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The Application of Unmanned Aerial Vehicle Remote Sensing Technology in Smart City Construction

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Abstract. Smart cities are the products of urbanization and informatization at a certain stage and represent the main trend of urban development. Against this backdrop of development, studying the application path of unmanned aerial vehicle (UAV) remote sensing technology in the construction of smart cities holds significant theoretical and practical significance for promoting the advancement of smart cities from initial construction to in-depth development. Specifically, the research context of this article is as follows: Firstly, systematically sort out the concept, connotation and current development status of smart cities, and build the theoretical basis for research; Secondly, from multiple dimensions. This paper elaborates in depth on the specific application scenarios and practical value of UAV remote sensing technology in the construction of smart cities. Finally, in combination with the trend of technological evolution and the demands of urban development, the future application directions of this technology in the field of smart cities are projected.

Keywords: Unmanned Aerial Vehicle, Remote sensing, Smart city Application, Research Progress

1. Introduction

Under the current backdrop of economic globalization, urbanization is profoundly altering the world order and people's lifestyles. In 2011, the proportion of the urban population in China reached 51.27%, marking China's official entry into the ranks of "urbanized" countries [1]. However, with the continuous acceleration of urbanization, cities are confronted with increasingly severe problems of "urban diseases", and the construction of smart cities has become an irreversible historical trend [2]. The concept of smart cities represents an advanced stage of urban informatization, which is fundamentally supported by surveying and geographic information. Geographic information technology serves not only as the foundation for the construction of smart cities but also acts as a catalyst for their development [3]. With the increasing demand for geographic information big data in urban sustainable development, low-altitude unmanned aerial vehicle (UAV) remote sensing (RS) technology, which features high mobility, high spatial resolution, high precision and high timeliness, is becoming an important means of obtaining geographic information in smart cities and showing broad application prospects in urban informatization construction [4].

This article takes the goals and tasks of smart city construction as the logical starting point, systematically sorts out the conceptual connotation and current development status of smart cities,

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and lays a theoretical foundation for the research. Subsequently, the research perspective shifted to the application level, and the application of UAV RS technology in smart city construction was explored from aspects such as urban planning, supervision of illegal buildings in cities, engineering environment monitoring, waste management, smart transportation, and urban safety prevention and control.

2. Overview of Unmanned Aerial Vehicle RS technology

2.1. The significance of technological advances in UAV RS systems

In modern society, RS technology has become an essential high-tech means for humans to obtain geographic information [5]. With the development of geographic information science and related industries, the demand for RS data (SD) in various countries has increased sharply. However, traditional aerospace RS systems have been limited in their wide application in many fields due to their high cost and technical threshold. As an RS platform for aerial photography and earth observation, UAVs have effectively broken through the above-mentioned predicaments. Meanwhile, it uses fixed-wing unmanned aerial vehicles, unmanned rotorcraft, etc., as RS platforms to obtain real-time high-resolution RS image data [6]. This not only overcomes the influence of manned aerial RS being restricted by long flight time, high maneuverability, and harsh environments, but also fills the gap that satellites cannot obtain RS information of the area of interest due to weather and time, providing multi-angle, high-resolution imagery while avoiding the shortcomings of ground-based RS, such as limited coverage and narrow field of view.

Moreover, with the rapid development of computer and communication technologies, as well as the continuous emergence of various lightweight, small-sized, and high-precision digital new sensors, the performance of UAVs has been constantly improving. This evolution has endowed UAV RS systems with unique advantages such as simple structure, low cost, minimal risk, and strong real-time capability. As a result, they have become an effective complement to traditional RS technologies and injected new vitality into RS applications [7].

