms where eVTOL aircraft can take off and land, complete with necessary facilities. (3) The air traffic management frameworks are designed to ensure robust and controlled operations in low-altitude urban airspace. These systems are enabled by communication, navigation, and surveillance (CNS) technologies, unmanned aircraft systems (UAS), automated and predictive systems, collision avoidance systems, and other advanced technologies.

1.2 History of UAM/AAM

The origins of UAM can be traced back to the early 1900s with the initial concepts of “flying cars”.

By the mid-20th century, helicopters began to offer air travel services[21]. In 1947, Los Angeles Airways launched the first regularly scheduled, commercial helicopter service[22]. From 1949 to 1979, New York Airways utilized helicopters to transport passengers between heliports in Manhattan and various airports. Additionally, between 1965 and 1968, Pan Am provided hourly flights between Midtown and JFK's WorldPort[20]. Tragically, during this period, the technology was still developing, and several accidents occurred. Combined with issues like noise and high operational costs, operators ceased their services in the late 1960s and 1970s[21].

Although business activities ended, innovation in personal air vehicles persisted[23]. Ref.[24] mentioned in 2003 engineer Paul Moller introduced the concept of the personal air vehicle, defining it as a self-operated aircraft. Since then, innovative concepts for personal air travel have re-emerged, including on-demand air taxi operations, door-to-door air travel, self-operated personal air vehicles, and intra-urban short air trips[25-26].

Since 2010, significant advancements in communications, sensors, and data analytics, particularly in the areas of distributed electric propulsion and battery storage, have created opportunities for personal air travel[27]. In 2016, Uber Elevate launched a project to explore on-demand air transportation and proposed the concept of UAM services[2]. Its reports outlined a detailed vision of both soft and hard requirements for air taxis, including vehicle design, operational infrastructure, and the economic viability of the future air-taxi market. Two years later, NASA formally defined UAM as a safe and efficient air transportation system in urban areas, supporting operations from small package delivery drones to passenger-carrying air taxis[20].

In 2020, NASA advanced this concept further by launching the AAM vision. The program seeks to create a safe development of a new air transportation ecosystem[28]. In Europe, the Single European Sky ATM Research (SESAR) program was established, followed by the release of the U-space blueprint[29]. U-space is a set of digital systems and services designed to safely and efficiently integrate UAS into controlled airspace. It provides the necessary infrastructure for registration, flight planning, communication, surveillance, and traffic management. The fourth edition of the U-space Concept of Operations, released in 2023, expanded its scope to include UAM operations[29]. The European Union Aviation Safety Agency (EASA) has begun creating a regulatory framework, including operations of UAS, the UAS traffic management (UTM) system, and the certification of VTOL aircraft, along with existing advice on vertiport designs[30].

Chinese manufacturer EHang[8] has conducted extensive passenger flight testing with autonomous eVTOL aircraft across multiple regions, including China, Europe, Japan, and South Korea. Additionally, EHang has collaborated with partners to conduct trial operations of aerial sightseeing or short-distance air transportation in cities like Guangzhou, Shenzhen, and Hong Kong. In 2023, the company launched a UAM center at Lleida-Alguaire International Airport in Spain, the first European facility for unmanned eVTOL aircraft.

Groupe ADP, a French company primarily known for managing airports in Paris, is also actively engaged in the field of UAM. The company is involved in planning and constructing its facilities around the managed airports and other strategic urban locations.

Volocopter GmbH, a German company, has conducted a series of test flights in various regions, including Finland, Germany, and the United States. These test flights aim to assess the performance and safety of their eVTOL aircraft and to lay the groundwork for future UAM operations.

Subsequently, UAM has been recognized as a crucial strategic path for future progress, attracting significant attention and interest from both academia and industry.

2 Data and Knowledge Mapping Analysis

2.1 Data and methodology

To identify emerging trends in the UAM field, this study draws on data from the Web of Science

Core Collection. The database spans numerous fields and offers long-term, high-quality data. These strengths make it a dependable source for accurate and meaningful analysis[31]. We searched for relevant publications using a predefined Keyword set: "Urban air mobility" "advanced air mobility" "air taxi" "flying car" "vertical take-off and landing (VTOL) " and "eVTOL". Articles containing these terms in their titles, abstracts, or keywords were retrieved from the database. The initial search yielded 1 682 records. After a detailed review on titles and abstracts to confirm relevance, 1 652 articles were retained for analysis.

A knowledge map visually illustrates the structure and interconnections within a body of knowledge. CiteSpace and VOSviewer are widely used bibliometric tools that employ co-citation analysis and visual mapping to identify core themes and trace the evolution of scholarly trends. Together, they offer a clear picture of the field's intellectual development[32-33]. In this study, all obtained publications were imported into CiteSpace and VOSviewer for analysis. The examination contained publication volume, Country Collaboration Networks, institutional collaboration networks, co-citation networks, and keyword co-occurrence analysis and evolution. The primary objectives of this paper are as follows:

(1) Identify key contributors, including authors, countries, and institutions, and assess their influence on the field.

(2) Construct the knowledge structure of UAM and analyze its intellectual organization.

(3) Examine the intellectual landscape to reveal major themes and emerging directions in UAM.

2.2 Trends in the number of published papers

The number of annual publications is shown in Fig.1. The developmental history can be divided into three distinct stages.

(1) Initial stage (1993—2002): During this period, only a few publications were recorded. The early studies primarily focused on helicopters. These efforts laid the conceptual groundwork for what would later evolve into the "flying car" vision.

(2) Emerging stage (2003—2015): During this phase, academic output increased modestly as interest in urban air transportation, particularly in aircraft design and VTOL technology, began to rise. A brief peak occurred in 2010, when 31 related papers were published. Although academic activity expanded slightly, the field remained in its formative stage. Most studies at the time focused on improving propulsion efficiency, developing lightweight materials, and constructing preliminary simulation models for short-range air transport. At this stage, urban air transportation has always lacked a unified theoretical framework and a comprehensive approach.

(3) Rapid development stage (2016—2024): Since 2016, scholarly work has entered a phase of rapid and continuous expansion. A major reason was Uber's publication of "Fast-forwarding to a future of on-demand urban air transportation"[2]. Subsequently, more formal strategic frameworks were introduced by NASA, the Federal Aviation Administration (FAA), and EASA, as well as by national aviation authorities such as Transport Canada and the Civil Aviation Administration of China. This phase represents a turning point, marking UAM's evolution from conceptual exploration to systematic study and practical development.

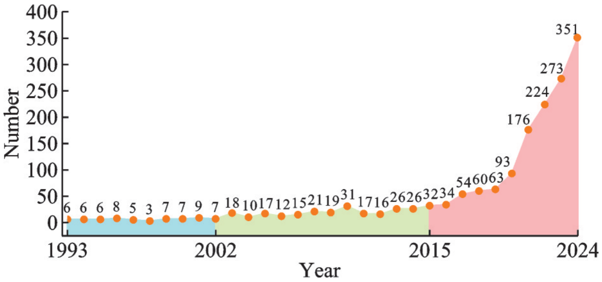


Fig.1 Publications of UAM-related literature 1993—2024

The rapid growth of publications indicates that UAM is transitioning from an initial vision to an active field of research and development. As UAM is recognized as a solution for urban transportation, we predict a continued increase in scholarly publications in the future.

2.3 Distribution of countries/regions

To explore cooperation models, CiteSpace was used to visualize the scholarly work connections among different countries and regions. A total of 63 countries and regions have contributed to the research of UAM/AAM. As shown in Fig.2, the arc length along the outer circle indicates each country's relative publication output in collaborative research, while the connecting chords represent bilateral or multilateral research partnerships. Thicker chords correspond to a greater number of co-authored publications. The structure of the collaboration network reveals a significant imbalance in global research efforts. Remarkably, the United States and China have published a significantly higher number of articles.

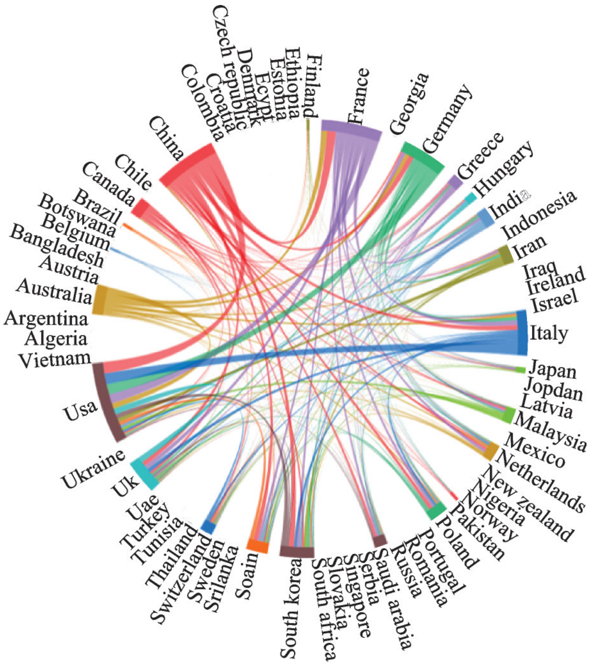


Fig.2 Country/region collaboration distribution in UAM research (1993—2024)

The United States emerges as the most prolific contributor with 318 publications and 4 237 citations. In 2017, NASA, working with the FAA and several industry partners, developed the first operational concept framework that laid the foundation for modern UAM initiatives[34]. Since then, NASA has led in advancing UAM technologies, with a particular focus on aircraft design and airspace integration. Meanwhile, the FAA establishes regulations, certifies UAM aircraft, and formulates key operational standards[35-37]. At the urban level, cities such as Los Angeles, Dallas, and Miami have launched pilot programs[38-40]. The United States focuses on the design of eVTOL, air traffic management, and safe operation in low-altitude airspace within the UAM domain. By formulating relevant regulations and certification standards, America has promoted the innovation and integration of UAM technology.

