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

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

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

ABBREVIATION

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

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

I. INTRODUCTION

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

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

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

Urban areas, however, are characterized by complex surfaces, numerous no-fly zones and agglomerated populations. It is difficult to effectively deal with conflicts between UAVs and "obstacles" at low-altitudes or near-surface areas merely by using UAV cloud-based control systems and USSs.

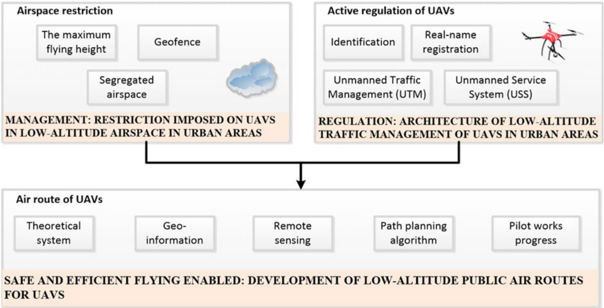

FIGURE 1. Reviewed policy and technology system aiming at safe UAV operations in urban areas.

To ensure the safe and efficient operation of UAVs at low altitude, countries or regions are exploring policies or technical means to manage UAV operations. Among these means, the technical scheme of planning a UAV's low-altitude air routes based on massive amounts of Remote Sensing (RS) data and Geographic Information Technology (GIS) is increasingly being recognized.

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

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

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

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

A. THE MAXIMUM FLYING HEIGHT FOR UAVS

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

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

B. UAV GEOFENCE

The risk of small UAVs flying into sensitive areas first came into public view in 2015 when a hobbyist lost control of a UAV that crashed on the southeast side of the 18-acre secure zone around the grounds of the White House, triggering a secret service lockdown of the compound [26]. ''It's only a matter of time before the threat manifests in a violent way,'' Defense Secretary James Mattis told a Senate panel in May [27]. To maintain absolute safety in sensitive areas, especially military zones, the second measure proposed by a variety of countries is publishing permanent

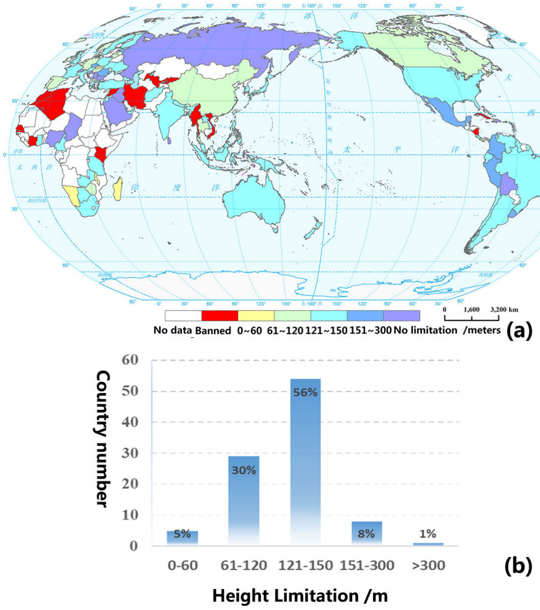

FIGURE 2. **(a) Distribution of the maximum flying height for different countries and its (b) analysis for countries with specific limitations. (Note: Both professional and entertainment UAVs at micro, light or large scales were surveyed, and the height limitations here were the maximum values for different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

or temporary "no fly" zones in laws and regulations, e.g., UAVs are off-limits in the airspace in the 15-mile radius around Washington and over areas such as the Hoover Dam, the Statue of Liberty and Mount Rushmore [28]. To prevent UAVs from flying into or out of a specific geographical area, geofencing - a core technique that defines virtual boundaries - has been developed [9], for example, US Senator Charles Schumer proposed a law requiring UAV manufacturers to build geofencing constraints to prevent UAVs from flying near airports and sensitive areas in 2016 [29]. Additionally, the Single European Sky ATM Research (SESAR) Center also launched the GEOSAFE project to establish state-of-the-art geofencing solutions regarding UAV traffic management regulations (U-space, in details in 2.1 part) that ensure public safety [30]. In China, the CAAC officially published the "Unmanned Aerial Vehicle fence" industry standard in 2017, providing a clear definition that specified the scope, configuration, data structure and performance requirements for UAVs [9]. It is the first standard related to a geofence and is widely recognized worldwide. Topxgun.com (a Chinese UAV company) has passed the system safety capability level inspection and has been authorized by CAAC to be the first enterprise with the geofence capability [31]. Some countries or regions have specified the minimum safe distance between UAVs and geofence element to initially supporting safe UAV flights. We counted countries that have clearly specified the safe distance of geofence elements and found that person, airport and buildings accounted for the largest proportions (Annex).