The traditional way of ground information collection in aerospace is accomplished by satellites and manned aircraft [8]. Both methods have similar limitations, including long revisit cycles, poor timeliness, stringent take-off requirements, high information acquisition costs, and difficulty in capturing imagery beneath cloud cover due to weather conditions. In contrast, UAV RS fully makes up for the shortcomings of traditional satellite RS and conventional aerial RS, leveraging its distinct advantages such as rapid image acquisition, large coverage area, short application cycles, high image clarity (with accuracy up to centimeter level), ease of data interpretation, low sensitivity to natural environmental constraints, cost-effectiveness, operational simplicity, and low running and maintenance costs. Currently, UAV RS has achieved exploratory applications in many fields of geographical conditions in China [9].

2.2. Composition of Unmanned Aerial Vehicle RS system (UAVRS)

UAVRS is an advanced and emerging aerial RS solution. It can automatically, intelligently, and professionally quickly obtain spatial RS information related to land, resources, environment, and events, and supports real-time processing, modeling, and analysis. An UAVRS is an unmanned aerial RS and photogrammetry system that uses an UAV as the platform, carries various imaging and non-imaging sensors as its primary payload, typically operates at flight altitudes within a few kilometers, and is capable of acquiring RS images, video, and other data [10].

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The unmanned aerial vehicle system primarily consists of three components, namely the unmanned aircraft system, the effective task payload, and the ground support system [11]. Among these, the unmanned aircraft system includes the aircraft platform, propulsion system, and other related elements. Then, the effective task payload is composed of various imaging and non-imaging sensors, such as high-resolution aerial cameras, small synthetic aperture radars, and hyperspectral imaging systems. Moreover, the ground support system comprises the ground part of the take-off and landing system, the ground part of the data transmission system, and other associated subsystems (see Fig. 1) [5].

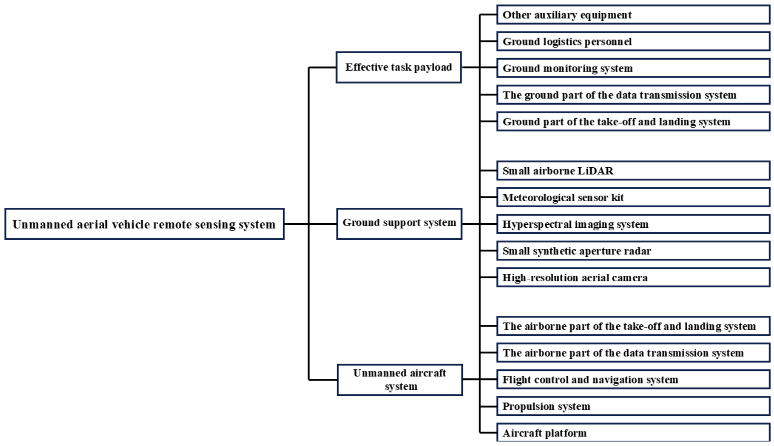

Figure 1. The composition of the unmanned aerial vehicle RS system (photo/picture credit: original)

3. Overview of the smart city

3.1. Definition of the smart city

Smart city is the intelligence of digital city, representing an extension, expansion and elevation of the functions of digital city [12]. Built upon the foundational framework of the digital city, various Internet of Things (IoT) sensors seamlessly connect the digital city with the physical city. By leveraging cloud computing and grid computing technologies, real-time SD are rapidly processed in a coordinated manner. Based on the processing outcomes, real-time automated control of the city is implemented, thereby enabling intelligent urban services and enhancing people's perceptual capabilities, logical thinking, self-learning and self-adaptation capacities, as well as behavioral decision-making abilities [3]. The definition of a smart city has undergone a gradual process of refinement (see Fig. 2). It has evolved from an initial focus on the digital city to the current model based on big data and mobile Internet, and in the future, it will move towards an unmanned and intelligent model. Overall, it is characterized by extensive coverage, deep interconnectivity, and intelligent processing capabilities [13].