China, ranking second with 305 publications and 3 180 citations. The Chinese government is accelerating the legislative construction related to UAM[41]. China has emphasized low-altitude airspace management, infrastructure planning, and regulatory development. Research focuses on vertiport layout, eVTOL design, and operational modeling. Demonstration projects and industry cooperation are also proceeding simultaneously. Clearly, China is making rapid progress in UAM research.

South Korea, Germany, and France have similar numbers of published articles (155, 101, and 75, respectively), ranking the 3rd, the 4th, and the 5th, respectively. South Korea released the Korean Urban Air Traffic Roadmap, outlining the commercialization plan for UAM. The plan aims to achieve high-level implementation of UAM by developing advanced infrastructure that supports innovative designs and configurations, while enhancing micro-weather and navigation capabilities[42-43]. Germany plays a pivotal role, with a strong focus on airspace integration, vertiport design, and system safety validation. These efforts are supported by initiatives such as the DLR's Horizon UAM projects[44]. France focuses on demonstration and certification pathways, particularly in collaboration with EASA, Airbus, and Volocopter[45-46]. Its main focus areas include air traffic management integration, noise reduction, and public acceptance, paving the way for sustainable commercial adoption.

Several countries with smaller arc segments demonstrate selective and targeted participation in specific research domains. Italian efforts emphasize infrastructure development, public acceptance, and demonstration projects, particularly in connection with the Rome and Venice test corridors for future eVTOL operations[47]. Canada launched the Canadian Advanced Air Mobility Consortium to promote sustainable and commercial AAM operations through coordinated public-private collaboration[48]. Australia introduced the Remotely Piloted Aircraft Systems and AAM Strategic Regulatory Roadmap, which outlines a plan for integrating UAM into national airspace while prioritizing safety and infrastructure readiness[49].

According to the CiteSpace analysis, the network density, calculated as 0.088 9, represents the ratio between the actual number of established collaboration links and the total possible number of collaboration links. The relatively low network density indicates that the cooperation among countries is relatively less tight. A small group of highly productive countries, such as the United States and China, holds a dominant position, while many others tend to engage in collaboration primarily within specific regions. At the current stage, most cooperation still takes place in the form of small-scale alliances, with a noticeable lack of large-scale multilateral platforms or globally integrated research initiatives. This structural characteristic contributes to the relatively loose and uneven nature of global academic collaboration in the domain. Overall, countries around the world have actively promoted the deployment of UAM through various innovation programs, demonstration projects, and regulatory measures. Their priorities and implementation strategies differ according to national contexts.

2.4 Document co-citation analysis

Co-citation refers to the simultaneous citation of two or more documents by other studies. It helps uncover relationships among publications and trace the evolution. By analyzing co-citation patterns, scholars can identify connections across disciplines and better understand the development of emerging fields. Fig.3 presents the co-citation network generated in CiteSpace with a minimum citation threshold of three, resulting in 1 037 reference nodes. The size of a node indicates the frequency of citations for the corresponding document. The links between nodes reveal the co-citation relationships among cited documents. The horizontal axis of the figure represents the time span from 1993 to 2024, with alternating red and white vertical bands marking yearly time slices. As shown in Fig.3, the field of UAM entered a rapid development stage after 2020. A significant concentration of co-cited references emerged during this period, indicating the rise of multiple research hotspots supported by highly cited publications. Over time, the number of links in the co-citation network has continued to increase, and the connections between nodes have become denser. This trend suggests a growing integration of research themes and a notable rise in interdisciplinary collaboration.

Table 1 presents the top 10 research articles ranked by internal citation counts. The review articles on UAM by Straubinger et al.[10] are currently among the most widely self-cited documents. Similarly, the review articles by Cohen et al.[21] and Garrow et al.[12] are also highly cited.

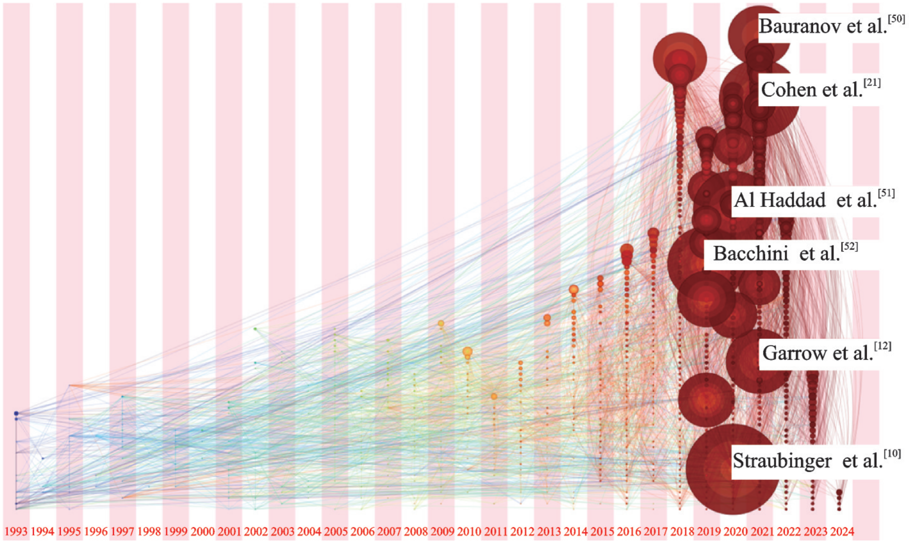


Fig.3 Timeline visualization of co-citation relationships in UAM studies (1993—2024)

Table 1 Top ten most frequently co-cited documents in the UAM field (1993—2024)

Author	Title	Citations	Source
Straubinger et al.[10]	An overview of current research and developments in urban air mobility-setting the scene for UAM introduction	104	Journal of Air Transport Management
Al Haddad et al.[51]	Factors affecting the adoption and use of urban air mobility	90	Transportation Research Part A: Policy and practice
Cohen et al.[21]	Urban air mobility: History, ecosystem, market potential, and challenges	88	IEEE Transactions on Intelligent Transportation Systems
Bacchini et al.[52]	Electric VTOL configurations comparison	87	Aerospace
Garrow et al.[12]	Urban air mobility: A comprehensive review and comparative analysis with autonomous and electric ground transportation for informing future research	74	Transportation Research Part C: Emerging Technologies
Bauranov et al.[50]	Designing airspace for urban air mobility: a review of concepts and approaches	70	Progress in Aerospace Sciences
Kasliwal et al.[53]	Role of flying cars in sustainable mobility	65	Nature Communications
Fu et al.[54]	Exploring preferences for transportation modes in an urban air mobility environment: A munich case study	62	Transportation Research Record
Thipphavong et al.[20]	Urban Air mobility airspace integration concepts and considerations	60	2018 Aviation Technology, Integration, and Operations Conference
Silva et al.[55]	VTOL urban air mobility concept vehicles for technology development	54	2018 Aviation Technology, Integration, and Operations Conference

Bacchini et al.[52] addresed the issue of selecting the optimal configuration for VTOL designs. They compared three representative eVTOLs based on five key parameters and three reference missions. By analyzing and evaluating these configurations, the authors aimed to identify the most suitable design that aligns with the specific requirements and objectives of UAM operations.

Silva et al.[55] outlined three principal configurations of VTOL aircraft and described the associated technologies and design strategies for both turboshaft-and battery-powered models.

The study by Thipphavong et al.[20] has received 60 citations. This paper describes NASA's early framework for UAM operations. It was the first work to formally define UAM and to describe its potential missions, vehicle types, and airspace concepts. This publication laid the groundwork for recognizing UAM as a distinct academic domain and continues to serve as a core reference for subsequent studies in the field.

Al Haddad et al.[51] conducted a questionnaire-based study to evaluate the factors influencing public acceptance and use of UAM. The study focused on user perception and behavioral intention. Results showed that safety, trust, and comfort with automation strongly affect acceptance. Data privacy concerns, social attitudes, and demographic factors also play important roles.

Similarly, Fu et al.[54] used questionnaire surveys to gain insights into the travel behavior impacts of UAM by deriving measures for transportation service attributes and identifying characteristics of potential users.

Kasliwal et al.[53] explored the potential role of flying cars in UAM, emphasizing their environmental benefits, such as reduced emissions and energy consumption. This paper also discusses the technological advancements required to make flying cars a viable and sustainable component of future transportation systems.