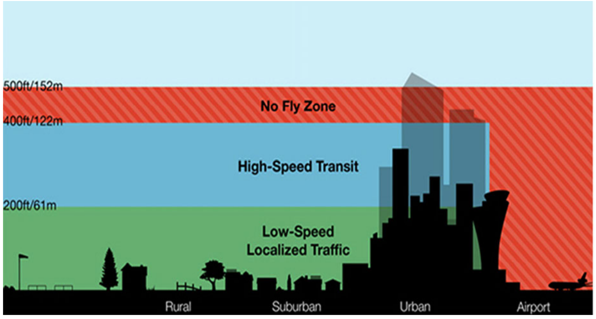

FIGURE 3. **Airspace division for UAVs proposed by Amazon [10].**

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

C. SEGREGATED AIRSPACE FOR UAV FLIGHTS

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

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

In 2017, Huawei, together with the CAAC and China Mobile, tested the low-altitude cellular network coverage and business characteristics in different urban scenes, such as the central zone and industrial parks in Nanjing, etc [11]. They tested and passed the position verification of UAVs under the cellular network, specified the end-to-end data

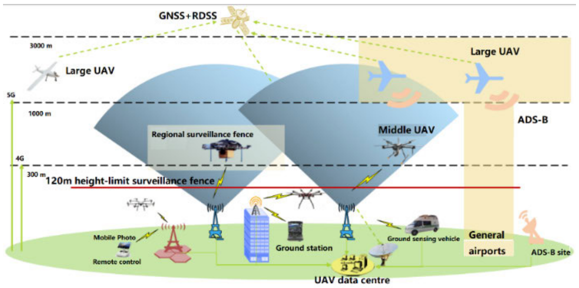

FIGURE 4. **Airspace division for cellular-networking UAVs proposed by CAAC and Huawei [11].**

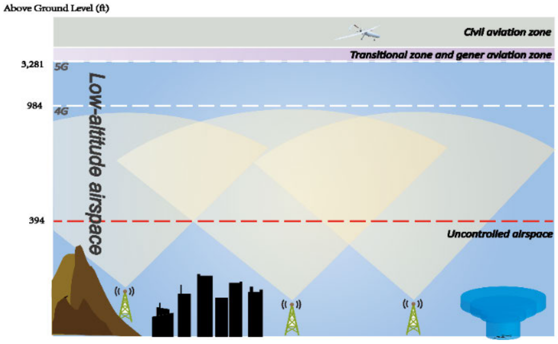

FIGURE 5. **Low-altitude airspace classification for UAVs proposed by Chinese Academy of Sciences (CAS).**

delay under the 4G network (50 ~ 300 ms), and tested and passed the Location Based Services (LBS) verification test of the UAV geofence (referring to the ability to obtain the location information of mobile terminal users through the cellular radio communication network [9]). It was concluded that the mobile cellular network meets the UAV industry application requirement in most scenes below 120 m and the business requirements of the UAV safe flight link in most areas below 300 m. They defined the exclusive low-altitude airspace of UAVs as follows: 120 m is defined as the exclusive airspace for agriculture and patrol UAVs within the height-limit surveillance fence supported by cellular mobile communications and Automatic Dependent Surveillance-Broadcast (ADS-B) technology; the 300 ~ 1000 m airspace, which is the maximum communication height of 5G technology, is defined as the exclusive airspace of medium-sized UAVs within the space-limit surveillance fence; the 1000 ~ 3000 m airspace is defined exclusively for large UAVs supported by ADS-B technology (Fig. 4).

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

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

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

A. IDENTIFICATION AND REAL-NAME REGISTRATION OF UAVS

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

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

B. UNMANNED AIRCRAFT SYSTEM TRAFFIC MANAGEMENT SYSTEM

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

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

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

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

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

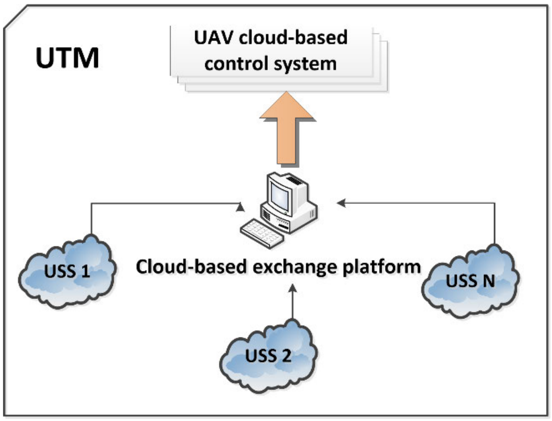

FIGURE 6. Relationship among the UTM, UAV cloud-based control system, USS and cloud-based exchange system.

the UAV flight standards for each level of airspace by UAV weights and has promoted flight approvals for the plans that fulfill UAV particulars [43].