The core of a smart city encompasses perception, interconnection, collaboration and intelligence, and its essential architecture is manifested through the following progressive layers [14]: Firstly, the IoT enables comprehensive perception of the physical city and real-time sensing of the core systems of urban operation, thereby intelligently acquiring diverse information of the physical city in real time. Secondly, the Internet facilitates the intelligent transmission and storage of SD, integrating multi-source heterogeneous data into a consistent format to build a smart data infrastructure [12]; Furthermore, based on the novel service model of cloud computing, all existing information resources are integrated and deployed to address the processing problem of multi-source

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heterogeneous massive data. Finally, by leveraging big data technology to rapidly and collaboratively process real-time SD and conduct parallel processing of massive SD, data mining and knowledge discovery can be achieved, providing people with low-cost and high-efficiency intelligent services, supporting scientific decision-making and predictive analysis, and thereby building smart cities [3].

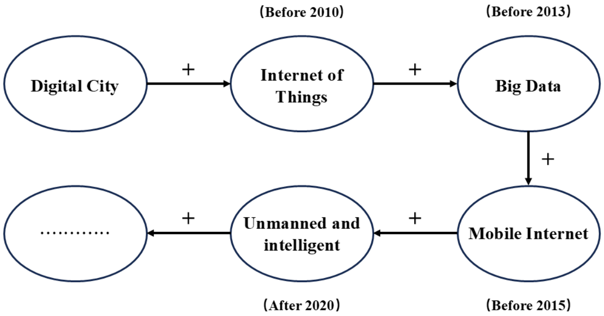

Figure 2. Evolution of the smart city definition (photo/picture credit: original)

3.2. Characteristics of the smart city

The smart city formed by integrating digital cities with the Internet of Things will possess the following characteristics [15]:

(1) The Smart City is an intelligent city based on the IoT

The core and foundation of the IoT remain the Internet, which enables the exchange and communication of information between objects. The Internet of Things possesses the following three fundamental characteristics: Comprehensive perception: Utilizing intelligent sensors and devices deployed throughout the urban environment to achieve real-time, integrated perception and dynamic information collection of urban physical space [16]. Reliable transmission: Relying on the integration of telecommunication networks and the Internet, real-time and precise transmission of object information is achieved. Intelligent processing: Applying intelligent computing technologies such as cloud computing to analyze and process massive amounts of information, thereby implementing intelligent control over objects.

(2) The Smart City is oriented towards applications and services:

Data-centric wireless sensor networks are the integration of wireless networks and data networks. A wireless sensor network consisting of tiny sensor nodes is typically application-specific and is an application-based wireless network. Each node within the network can collaboratively monitor, perceive, and collect various environmental information across the distributed area in real time. After processing, the information is transmitted to users who require it.

(3) The Smart City integrates with the physical city

In wireless sensor networks, each node is equipped with various types of sensors to measure signals such as thermal, infrared, and seismic waves, thereby detecting numerous material phenomena of interest to people, including temperature, humidity, noise, soil composition, and the size of moving objects.

(4) The Smart City enables autonomous networking and self-maintenance:

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The wireless sensor networks composed of a large number of nodes require the capabilities of self-organization and automatic reconfiguration [14]. Meanwhile, when some nodes fail due to environmental changes or other reasons, the network topology should be capable of changing dynamically over time. Therefore, it is required that the network should have the function of maintaining dynamic routing to ensure stable operation even when some nodes fail.

3.3. Key technologies for smart city construction

3.3.1. IoT-Based real-time information sensing and interconnection technology

Intelligent sensors can achieve comprehensive and integrated perception of the physical city, as well as conduct real-time monitoring of its core operational systems. On the one hand, the IoT can interconnect ubiquitous intelligent sensors; On the other hand, the Internet can be utilized to achieve the intelligent transmission and storage of the acquired SD. Therefore, based on the complete connection and integration of urban smart information infrastructure, the Internet of Things and the Internet, multi-source heterogeneous data can be consolidated into unified data, enabling all elements, units, systems, and their participants to operate harmoniously and efficiently, thereby achieving the optimal state of urban operation.