To further analyze the references, we used the R programming language to create a historical mapping. This visualization traces the scholarly evolution and highlights the key works that shaped the field, as shown in Fig.4. The network clearly reveals several highly cited core publications. Each node in the figure represents a cited document, and

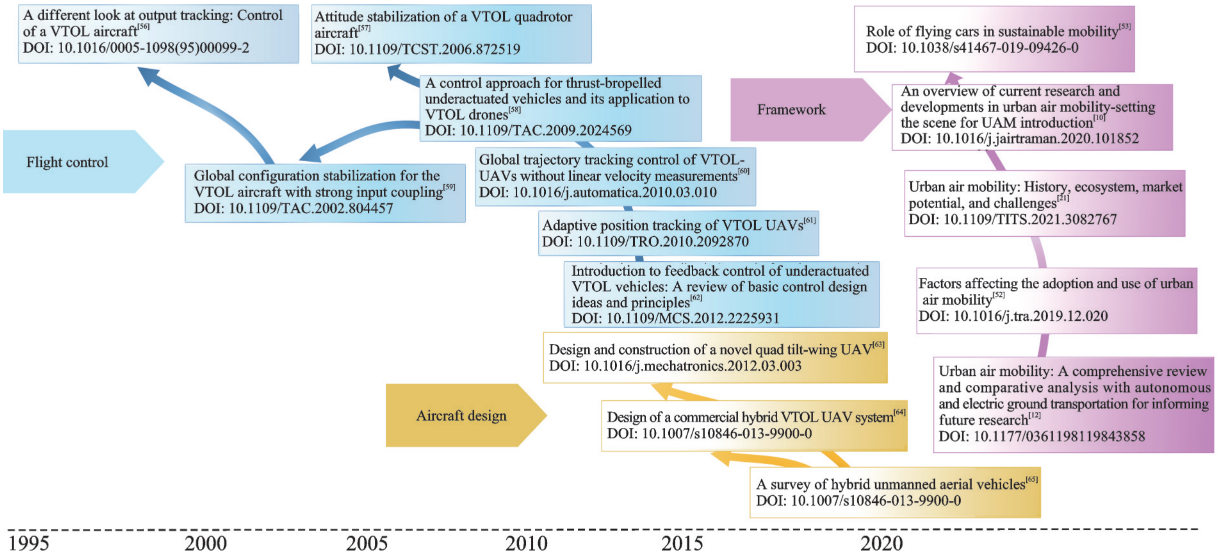


Fig.4 Research trajectory and core literature in UAM (1993—2024)

each connecting line denotes a direct citation relationship. Along the horizontal axis, the publication year reflects the chronological progression of the field.

In the early phase, flight control has emerged as a major theme. Martin et al.[56] proposed a new control method for VTOL aircraft based on output tracking. The approach improved flight stability and precision. It effectively compensated for dynamic disturbances and ensures reliable output control. In related work, Olfati-Saber et al.[59] studied the global stabilization of VTOL configurations, focusing on systems with strong input coupling. Tayebi et al.[57] addressed the attitude stabilization of a VTOL quadrotor, proposing a robust control method to ensure precise orientation and stability, with a focus on practical implementation for real-world applications. Hua et al.[58] introduced a control strategy for thrust-propelled underactuated vehicles, specifically applied to VTOL drones. Abdessameud et al.[60] presented a robust control strategy for trajectory tracking of VTOL UAVs without linear velocity measurements, improving performance in dynamic environments. Roberts et al.[61] proposed an adaptive position-tracking strategy for VTOL UAVs. The method maintains accurate flight performance under uncertain conditions, a key requirement for autonomous operations.

Another major research focus lies in aircraft design, especially in aerodynamic optimization and flight dynamics modeling.

Çetinsoy et al.[63] developed a quad tilt-wing UAV that merged the advantages of fixed-wing and rotary-wing configurations. Ozdemir et al.[64] designed a hybrid VTOL UAV for commercial operations, emphasizing performance, stability, and energy efficiency. Their work demonstrated strong potential for logistics and short-range transport missions. Saeed et al.[65] investigated hybrid UAV architectures, showing that combining multiple propulsion systems enhances flexibility for commercial and industrial use.

Since 2017, framework-oriented studies have gradually become dominant. The core literature within this category closely aligns with the top-cited articles listed in Table 1. Primarily comprising review articles, these works focus on technological features, traffic management, system architecture, and developmental pathways.

Analysis of the core cited literature shows that advances in flight control technology have greatly accelerated the development of specialized UAM aircraft, providing strong momentum for the overall growth of the field. Aircraft design tailored for UAM operations has remained a central research focus, with ongoing technological innovation accompanied by regulatory progress, bringing the concept closer to real-world deployment. With the progression of research, increasing attention has been directed toward the coordinated development of key subdomains within UAM systems, including aircraft design, airspace management, and ground infrastructure planning.

2.5 Distribution of research institutions

Based on the analysis conducted using VOSviewer, research institutions with fewer than 20 publications or fewer than 20 citations were excluded. As a result, 38 institutions met the inclusion criteria and are visualized in Fig.5. The brightness and size of each label correspond to the intensity of research activity and citation impact.

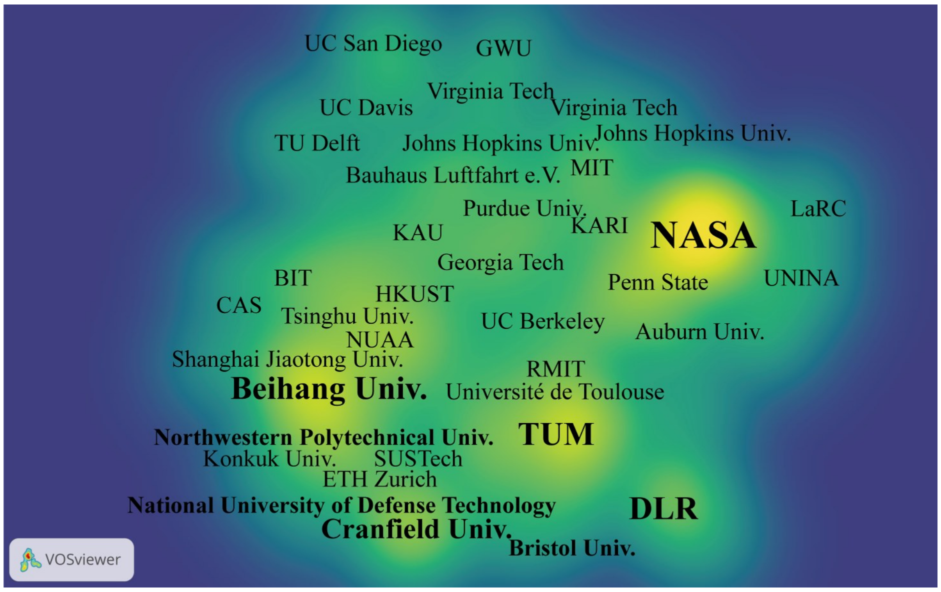


Fig.5 Visualization of institutional cooperation (1993—2024)

NASA stands out as the most influential institution, with 257 publications and 1 156 citations, underscoring its central role in advancing UAM development. NASA's main areas of focus include aircraft design, flight control, risk assessment, communication systems, air traffic management, and UAM operational frameworks[19,66-67]. NASA integrates vehicle design, airspace management, and ground infrastructure into a unified operational framework. Its studies emphasize eVTOL performance, low-altitude traffic management, and automation for safe and scalable operations. Work in this area also extends to vertiport planning, digital communication systems, and public acceptance. Through this system-level approach, NASA provides the technological and regulatory foundation for future UAM deployment.

Beihang University (BUAA) is a leading institution in China's UAM research, emphasizing aircraft design, airspace management, and operational optimization. Its studies focus on eVTOL configuration design, vertiport network planning, and low-altitude traffic management supported by digital-twin and artificial intelligence (AI) technologies. BUAA also explores fleet scheduling and energy management to enhance operational efficiency. Through this integrated approach, the university contributes significantly to the theoretical and practical advancement of UAM in China[68-70].

The research team at the Technical University of Munich (TUM) has been highly active in the field of UAM, with a strong emphasis on system-level modeling and simulation. Their work explores potential development trajectories through scenario-based modeling while advancing the conceptual design and validation of the UAM system architecture[10,51,71].

The DLR work encompasses low-altitude airspace integration and operational concepts, vertiport design and infrastructure optimization, system safety analysis and certification frameworks, as well as transport system simulation and service benefit assessment. By leading and participating in international collaborative initiatives such as the Horizon UAM projects, DLR contributes both foundational knowledge and practical methodologies that support the safe, efficient, and sustainable deployment of UAM systems[14,72].

Over the past year, Cranfield University has addressed topics such as infrastructure planning, propulsion systems, air traffic and conflict management, network modeling, flight control, and digital twin applications[73-75].

These institutions also reflect the inherently multidisciplinary nature of UAM research, which integrates both engineering and societal dimensions.

2.6 Keyword analysis

In academic publications, keywords not only define the core themes of a study but also offer a brief overview of its content[76]. Excluding the terms previously defined in the keyword set, Fig.6 presents a comprehensive list of the top 30 high-frequency keywords. Each rectangle represents a distinct keyword, with its size proportional to the frequency of occurrence.