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

C. UAV SERVICE SYSTEM AND THE DATA EXCHANGE PLATFORM

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

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

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

USS	Approcal Time	Capability	Website of UACS or USS
U-cloud	2016.3.12	Real-time	https://www.u-cloud.cn/
U-care	2016.3.21	UAV and pilot management, flight mission and service management, data analysis and management, airspace resources query	http://www.u-care.net.cn/
BD-cloud	2017.8.28	Pilot registration, training management, flight plan, tracking、geofence, collision avoidance、path optimization, climatology service	http://www.ccompass.com.cn/
5U	2018.1.1	B-level control of authorized UAVs	http://www.5u-cloud.com/
Air Dwing.com	2018.3.1	Monitoring , path planning, data 3D visualization	https://www.airdwing.com/
Qianxun SI.com	2018.3.21	4D spatiotemporal geofence, data analysis and management	https://www.qxwz.com/
TY.IW.com	2018.6.3	Airspace query、climatology service, UAV issurance	http://www.tianyujingwei.com/
XAG.com	2018.9.19	Spraying mission	https://www.xa.com/about
TopGun .com	2019.2.12	Airspace query, climatology service	http://www.topxgun.com/
China-Skynet	2019.4.4	Real-time regulation, low-altitude air route network planning	http://skygrid.mapscloud.cn

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

There are eleven USSs that have been issued a "Unmanned Aircraft Cloud System (UACS) Approval Letter" by the CAAC in China, and ten of them are currently in service [4]. Those USSs are operated by different operators in different function structures and service focuses, as follows (other details are shown in Table 1): The U-cloud system is the

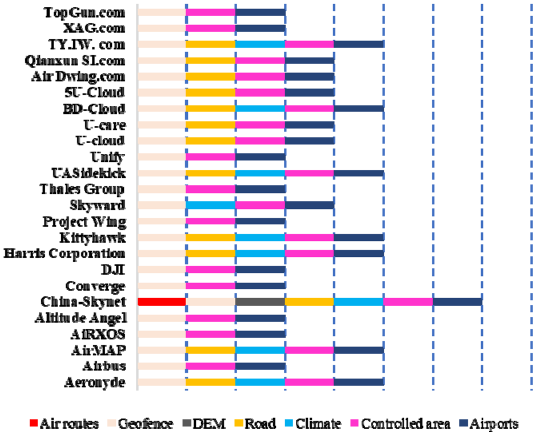

FIGURE 7. **UAV cloud service systems around the world.**

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

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

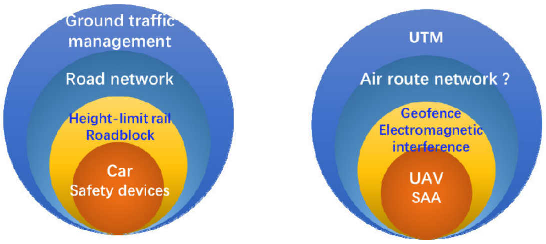

FIGURE 8. **Comparison between safety management of vehicles and UAVs.**

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

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

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

A. THEORETICAL SYSTEM OF THE LOW-ALTITUDE AIR ROUTES

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

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

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

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

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

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

B. GEO-INFORMATION AND LOW-ALTITUDE AIR ROUTES

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

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

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

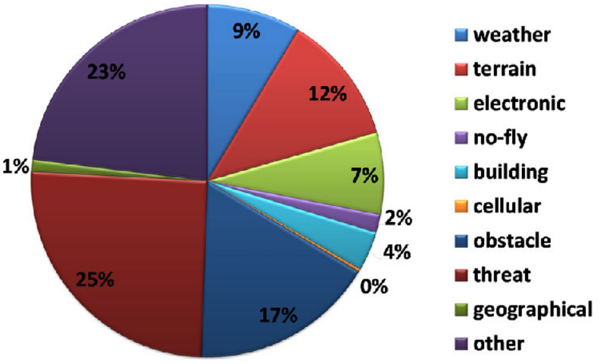

FIGURE 9. Reference statistics of flight constraints for UAVs.