3.3.2. Cloud computing-based multi-source data association and service collaboration

Cloud computing has solved the problems of establishing an information resource association and communication platform and information silos. By applying the theories and methods of information resource planning, cloud computing systematically sorts out the urban information resources from the perspectives of technology, business management, and resource allocation, formulating corresponding data and technical standards, based on which existing data are integrated and migrated. Under a unified spatio-temporal reference system and based on the urban geospatial dataset and the urban basic dataset, thematic data such as for planning, land management and environment are constructed in sequence, ensuring the spatiotemporal consistency and organic interrelation of various types of urban data. By leveraging the new service model of cloud computing, we can fully mobilize information resources to conduct parallel processing and knowledge discovery on massive SD, thereby providing people with low-cost and high-efficiency intelligent services [3].

3.3.3. Big data-based data mining and intelligent analytics technology

The essence of big data lies in leveraging a big-data mindset to uncover its potential value and in establishing a mutually reinforcing relationship with the construction of smart cities. By employing parallel processing technology to process massive volumes of perceptual data, combined with real-time dynamic visualization analysis, and based on the principle of integrated information transformation, multi-dimensional decision-making knowledge is provided for users [16].

4. Application of UAV RS technology in smart cities

While IoT and big data technologies have propelled the development of smart cities, without the support of spatiogeographic information, it is difficult for smart city construction to truly achieve intelligent and informationbased development [3]. Low-altitude UAV RS technology can be used to conduct real-time dynamic monitoring and information collection of elements such as people,

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events, infrastructure and the environment within the urban area. Concurrently, by leveraging technologies such as the Internet of Things and big data, comprehensive perception and rapid extraction of information data can be achieved, thereby providing more valuable information for the construction of smart cities.

4.1. Application in urban planning

Urban planning, as an important component of urban management, primarily aims at studying the future development direction of the city, the comprehensive layout of the city and the deployment of urban engineering construction [17]. The application of UAV RS technology can obtain substantial high-precision measurement information, which serves as the basis for constructing digital terrain models and producing largescale topographic maps, thereby achieving the rapidity and accuracy of urban planning surveys and providing robust data support for scientific urban planning decisions [18]. Additionally, utilizing the highresolution orthophoto maps obtained through UAV RS technology as the basic maps for current situation investigations can not only assist in urban master planning and reduce the blindness of current situation investigations, but also address the needs of thematic planning research and the application of new technologies [19]. Amid rapid urbanization, urban realscene 3D models provide new integrated services and solutions for urban planning and gradually become a key component of the urban spatial data framework [20].

UAV oblique photogrammetry technology can collect data from multiple angles. Through human-computer interaction for 3D modeling, it can accurately restore the detailed composition of architectural models and output high-spatial-resolution triangular mesh models with realistic textures, reducing the cost of urban 3D modeling. On the other hand, this technology can rapidly extract information about urban features, including the outer frame information and elevation information of urban buildings, successfully addressing the limitation of conventional aerial photography technology in monitoring changes in building height [21].

4.2. Application in the supervision of illegal urban buildings

In the process of urban development, illegal and non-compliant construction activities occur from time to time, especially in suburbs and urban villages, where unauthorized construction and unauthorized additions, expansions and alterations are particularly common. The traditional monitoring of illegal structures, which primarily relies on manual inspection, demands substantial human and material resources, operates inefficiently, and has blind spots and lagging phenomena. In contrast, the use of UAV RS technology can promptly obtain highspatialresolution RS images of the monitored area, allowing for the precise and rapid acquisition of information such as the geographical location and morphological structure of illegal and non-compliant buildings, thereby providing a strong decision-making basis for the government [22].

4.3. Application in engineering environmental monitoring

Urban engineering construction requires a comprehensive understanding of the environmental information of the working area and its surrounding areas, and adheres to the coordination of environmental protection with economic and social development.

UAV RS technology can play a significant role in the environmental protection management of engineering construction projects and has been widely applied in environmental protection management stages such as environmental impact assessment, environmental acceptance inspection,

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and soil and water conservation monitoring of construction projects. This technology can conduct investigations and measurements on the area of the project zone, the volume of earthwork and stonework, and the degree of vegetation coverage, thereby providing a basis for environmental protection departments to evaluate the rationality of environmental protection measures.