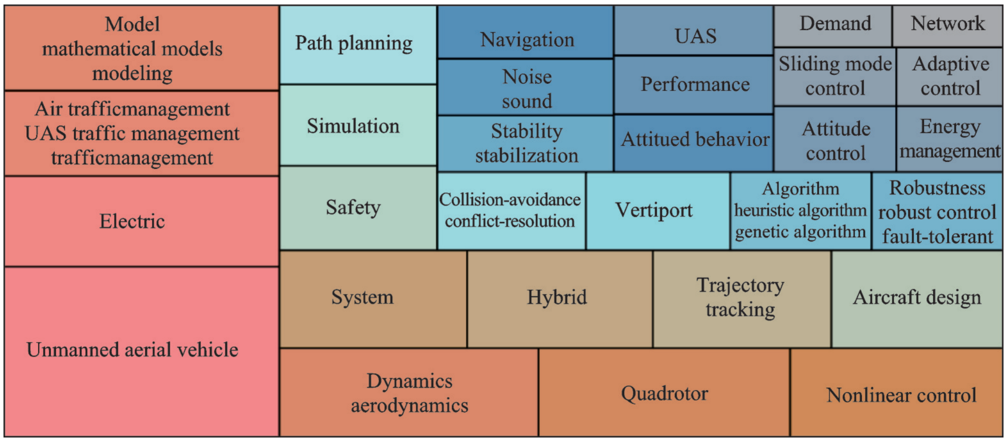


Fig.6 Treemap visualization of high-frequency keywords in UAM literature (1993—2024)

These high-frequency keywords indicate that aircraft design is a core component. This domain encompasses various propulsion architectures (electric, hybrid, turboshaft, diesel), air vehicle configurations (fixed-wing, rotary-wing, tiltrotors, multirotors), and aircraft aerodynamic performance. Designing suitable aircraft constitutes a critical factor in the effective establishment of a successful UAM transportation system[77].

Aircraft flight control is fundamental to flight performance and operational reliability. It maintains stability and enables safe landings under varying conditions, while also improving efficiency, comfort, and emergency response. Flight control systems are generally divided into manual and automatic modes. In current UAM research, the focus has shifted strongly toward automation. Within this domain, the main areas of interest include trajectory tracking, attitude control, and stability or stabilization.

Keyword analysis also reveals that nonlinear control, robust control, adaptive control, and sliding-mode control are among the most frequently applied methods.

Modeling and simulation also emerge as essential scholarly themes, occurring 75 and 41 times, respectively.

Safety remains a timeless and enduring theme within the realm of aviation flight. This is reflected in keywords related to aviation safety, such as collision-avoidance and conflict-resolution.

From a sustainability perspective, current UAM aircraft work prioritizes electric propulsion, aligning with the global shift toward environmentally responsible aviation. Attention has also expanded to energy management, underscoring the need for efficient power distribution in advanced flight systems.

Another recurring topic is noise, which remains a major obstacle to large-scale UAM deployment in urban environments.

By analyzing the evolution of keywords related to UAM, it is clear that the field has been continuously deepening from macro to micro levels and from concept to practice. Initially, the focus was on aircraft design, power systems, and technical feasibility. Gradually, studies have increasingly explored the optimization of aircraft performance, airworthiness standards, and safety. Further work has shifted towards achieving efficient and safe operations in a complex urban environment. At the same time, its commercial potential and economic viability have emerged, involving analyses of market demand, noise, network, and other aspects. Methodological approaches have gradually evolved from the initial theoretical models and experimental verifications to more complex approaches such as system analysis, simulation, and big data analysis.

3 Research Development

Through an analysis of relevant literature, it is evident that current UAM research spans a broad range of topics, with increasing diversity in both subject matter and research focus.

To better identify key areas, this study utilizes VOSviewer to create a keyword co-occurrence knowledge map, as shown in Fig.7. The analysis was conducted based on a minimum occurrence threshold of five. Each node in the network represents a keyword, with node size proportional to its frequency of occurrence. The links between nodes indicate co-occurrence relationships, revealing how frequently pairs of keywords appear together in the same publication.

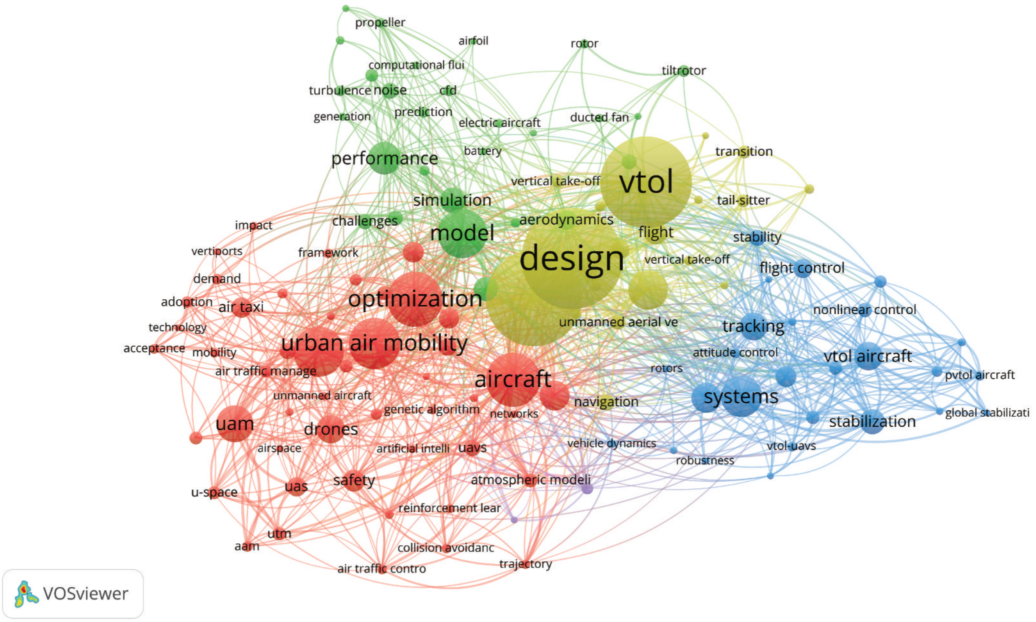
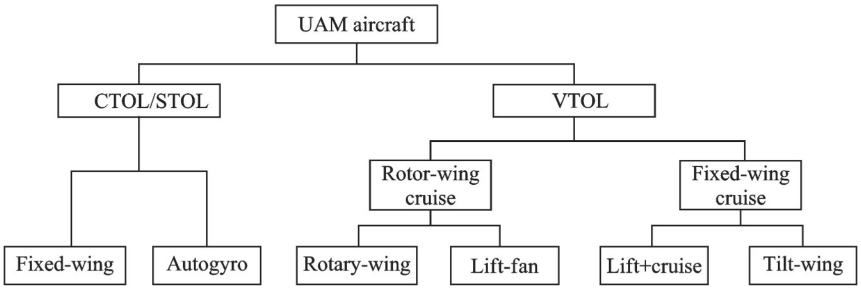


Fig.7 Keyword co-occurrence network (1993—2024)

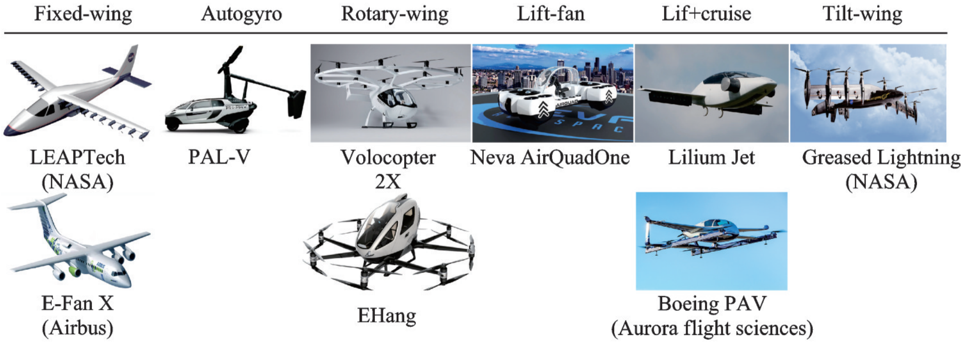
Through the built-in VOS clustering algorithm, keywords were automatically grouped into distinct clusters based on their semantic proximity and co-occurrence relationships. Each cluster is assigned a unique color to visually distinguish different thematic areas within the field. The clustering results reveal several major research directions, including aircraft design, air traffic management, infrastructure, and operations.