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

C. UAV REMOTE SENSING AND LOW-ALTITUDE AIR ROUTE

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

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

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

D. PATH SEARCHING ALGORITHM

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

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

Artificial Fish Swarm (AFS) algorithm [110]. The integration of ACO and other algorithms have made great progress in the study of this algorithm, both in breadth and depth, and its application range is also expanding. There is a broad prospect of the comprehensive application of ACO and other algorithms.

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

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

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

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

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

V. DISCUSSION AND CHALLENGES

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

A. SUMMARY AND CHALLENGES

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

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

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

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

B. OPEN ISSUES

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

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

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

deepen the research of airspace policy (especially geofence). These are discussing in the following.

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

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

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

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

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

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

Countries	Geofence	Clearly-defined constraints
Australia	> 30 m of a person who is not directly associated with the operation of the Remote Pilot Aircraft (RPA) UAV.	person
Austria	> 2500 m from airport only with permission of the owner.	airport
Belgium	> 2778 m (1.5 nm) distance from airports > 926 m (0.5 nm) from heliports > 50 m from buildings, persons, animals	person, airport, heliport, building, animal
China	> 2 km from temporary landing points for manned aircrafts; > 5 km from national boundary lines and >2 km form borderlines; > 1000 m form military reservation; >200 m form party and government offices, nuclear power stations; >5000 m from radio observations; >2000 m from satellite earth stations; > 1000 m thunder heads; 100~200 m from warehouses with inflammable and explosive objects, electric power facilities, petrol stations; > 1 km from buildings, tall towers, power grids, wind power; >500 m from high-speed railway; > 200 m from mountains.	airport, national boundary lines and borderlines, military, party and government offices, nuclear power stations, radio observations, satellite earth stations, thunder heads, warehouses, buildings, tall towers, power grids, wind power, railway, et. Al.
Czech Republic	>100 m from 3rd persons; > 150 m from congested area.	Person, congested area
Croatia	>30 m from people and structures; >150 m from group of people; >3 km from airport and approach/departure zone.	person, structure, airport
Germany	> 1.5 km from airports; Not above people, accident and disaster areas, prisons, military installations, industrial areas and power stations.	person, airport and no-fly zone
Ireland	> 8 km from airport; > 150 m from assembly of people; > 150 m from person, vessel, vehicle and structure; > 2 km from aircraft in flight.	person, airport and structure, vehicle, vessel
Italy	> 150 m from congested area; 50 m from persons and property; > 5 km from airport.	person, airport and property, congested area
Japan	> 30 m from persons or properties; Do not operate UAs over event sites where many people gather.	person, property
Latvia	> 50 m from people, property on ground; >3 km from another aerodrome.	person, airport and property
Lithuania	> 50 m from vehicles, people and buildings; > 1.8 km from airfield; 1852 (1 nm)~5556 (3 nm) from obstacles	person, airport and structure, obstacles, vehicle
Malta	> 150 m from congested area, infrastructure, assembly of persons; > 50 m from person; > 150 m from vessel, vehicle, structure; > 7.5 km from aerodrome.	person, airport and structures, obstacles, vehicle, vessel
Netherlands	> 150 m from building-up area, crowds of people, main roads; > 50 m from railway, industrial area.	person, road, railway, industrial area
Poland	> 5 km from airport; safe enough distance from people and property	airport
Slovenia	> 300 m above crowds; > 50 m from powerlines, roads, railways etc.	person, obstacles
South Africa	> 50 m over people and a public road and from any structure or building; > 122 m within a radius of 10 km from an airport/within restricted/prohibited airspace/adjacent to or above nuclear powerplant, prison, police station, crime scene, court of law, national key points or strategic installations.	person, airport and structure, road
Spain	> 8 km from airport	airport
Sweden	> 50 m from people, animals and property.	person, property
Switzerland	> 100 m away from crowds; > 5 km from airfields	person, airport
UAE	>150 m from public, private properties or crowd; > 5 km from Airports, Heliports, and airfields or in controlled airspace.	person, airport, heliport,
UK	> 150 m from congested area; > 50 m from person, object, vehicle.	person, structure, vehicle, congested area

Note: Data come from policy documents for each country issued by national airspace management department.

VI. CONCLUSION

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

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

ANNEX

See Table 3.

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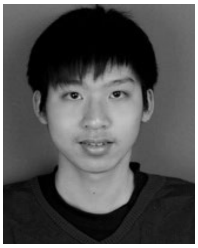

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