In the South-to-North Water Diversion Project, in order to monitor the water quality security of the eastern route of the project, the Satellite Environment Application Center of the Ministry of Environmental Protection of China carried out a UAV RS monitoring test flight mission [9]. This experiment achieved effective monitoring of risk sources and industrial discharges along both banks and in the water bodies through the combined use of multiple models and multiple loads. Li et al. took the Wuhan-Guangzhou High-Speed Railway as a case study, established a system for classification of image information of unmanned aerial vehicles for check and acceptance of high-speed railway in environmental protection, and created a corresponding image interpretation database and cartographic symbols [23]. While completing the check and acceptance in environmental protection, the RS images captured during different construction phases can also be utilized to analyze the dynamic changes of vegetation coverage. Liang et al. proposed a novel monitoring method for soil and water conservation that integrates UAV RS with existing monitoring technologies in response to the issue of soil erosion in production and construction projects [24]. This method employed GIS slope analysis to derive slope information from the spatial analysis of DEM data, and the soil erosion intensity was classified through the overlay analysis of vector layers. Through the comparison of data in different periods, the dynamic monitoring results of soil and water conservation were obtained.

4.4. Application in waste management

UAV RS technology possesses notable advantages of low cost and low risk in the field of environmental data collection. With this technology, highspatialresolution data over landfill sites can be obtained in real time and three-dimensional models can be created, thereby accurately calculating the remaining capacity of landfills and making corresponding plans [25]. From the perspective of international practices, the application of UAVs in waste management and environmental supervision has formed diversified scenarios: in the United States, UAVs are used to supervise waste treatment plants; in Japan, the central government is adjusting policies to support the adoption of commercial drones for monitoring illegal dumping of industrial waste.

4.5. Application in smart transportation

In the field of urban transportation, varying degrees of congestion in cities have become a challenge, restricting the rapid and sustainable development of cities. Conventional traffic flow detection methods suffer from shortcomings such as limited coverage, low efficiency, proneness to misjudgment, and high cost. UAVs, with their advantages of flexibility, mobility, and wide field of vision, can collect real-time traffic condition information on a large scale over urban areas, enabling rapid and automated identification of congested sections and their severity levels. This not only comprehensively enhances the dynamic monitoring intensity of urban traffic but also effectively elevates the intelligent level of traffic management, thereby ensuring the safety and smoothness of urban transportation [2].

The Chongqing Rail Transit Construction Office proposed to apply low-altitude UAV aerial photography combined with image change detection technology to replace the traditional manual inspection method [26]. Under remote control, UAVs can reach designated points or areas to capture

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videos and images, conducting remote real-time supervision of construction projects and surrounding environmental changes within the control protection zone. By utilizing image change detection technology, alterations between sequentially acquired datasets can be accurately identified, providing a valuable reference for the safety management of urban rail transit protection zones in China.

5. Constraints of UAV RS

5.1. Remote SD

5.1.1. Acquisition of remote SD

Due to the lightweight airframe of UAV RS platforms, they are susceptible to high-altitude wind, which can cause instability in flight trajectories. This instability leads to inconsistent image overlap, with significant variations in overlap and rotation angles between adjacent images. Since UAV platforms operate at low altitudes, the acquired images often exhibit large, irregular tilt angles, and terrain relief considerably affects the imagery. Additionally, the cameras equipped on UAV platforms are typically non-professional aerial surveying cameras, resulting in issues such as substantial image distortion and limited data capacity [9].

5.1.2. Transmission and storage technology of remote SD

The primary RS sensor carried by unmanned aerial vehicles is an area-array CCD digital camera. However, current domestic small-format professional digital cameras still cannot meet the accuracy requirements for surveying. To ensure that the acquired RS images satisfy the precision standards for large-scale mapping, geometric imaging models should be applied to perform relevant calibration procedures to obtain the camera's internal and external parameters. When necessary, the distortion of each pixel must be measured. Furthermore, the image data acquired by large-format CCD digital cameras is voluminous, necessitating the development of dedicated data transmission and storage systems. Real-time data transmission from the aircraft can also be achieved via satellite communication [27].