3.1 Theme 1: Aircraft design

Appropriate UAM aircraft play a crucial role in the development of UAM transportation systems[78]. Numerous UAM aircraft design projects have been launched. As shown in Fig.8(a), these are classified into two categories based on cruising and vertical take-off and landing methods: Conventional take-off and landing (CTOL)/short take-off and landing (STOL), and VTOL. The left branch of the morphology tree includes conventional fixed-wing configurations, which require runways and are thus unsuitable for inner-city operations. However, they remain viable for intercity and airport connections, as seen in NASA's LEAPTech[79] and the E-Fan (Airbus) [80]. Autogyros, typically associated with STOL operations, use rotor lift and propeller thrust for short takeoffs, exemplified by the PAL-V[81]. Their dependence on dedicated runways limits their integration into UAM networks. In contrast, the right branch includes VTOL aircraft, which can operate with minimal ground space and are central to current UAM initiatives[82]. VTOL designs are classified by lift generation during cruise into rotary-wing, lift-fan, lift+cruise, and tilt-wing types. Rotary-wing models, such as the Volocopter 2X[83] and EHang[84], provide excellent hover performance but limited range and efficiency. Lift-fan concepts, like the AirQuadOne[85], allow compact, safer designs but produce higher noise. Lift+cruise and tilt-wing configurations, as exemplified by the Lilium Jet[86] and Boeing PAV[87], achieve greater efficiency and range at the cost of increased complexity.



(a) UAM aircraft classification



(b) Representative examples from UAM aircraft classes

Fig.8 UAM aircraft classification and representative examples

By 2024, over 800 eVTOL concepts had been documented[88]. VTOL vehicles are the most pertinent when discussing the realization of UAM services[2]. The vertical flight society (VFS) website provides detailed information on various types of eVTOL aircraft and maintains a comprehensive database of eVTOL designs, making it an invaluable resource in this field. According to VFS, there are a total of 782 aircraft, including 283 vectored thrust, 146 lift+cruise, 243 wingless (multicopter), 110 hover bikes/flying devices, and 53 electric rotorcraft. In particular, quad-rotor VTOL has received significant attention from scholars, particularly in the logistics field[89].

The requirements and constraints related to UAM aircraft design are complex and vary. Cruise speed influences both aerodynamic design and propulsion system choices, while range determines energy storage and efficiency requirements. Payload capacity dictates the structural design and weight management, and maximum flight altitude impacts the aircraft's pressurization and propulsion needs. Additionally, low noise emissions will exert a substantial influence on the viability of a UAM vehicle concept, given that public reception is a major factor[90]. To ensure the sustainable operation of UAM systems, it is imperative to take into account energy efficiency, hover efficiency, range considerations, as well as various costs associated with the operational lifecycle during the aircraft design process[91]. Current UAM aircraft projects exhibit significant differences. Uber outlines a design mission range of approximately 95 km, with a reserve range of nearly 10 km, at a minimum cruise speed of 240 km/h and a cruise altitude of 300 m. Additionally, a payload of 500 kg is indicated for accommodating four passengers[2]. NASA recommends a cruise altitude of 1 200 m above ground level, with cruise speeds ranging from 150 to 200 km/h, each designed to accommodate either 545 kg of payload or up to six passengers[77].

As UAM design continues to mature, the study on UAM aircraft, particularly eVTOL vehicles, has evolved from concept to prototype demonstration and initial commercialization. The current frontier topics can be summarized into the following aspects.

(1) Innovative configurations and aerodynamic optimization: Recent studies have explored diverse eVTOL configurations to balance vertical take-off capability with cruise efficiency. These works emphasize aerodynamic modeling, distributed propulsion integration, and trade-off optimization between energy use, payload, and noise[92].

(2) Autonomy and intelligent flight control: Autonomous flight control is a core enabler for high-density UAM operations. Current investigation extends beyond basic automation toward the development of intelligent, adaptive, and cooperative control systems that can function reliably in complex and dynamic urban environments. Intelligent flight management focuses on real-time trajectory optimization, distributed decision-making, and conflict resolution among multiple eVTOL aircraft sharing constrained airspace[93-94].

(3) Energy and propulsion systems: The propulsion and energy systems define the operational feasibility of eVTOLs. Current research emphasizes battery and hybrid powertrain optimization, distributed electric propulsion, and energy-efficient flight mission design[95-96].

(4) Acoustics and aerodynamics of rotor interaction: Noise reduction and aerodynamic safety around vertiports remain key barriers to societal acceptance. Studies focus on rotor-wake interactions, downwash/outwash modeling, and acoustic signature prediction[97].

(5) Safety and certification frameworks: Ensuring system reliability and compliance is a major frontier as eVTOLs approach commercial deployment. Current work addresses certification methodology, redundancy, and integrated safety management[96,98].

Across these domains, scholars employ a wide range of quantitative and computational methods, including: Computational fluid dynamics (CFD) and aeroacoustic coupling for aerodynamic and noise modeling[99]; multi-disciplinary design optimization for configuration and propulsion analysis[100]; system safety analysis and fault-tree modeling for certification frameworks[77, 101]; digital twin technologies that are increasingly applied across the entire UAM system lifecycle[102].

Aircraft design remains the foundation of UAM advancement, with many companies actively developing and testing prototypes. Although eVTOL technologies have achieved significant milestones, challenges remain in airworthiness certification, flight modes, safety, and reliability. As the complexity of UAM systems grows, aircraft design is becoming increasingly integrated and modular. In addition to prioritizing safety and efficiency, there is a strong focus on achieving a high level of autonomous flight. Current research emphasizes multi-redundant architectures, aerodynamic optimization, energy efficiency, and intelligent flight control.

3.2 Theme 2: Air traffic management

The current ATM system's inadequacy in managing urban airspace is the main barrier to UAM development[103]. As illustrated in Fig.9, in accordance with ICAO guidelines[104], the FAA commonly uses six of these categories: Class A (5 489—18 288 m), Class B (around the busiest airports), Class C (around medium-sized airports), Class D (around smaller airports with control towers), and Class E (around smaller airports without control towers). Uncontrolled airspace, Class G, is below 366 m and lacks air traffic management, relying on visual flight rules (VFR)[105].

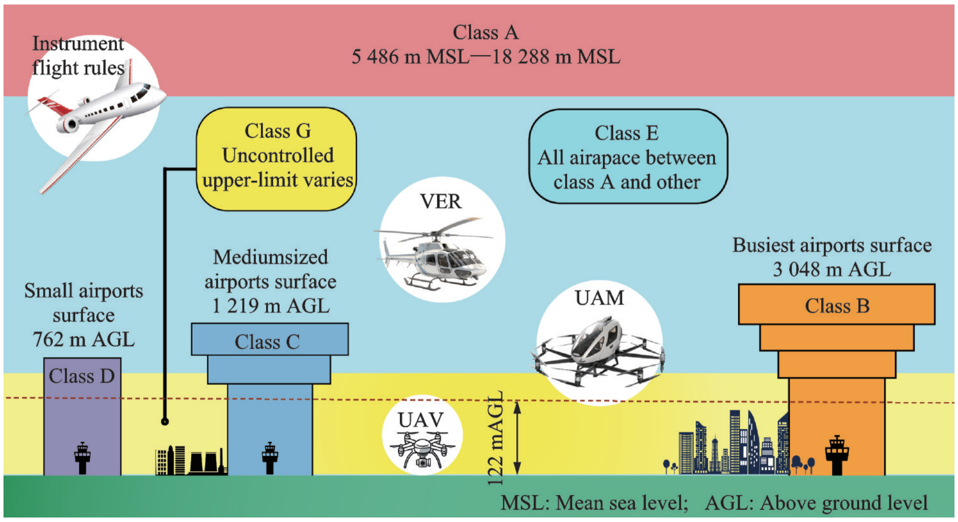


Fig.9 Classification of airspace adapted from Ref.[104]

Vascik et al.[106] suggest that the low altitudes of Classes E and G airspace enables eVTOL operations without requiring air traffic control (ATC) separation and routing services, making it suitable for highly autonomous eVTOL vehicles. However, further analyses suggest that as UAM transport scales increase, expanded airspace will be necessary for UAM operations[20,50,107]. NASA has proposed extending the use of airspace above 120 m for both general aviation and UAM activities[108]. The FAA's UAM Concept of Operations specifies that UAM operations are typically conducted below 1 524 m, ensuring safe integration with existing airspace structures and minimizing potential conflicts with conventional commercial aviation[34]. In general, UAM airspace is categorized within Classes B, C, or D.

Once the airspace boundaries are established, it is essential to further discuss a feasible and standardized airspace architecture for UAM operations. The Metropolis Project has proposed four decentralized airspace concepts, full mix, layers, zones, and tubes, each based on the increasing number of constraints applied in the respective designs[109-110]. Fig.10 illustrates a comparison of four airspace configurations: (1) The full mix concept refers to an unstructured airspace in which aircraft can freely move in all directions. (2) The layers concept, characterized by three degrees of freedom, divides the airspace into vertical altitude layers. Each layer allows for specific heading velocity and horizontal routes, except for aircraft ascending or descending. (3) The zones concept divides airspace into radial or circular zones, similar to the ring roads used in ground transportation. Aircraft can move clockwise or counterclockwise to enter and exit these zones, with inbound and outbound radial routes facilitating their movement. This concept operates with two degrees of freedom: Altitude and speed. (4) In the tubes concept, all flights within tube travel at uniform altitude, direction, and speed, adhering to predefined space-time routes. Aircraft operate with zero degrees of freedom, ensuring movement along preplanned, collision-free routes. This structure significantly enhances the predictability of traffic movement.