5.1.3. Post-processing technology of remote SD

Unmanned aerial vehicle RS systems commonly use small-format digital cameras as onboard sensors, which present challenges such as a small image format and a large number of images. In response to these characteristics, as well as camera calibration parameters, attitude data, and related geometric models, geometric and radiometric corrections should be applied to the images. Dedicated software should be developed for interactive processing. Simultaneously, automatic image recognition and rapid mosaicking software should be created to enable quick inspection of image quality and flight performance, as well as rapid data processing, thereby meeting the technical requirements for real-time, high-speed processing of the system [28].

5.2. Autonomy of UAV RS platforms

As UAVs accomplish tasks through the interaction between integrated sensors and operators, the autonomy of UAV control programs directly influences their reliance on uplink and downlink connections, playing a crucial role in managing the UAV and its information under unconventional

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conditions. Currently, UAV RS platforms possess limited autonomy; they struggle to automatically resolve malfunctions encountered mid-flight, particularly during takeoff and landing, which still require manual intervention [29].

5.3. RS sensors and their attitude control technology

Due to the highly restricted payload capacity of UAVs, high-precision aerial surveying missions demand correspondingly high-precision sensors. Traditional sensors are limited in selection because of constraints in size and weight. Therefore, there is a need to develop small, lightweight sensors suitable for UAV integration, making full use of the platform's limited payload capacity [11]. Furthermore, further research is required on sensor control systems. These systems should be able to automatically calculate and control the operation of RS sensors based on preset aerial survey parameters and real-time data—such as flight altitude and speed—provided by the flight control system. This ensures that the acquired remote SD meets technical requirements in terms of accuracy, scale, and overlap.

5.4. Information acquisition and security of UAV RS

UAV operation is relatively simple, and its compact size makes it inconspicuous during real-time data collection. This characteristic has led to the frequent occurrence of unauthorized "rogue flights," where geographic information data is acquired without regulatory oversight. During information transmission, UAV RS platforms are vulnerable to hacking and data theft; even encrypted transmissions face the risk of being deciphered (i.e., passive attacks). However, a more severe threat than passive attacks is active attacks, where hackers infiltrate the UAV RS system to alter camera orientation and angles, or even hijack or crash the drone. In 2011, the ground control system of a U.S. military "Reaper" drone was infected by a virus, and the same year, a U.S. military stealth drone was captured by Iran through spoofing its navigation system [30]. Given these security concerns, higher demands are placed on the confidential research and development of UAV RS technology, yet this remains a weak link. It can be argued that security issues represent one of the key bottlenecks to its widespread application.

6. Conclusion

In the era characterized by the deep integration of Internet Plus and Internet of Things Plus, UAV RS technology, as one of the cutting-edge technologies in the field of artificial intelligence, is gradually aligning with technological development trends to establish a networked service system for UAVs. Through continuous technological innovation and business model renewal, this technology adopts an integrated Internet Plus UAV services approach to provide RS services that are faster, more convenient, and of higher quality across various sectors of society. Currently, it is driving the expansion of such services into broader application dimensions and deeper service scenarios, further unleashing the application value of the technology.

Under the extensive practice of the public-private partnership (PPP) model and the strong support of relevant policies, the implementation process of smart city construction projects in various regions of China is expected to be significantly accelerated. However, it should be noted that geospatial big data serves as a core and fundamental supporting element for the operation of smart cities. Without its technical and data support, the advancement of related smart city projects would encounter numerous obstacles, making it difficult to achieve the expected construction objectives.

As one of the important means to obtain geospatial big data, the continuous advancement of UAV RS technology can provide comprehensive information assurance and technical support for urban planning, construction, and management. This role will undoubtedly provide critical guarantees for the transformation and upgrading of digital cities to smart cities, thereby facilitating the implementation of the construction of both types of urban development initiatives.

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