Inspired by terrestrial road traffic, Jang et al.[111] from NASA proposed three multilayered airspace structure design concepts for use between high-rise buildings: Sky-lanes, sky-tubes, and sky-corridors. According to NASA, air corridors will become the primary mode of operation in the near-future phase

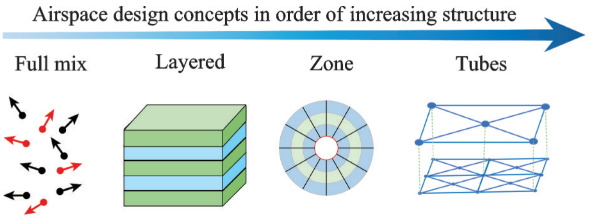


Fig.10 Four concepts of airspace design, adapted from Refs.[109-110]

of UAM development[108]. The FAA proposes that UAM operations occur in structured airspace, generally described as UAM corridors[34].

The establishment of urban low-altitude airspace also needs to consider the minimum horizontal separation from tall buildings on the ground, as well as restrictions imposed by certain no-fly zones. Mohamed Salleh et al.[112] have proposed three types of urban low-altitude airway network design concepts: The airmatrix network, the over-buildings network, and the over-roads network. These designs suggest utilizing existing urban infrastructure, such as ground road networks and airspace above rooftops, or natural areas, like rivers and woodlands, for the planning of aerial routes.

With the rapid development of UAM, the traditional ATM system can no longer be directly extended to accommodate the low-altitude, high-density, and multi-vertiport operational environment envisioned for UAM. Based on this, Mathur et al.[113] mentioned two potential models for the future development of urban air traffic: (1) A manned development approach, which extends the traditional air traffic control functions of the existing ATM system to urban air traffic management; (2) an unmanned development approach, which relies on advancements in autonomous driving, automatic control, and intelligent technologies within the UAS framework.

As the domain advances, a new UAM-ATM architecture is beginning to develop. Automation, digitization, and human-machine teaming become foundational. Yan et al.[114] discussed the necessity of digital scheduling, collaborative traffic management, and data-driven coordination mechanisms to enable large-scale UAM operations. Fas-Millán et al.[115] demonstrated a digital controller concept within the U-space architecture, where automated strategic and tactical conflict-resolution services replace routine controller tasks, while human supervisors retain oversight and exception handling responsibilities. Similarly, Schuchardt et al.[116] emphasized that digital tower concepts and automated controller services will constitute the operational backbone of high-density UAM networks, transforming human operators from manual controllers into supervisory collaborators within a human-machine teaming paradigm.

Ground infrastructure, communication, network support systems, and information exchange architectures constitute the critical components. NASA[117] proposed that the UAM communication architecture which is composed of three core layers, the air-ground command and control link, the information exchange service layer, and the UAM-ATM service layer. It forms the most authoritative framework for UAM network communication. Within the U-space[29] system, the concept of a digital service network was introduced, defining the structure of air-ground communication links, data exchange nodes, and the coordination mechanisms among digital service providers.

Advanced communication, navigation, surveillance (CNS) capabilities remain a cornerstone of UAM system development. The emergence of next-generation 5G/6G-B5G communication networks is a key development. Hybrid navigation architectures are also advancing, combining Global navigation satellite systems, inertial navigation systems, and vision-based positioning. Additionally, multi-source surveillance integration is being leveraged, incorporating automatic dependent surveillance-broadcast, UAS Remote ID, and satellite-based tracking[118].

UAM-ATM in low-altitude urban environments exhibits high traffic density, spatial constraints, strong dynamics, high digitalization, and pronounced uncertainty. Within such a complex operational context, UAM-ATM faces several technical bottlenecks.

First, communication latency and network reliability constitute prepresent major barriers to high-density UAM operations. The UAM-ATM framework relies heavily on continuous low-latency bidirectional data exchange for state broadcasting, trajectory negotiation, separation management, and contingency handling. Under dense traffic conditions, communication load increases nonlinearly, potentially degrading synchronization and system stability. Current research explores the adoption of 5G/6G URLLC network slicingand dedicated spectrum allocation for enabling low-latency communication architectures[119], as well as employing multichannel redundancy via cellular, satellite, and dedicated command-and-control (C2) links[120]. The NASA UTM concept[64] and the SESAR joint undertaking U-space architecture[29] emphasize digital data exchange and service-oriented communication layers.

Second, uncertainty in the urban low-altitude meteorological environment has emerged as a critical constraint on system capacity. Complex urban wind fields, building-induced turbulence, and localized thermal circulation phenomena introduce highly nonlinear and time-varying disturbances that directly affect trajectory tracking accuracy and separation requirements. Existing studies primarily rely on high-resolution numerical weather prediction models to simulate localized wind conditions[121], and utilize CFD simulations based on three-dimensional urban models, deploy low-altitude sensing networks[122], LIDAR systems, and UAV-based measurements to improve situational awareness[123].

Third, airspace structure and capacity management present scalability challenges as traffic density increases. To enhance flexibility, dynamic reconfigurable airspace structures and UAM-specific grid-based management concepts have been proposed, emphasizing real-time adjustment of airspace boundaries and capacity allocation in response to traffic demand fluctuations[29].

Finally, conflict resolution and algorithmic provability are significant challenges. In high-density multi-agent environments, decentralized decision-making may produce oscillatory behaviors or convergence failures, particularly under communication delay and environmental disturbances. The current research primarily focuses on distributed conflict resolution, with multi-agent systems and deep reinforcement learning becoming key areas of emphasis[124].

The frontier technologies driving the evolution of UAM-ATM include the following aspets.

(1) Digital air traffic control: AI-assisted air traffic management systems perform automated trajectory allocation, conflict detection, and traffic-sequence optimization, replacing conventional manual control tasks with digital services[125].

(2) Human-machine teaming decision-support systems: By combining cognitive computing, visualization interfaces, and adaptive workload management, these systems enhance controller situational awareness and collaborative decision-making between humans and autonomous agents[126].

(3) Multi-agent reinforcement learning: It enables self-organizing traffic management and dynamic priority scheduling within complex urban airspace, facilitating adaptive trajectory planning and autonomous conflict resolution to enhance operational scalability and efficiency[127].

(4) Digital twin technology: Digital-twin platforms integrate multi-source data, AI, and real-time sensing to dynamically replicate UAM operations, enabling virtual testing and operational optimization[128].

(5) Traffic management: Dynamic airspace allocation allows corridors and capacities to adapt in real time to demand and traffic density[117]. Trajectory-based operations place the trajectory at the center of flow management, enabling predictive conflict prevention and demand-capacity balancing. Together, they enhance operational flexibility and scalability in high-density environments[129].

(6) System-wide information management enables standardized data exchange and seamless interoperability among operators, service providers, and regulatory entities, establishing a unified information-sharing framework essential for coordinated UAM-ATM operations[130].

(7) Predictive airspace management and ai-based scheduling. Time-series models and decision-tree algorithms support traffic forecasting, predictive deconfliction, and intelligent scheduling, im-

proving efficiency and resilience under uncertainty[131].

UAM air traffic management presents significant challenges, requiring flexible and real-time allocation and adjustment of low-altitude airspace resources. To address this, current research increasingly focuses on automated flight control systems and AI technologies. Core areas include multi-source data fusion, precise trajectory control, and reliable communication. However, suitable theoretical and operational frameworks for dense urban environments remain underdeveloped. Emerging directions emphasize integration between UAM and traditional aviation systems, development of automated and predictive airspace management approaches, and the application of 5G and satellite navigation technologies to enhance safety and situational awareness.

3. 3 Theme 3: Infrastructure

To enable UAM operations, specialized infrastructure is essential[2]. Infrastructure primarily includes facilities for parking, charging, staging, and other essential ground operations. Similarly, ground-based navigation facilities are also crucial.

The essential infrastructure of a UAM airport primarily includes both landside and airside[132]. As illustrated in Fig.11, the landside typically consists of passenger waiting areas, ticketing zones, and other related facilities. In Fig.11, TLOF means touchdown and lift-off area, and FATO means final approach and take-off area. The airside, designated for aircraft operations, is subject to strict regulations regarding touchdown and liftoff areas, final approach and takeoff areas, safety areas, and taxiways. The elements, functions, sizes, and throughput of UAM airports vary depending on the time frame, maturity level, and traffic density. Several institutions are focusing on the structure and design of vertiports, with the EASA[30] and the FAA[36] being the leading authorities. Their document details vertiport physical characteristics, including obstacle environments, visual aids, lighting, and markings. Vascik et al.[133] discussed various layout options for vertiports, including linear, satellite, and pier topologies.

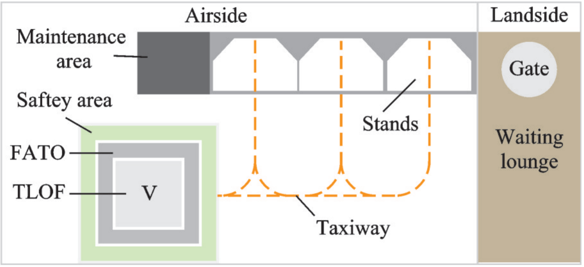


Fig.11 An example layout of a UAM vertiport adapted from Ref.[134]

The main contents of the vertiport research are as follows:

(1) Vertiport layout

Vertiport is usually located in the city center or its surrounding areas. When designing it, the limited space resources must be fully utilized. The size and position of the take-off and landing platform, the layout of the parking area, and the balance between vertical and horizontal spaces are all key issues in the design of vertiport. In response to the limitations of urban space and the diverse demands of aircraft, many investigators have proposed various layout patterns, including star layout, linear layout, and circular layout, among others[134]. Environmental and sustainable design, especially noise control and environmental impact assessment, are also key considerations in the design of vertiports.

The following are several commonly used techniques in vertiport layout design: ① Digital twin technology creates a virtual model of the Vertiport to monitor and analyze its operational status in real-time, optimizing layout design and operational efficiency[135]; ② simulation technology plays a significant role in the layout design of vertiport, capable of optimizing multiple aspects such as aircraft takeoff and landing, traffic flow, safety management, and energy utilization[136].

(2) Vertiport site selection

Location and network layout represent one of the core directions in vertiport studies. In the early stage of site feasibility analysis, Fadhil[137] presented several options for UAM ground infrastructure, including rooftops, barges over water, inside highway cloverleaves, and on top of existing ground-transport infrastructure. Johnson[138] considered factors such as population density, job density, median income, existing noise, and ground-based transport accessibility as the primary considerations to conduct site selection. From the perspective of UAM fleet operators, Shon et al.[139] aimed to minimize operating costs. Constrained by airspace capacity, aircraft performance, vertiport capacity, demand, and investment, they utilized multi-objective optimization algorithms to optimize the layout and resource allocation of Vertiports.

To capture these multidimensional factors, recent studies employ geographic information system-based spatial analysis combined with multi-criteria decision-making methods to comprehensively assess geographic suitability, noise sensitivity, grid connectivity, and land-use compatibility[140].

Meanwhile, clustering algorithms have been applied to large-scale mobility datasets to identify potential origin-destination hotspots and high-demand corridors, serving as primary candidates for vertiport deployment[141].

Optimization models such as the maximum coverage location problem, p-median, and p-hub location models are widely used to design optimal spatial layouts of vertiports and routes within UAM networks. The hub-and-spoke structure is also used to formulate the UAM network[142-144].

(3) Capacity assessment and operational simulation

Capacity research focuses on identifying the internal operational bottlenecks and evaluating scheduling strategies within vertiports to determine their service capability and efficiency. Queuing models are typically used to evaluate service capacity, waiting times, and utilization rates under varying arrival rates and service disciplines[145]. Discrete event simulation (DES) methods are widely applied to model the stochastic behavior of aircraft and passengers in sequential operations[146]. System dynamics models, on the other hand, enable high-level performance evaluation and feedback analysis over long-term operational cycles[147].

The design and site selection analyses of multifunctional vertiports have always been core components of the UAM infrastructure. Over time, development in this area has gradually shifted from initial single-function analysis to comprehensive, coordinated approaches that integrate urban transportation, environmental, and energy considerations, leading to deep integration with various urban systems.

3.4 Theme 4: Operations

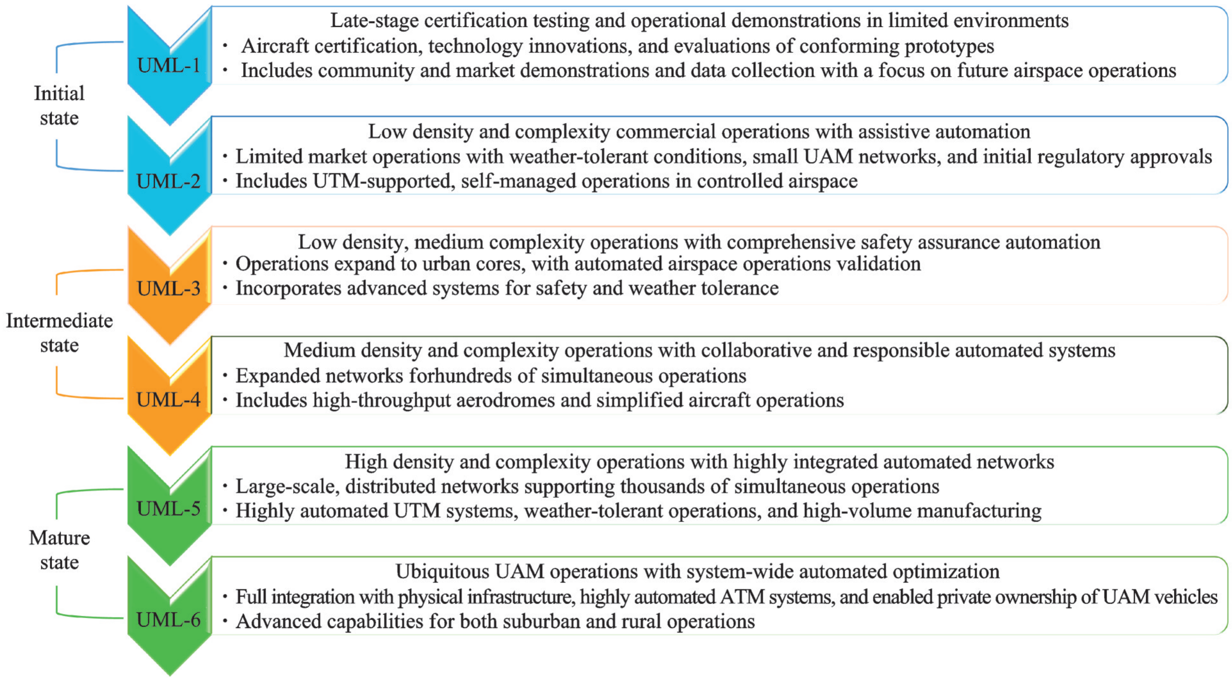
The operational concept and business model approach have been identified as crucial factors for a successful introduction of UAM[148-149]. As illustrated in Fig.12, NASA[19] presents a framework for UAM maturity levels(UML). The future development stages of UAM are organized into six levels, focusing on carriers, airspace, and community acceptance, with each level designed to address specific challenges. Meanwhile, NASA has identified UAM markets across 16 categories. UAM markets across 16 market categories[150].

Differences in technological maturity and market orientation result in differentiated UAM operational models. Table 2 describes the typical operational models for air commuting. Berger et al.[151] identified specific technological and operational requirements for three main use cases of UAM service, air taxis, airport shuttles, and intercity flights. Uber also pointed out that on-demand flights and shared mobility would be key competitive factors in UAM operational models[2]. On-demand UAM directly responds to customer needs, utilizing small eVTOLs to provide rapid, personalized air transport. This operational model enables door-to-door services, better fulfilling passenger travel requirements. Shared mobility in UAM involves providing air transport services to multiple passengers simultaneously, maximizing efficiency and reducing costs by sharing flights.

Different operation models have put forward differentiated requirements for the operation of UAM, mainly in the following key directions.

(1) Flight scheduling and task allocation

Flight scheduling is one of the core components of the UAM system, and its efficiency directly affects the utilization rate of aircraft, punctuality,



Late-stage certification testing and operational demonstrations in limited environments

- Aircraft certification, technology innovations, and evaluations of conforming prototypes
- Includes community and market demonstrations and data collection with a focus on future airspace operations

Low density and complexity commercial operations with assistive automation

- Limited market operations with weather-tolerant conditions, small UAM networks, and initial regulatory approvals
- Includes UTM-supported, self-managed operations in controlled airspace

Low density, medium complexity operations with comprehensive safety assurance automation

- Operations expand to urban cores, with automated airspace operations validation
- Incorporates advanced systems for safety and weather tolerance

Medium density and complexity operations with collaborative and responsible automated systems

- Expanded networks forhundreds of simultaneous operations
- Includes high-throughput aerodromes and simplified aircraft operations

High density and complexity operations with highly integrated automated networks

- Large-scale, distributed networks supporting thousands of simultaneous operations
- Highly automated UTM systems, weather-tolerant operations, and high-volume manufacturing

Ubiquitous UAM operations with system-wide automated optimization

- Full integration with physical infrastructure, highly automated ATM systems, and enabled private ownership of UAM vehicles
- Advanced capabilities for both suburban and rural operations

Fig.12 Framework for UAM maturity levels adapted from Ref.[19]

Table 2 Typical operational models for UAM in air commuting

Operational model	Definition
Airport shuttle	Fixed-route airports that serve passenger transportation to, from, or between locations
Air taxi	On-demand service that provides point-to-point transportation
Air pooling	Aggregating multiple individual users into a single vehicle for flights
Private service	Serving only one individual or party for a length of time greater
Train	Providing concentrated point-to-point travel along network infrastructure

cost control, and the overall experience of passengers. Aircraft usually need to take off and land among multiple vertiports and allocate flight tasks according to different demands and tasks. The dynamics and real-time nature make UAM task allocation a challenging difficulty. Tang et al.[152] proposed a flight planning model that integrated multi-objective optimization and real-time dynamic scheduling, aiming to minimize the operating costs of aircraft in UAM systems. By combining particle swarm optimization and genetic algorithm, this model can optimize flight paths and aircraft scheduling while taking into account energy consumption, flight time, and task priority.

In addition to the widely used multi-objective optimization algorithms, simulation-based methods are also a solution for implementing UAM resource scheduling. Onat et al.[147] presented a detailed simulation-based framework designed to evaluate the performance of eVTOL networks and the dynamics of fleet operations. The model integratd multiple components, including fleet size, flight routing, demand distribution, and scheduling algorithms, to simulate real-world conditions. It used discrete-event simulation to model time-based processes.

AI and machine learning are widely applied to optimize flight scheduling. Paul et al.[153] proposed a graph-based reinforcement learning framework for UAM fleet scheduling, which efficiently allocates resources, and handled dynamic conditions, and manages complex scheduling tasks within UAM systems. In this model, vertiports were represented as nodes, and edges denote the connections between them. Reinforcement learning was employed to optimize flight schedules while considering various operational constraints. This approach aimed to enhance the efficiency and adaptability of UAM operations, especially in dynamic environments.

Facing the problem of dynamic scheduling and demand response, multi-agent systems are widely used. Park et al.[127] proposed a multi-agent reinforcement learning framework for implementing collaborative air transport services in city-wide automated UAM. This method aimed to optimize the collaboration and scheduling of multiple eVTOL aircraft in complex urban air traffic systems to address issues such as task allocation, conflict avoidance, and flight efficiency in air transportation.

(2) Urban integration and multimodal transportation management

As a new type of urban travel mode, the efficient operation of UAM depends not only on the optimization of the air traffic system itself, but also on the degree of integration with the overall urban transportation system. Achieving a seamless connection between UAM and ground transportation is the key to building an efficient urban air travel network.

Through geographic information system (GIS) analysis and multi-criteria decision analysis, the location of vertiport can be reasonably determined, which can effectively ensure the effective connection between UAM and the existing transportation system. Rahman et al.[154] integrated urban data, such as existing transportation networks and population density, to ensure effective connectivity and accessibility between vertiports and public transit systems. Based on GIS and multi-modal transportation network analysis, Zhao et al.[155] comprehensively considered multiple targets such as total passenger capacity, total facility cost, and ground travel distance to vertical airports. A method for strategically integrating vertiport planning with multimodal transportation was proposed.

(3) Market demand forecasting

Market demand forecasting is a fundamental link in the planning and operation management of UAM systems, and its accuracy directly affects strategic decisions such as network layout, vertiport site selection, route design, and capacity allocation. The market demand for UAM has significant characteristics of spatial-temporal heterogeneity and high volatility. Therefore, constructing a scientific prediction model is crucial for the economic feasibility assessment of the system.

Since UAM has not yet been operated on a large scale, questionnaire analysis and travel behavior models have become the main methods for UAM demand forecasting. Hwang et al.[156] used a questionnaire Survey to analyze key factors influencing consumers, including price, safety, comfort, travel duration, and accessibility of urban air traffic, to predict future demand for UAM.

The travel behavior model is used to predict the possibility of users choosing different modes of transportation. Coppola et al.[157] used discrete choice models to assess consumer preferences and adoption intentions for various UAM services, such as air taxis and airport shuttles.

(4) Environmental impact

In the UAM system, environmental impact and sustainability management are important prerequisites for ensuring the acceptability and social recognition of urban air traffic. Especially, there are significant challenges that need to be addressed to ensure they are ecologically viable and socially acceptable.

Noise pollution is one of the most critical issues in UAM operations. Bian et al.[158] established a quantifiable UAM noise environment assessment model through virtual flight simulation, which was used to predict the noise distribution and environmental impact under different operating conditions, providing a scientific basis for urban airspace planning and policy-making. Gao et al.[159] took noise equity as its core objective and proposed a noise-aware and equity-oriented urban air traffic management optimization framework. The framework integrated demand satisfaction, community noise exposure, energy consumption, and equity constraints, formulating them into a multi-objective optimization problem.

Life cycle assessment is often used to measure UAM environmental sustainability. Liberacki et al.[160] proposed the environmental life cycle cost framework, quantifying the environmental cost of UAM systems and revealing the environmental and economic impacts of UAM throughout the entire cycle of production, operation, and decommissioning.

As the UAM system has not yet entered the full commercialization stage, demand forecasting and the development of operation models remain key challenges. The current studies are mainly based on questionnaire surveys and simulation deduction, lacking real operational data support. However, the accuracy and reliability of these approaches in evaluating UAM demand remain uncertain. In addition, environmental and social impact assessment is another research focus in operational studies.

4 Conclusions

4.1 Summary

Based on 1 652 articles retrieved from the Web of Science Core Collection database, this study employed CiteSpace and VOSviewer to systematically analyze existing UAM work. The main findings are summarized as follows.

(1) Publication trends: UAM research has experienced rapid growth since 2016, with a sharp increase in scholarly output after 2020, indicating rising academic interest in the field.

(2) National-level analysis: Studies in the United States, China, and Europe have continued to expand, yet collaboration between regions remains limited. Noticeable differences exist in terms of technological maturity, policy support, and industrial cooperation models across countries.

(3) Major institutions: Leading institutions include NASA, BUAA, TUM, DLR, and Cranfield University, which together constitute the global academic and technological backbone of the UAM field.

(4) Co-citation analysis: The highly cited literature forms the knowledge base of UAM studies, focusing primarily on system framework construction, technical feasibility analysis, and developmental pathways.

(5) Keyword co-occurrence analysis: The high-frequency terms such as UAV, VTOL, electric, and ATM. The keywords reflect the current focal areas.

(6) Cluster analysis: The UAM knowledge system can be categorized into four primary themes, aircraft design, air traffic management, infrastructureand operations, and scheduling. The results indicate that aircraft technology and airspace management remain the core areas of study, while infrastructure design and operational frameworks are emerging as new focal points for future study.

In summary, this study employs bibliometric knowledge mapping to analyze the UAM domain, revealing its developmental trajectory, structural composition, and emerging focal areas. The results provide a visual and analytical foundation for future work.

4.2 Future research

It is important to acknowledge that this study is solely based on data extracted from the Web of Science Core Collection. Consequently, some high-quality and relevant publications indexed in other databases may have been omitted. Furthermore, the clustering and node algorithms in CiteSpace, while effective, may exhibit limitations in accuracy when handling heterogeneous research themes. Future studies are encouraged to incorporate multi-source databases and adopt a broader range of bibliometric tools to cross-validate findings and ensure a more comprehensive analysis.

Building on the current findings and addressing the observed gaps, future research may consider the following directions.

(1) Enhancing international and institutional collaboration: Future work should aim to build global collaborative research platforms, promote inter-organizational partnerships, and strengthen international consensus on literature, data standards, and technical protocols. These efforts can reduce research duplication and accelerate technological convergence.

(2) Strengthening coordination across the major domains of UAM research: Subsequent studies should prioritize the development of unified, system-level planning frameworks that seamlessly connect aircraft design, air traffic management, infrastructure development, and operational strategies. Such integration will support more consistent and data-informed decision-making, strengthen the alignment between technological advances and regulatory poli-

cies, and ultimately promote a more resilient and scalable UAM ecosystem.

(3) Quantitative assessment of social dimensions: Future studies could adopt methods such as surveys, behavioral simulations, and social network analysis to develop multidimensional models of social acceptance.

In the long term, UAM is expected to become an integral component of future smart transportation and sustainable urban systems, fostering the deep integration of aviation, energy, information, and traffic management sectors. Through the coordinated development of research, industry, and policy, UAM is anticipated to achieve a significant transition from pilot demonstrations to large-scale commercial operations within the next decade.

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基于文献计量的城市空中交通研究综述

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摘要:随着城市交通拥堵问题日益严峻,传统地面交通已难以满足人们的出行需求。在此背景下,城市空中交通(Urban air mobility, UAM)作为一种新型交通方式,通过开发利用城市低空资源来提升出行效率,已成为全球研究热点。为系统梳理城市空中交通的研究现状与核心问题,识别当前研究热点与未来发展方向。本文借助VOSviewer和CiteSpace等可视化分析工具,对Web of Science核心合集数据库1993—2024年间收录的相关论文开展文献计量分析。研究从出版物产出趋势、国家/地区合作网络、高影响力研究机构、共被引网络、高频关键词以及研究主题演化等多个维度,对城市空中交通领域的发展脉络、知识结构与研究热点进行了系统分析。结果表明,城市空中交通研究总体呈现快速增长趋势,美国、中国、法国等国家在该领域处于主导地位,当前研究热点主要集中于UAM航空器、低空空域管理、基础设施、市场运营等方向。同时,随着人工智能、大数据与智能交通技术的不断发展,UAM研究正逐渐向智能化、协同化与系统集成化方向演进。

关键词:先进空中交通; 城市空中交通; 研究趋势; 可视化分析;

研究亮点:

1. 基于Web of Science文献,利用VOSviewer与CiteSpace从多维度开展量化分析,系统揭示了城市空中交通领域的发展脉络、知识结构与演化趋势。

2. 分析UAM航空器、垂直起降机场、低空空域管理、市场运营等核心研究热点,识别了人工智能、大数据及智能协同调度等前沿研究方向,为后续UAM相关研究与实践提供了参考。