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A Review of UAV Coverage Rate for Different Application Scenarios

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Abstract: This paper aims to review the coverage rate of Unmanned Aerial Vehicles (UAVs) for different application scenarios. With the continuous development of science and technology, UAV technology has become an important tool widely used in military, civil and other fields. In these various applications, the coverage capability of UAVs is a key factor. This review will introduce the concept of UAV coverage capability and its performance in different applications, and discuss the factors affecting UAV coverage capability. Through the collation and analysis of relevant literature, this review will provide readers with a comprehensive and in-depth understanding to guide practical applications and research directions.

Keywords: Unmanned Aerial Vehicle (UAV); Coverage Rate; Path Planning; Application Scenarios; Coverage Algorithm; Communication Deployment.

1. Introduction

As a new type of air transportation tool, UAVs have the advantages of strong mobility, low flight altitude, and strong anti-interference ability, and have been widely used in various fields [1]. Different application scenarios have different requirements for UAV coverage rate: agricultural monitoring emphasizes wide coverage and high frequency, urban traffic management requires high real-time and accurate positioning, and disaster rescue focuses on rapid coverage and comprehensive information collection [2,3]. Therefore, how to optimize the coverage rate of UAVs according to the needs of different application scenarios and improve their work efficiency and accuracy has become an important issue in current research [4]. With the continuous development of UAV technology, its application scope is expanding, and the requirements for coverage rate are constantly upgrading [5]. This review systematically sorts out the research status, cutting-edge achievements and existing deficiencies of UAV coverage rate, to provide a reference for subsequent research and practical applications.

2. Overview of Technology Development

With the rapid development of UAV technology, the coverage rate of UAVs for different application scenarios has become a research hotspot. This section summarizes the research status of UAV coverage rate at home and abroad, providing a basis for in-depth discussion of subsequent results.

2.1. Domestic Research Status

In China, research on UAV coverage rate mainly focuses on practical application scenarios and technical implementation:

(1). **Power inspection:** UAVs equipped with high-resolution cameras and infrared sensors inspect high-voltage transmission lines, which improves the inspection efficiency by 3-5 times compared with manual work and reduces safety risks [6].

(2). **Agricultural plant protection:** UAVs with sprayers realize precise pesticide spraying and fertilization, covering 3-5 hectares per hour, and the utilization rate of pesticides is increased by about 20% [7].

(3). **Security monitoring:** UAVs with panoramic cameras monitor key areas, and the coverage response time is shortened to within 5 minutes, significantly enhancing the security prevention effect [8].

(4). **Urban traffic management:** UAVs collect traffic flow data in real time, and the accuracy of traffic condition analysis is improved by more than 30% compared with traditional methods [9].

2.2. Foreign Research Status

Abroad, research on UAV coverage rate focuses on technical refinement and cross-field application:

(1). **Military reconnaissance:** UAVs equipped with high-definition cameras and radar systems perform reconnaissance tasks, with a detection range of more than 50 km and a recognition accuracy of over 90% [10].

(2). **Disaster rescue:** UAVs with thermal imaging cameras and environmental sensors monitor disaster-stricken areas, providing comprehensive scene information within 1 hour after the disaster, which improves the rescue efficiency by 40% [11].

(3). **Environmental monitoring:** UAVs equipped with gas sensors and water quality detectors monitor atmospheric and water quality parameters, with a data collection accuracy of ±5% and a coverage range of 10-20 square kilometers per mission [12].

2.3. Future Development Trends

With the continuous development of UAV technology and the expansion of application fields, research on UAV coverage rate will usher in new development opportunities and challenges. In the future, research on UAV coverage rate will focus more on the following aspects:

(1). Develop high-precision UAV coverage algorithms to improve the coverage efficiency and accuracy of UAVs.

(2). Explore the application of UAVs in new application scenarios, such as medical care and education.

(3). Strengthen research on the safety of UAVs to improve

their adaptability and stability in various complex environments.

(4). Promote the standardization of UAV technology to promote the healthy development of the UAV industry[13].

In summary, UAV coverage rate for different application scenarios is an important research field, and scholars at home and abroad have achieved certain research results in this field. In the future, with the continuous development of UAV technology and the expansion of application fields, research on UAV coverage rate will face new opportunities and challenges.

3. Cutting-Edge Theoretical Achievements

3.1. Domestic Cutting-Edge Theoretical Achievements

Domestic scholars have conducted in-depth research on UAV coverage optimization, technological breakthroughs, and application expansion in different scenarios, forming multi-dimensional achievements:

3.1.1. Path Planning and Coverage Algorithm Optimization

Inspired by wireless cellular communication cell division and regular hexagonal tessellation segmentation, Li, B. K. proposed a new full-coverage path planning method for UAVs in open areas, which eliminates absolute blind spots, shortens the maximum revisit time of temporary blind spots, and reduces coverage time. Meanwhile, an extended ant colony algorithm based on a hybrid feedback mechanism was improved; by means of priority punishment, the priority of target nodes is increased to solve the problem of continuous exploration of multiple target points, enhancing the stability and efficiency of the algorithm[14]. Dong, J. X. improved the DARP algorithm for multi-UAV regional coverage task allocation, optimized the traditional regional coverage path planning algorithm, and proposed a new scheme based on the DQN algorithm. In addition, aiming at the problem of aerial image stitching, a method of overlapping region division and mask establishment based on edge cropping, as well as an image pyramid fusion method, were proposed. Finally, a multi-UAV regional coverage system was built to realize fully automatic complete coverage of the task area and aerial image stitching[15]. Wang, Z. X. applied deep reinforcement learning to UAV intelligent coverage, designed an improved Double Deep Q-Network (DDQN) algorithm to maximize the target area coverage rate, and proposed the MHADDQN algorithm combined with a multi-head attention mechanism to improve data collection efficiency. Experiments have verified the effectiveness of both methods[16].

3.1.2. Positioning and Path Planning in Special Environments

Focusing on the problem of UAV ground data collection in GPS-denied environments, Ren, M. M. designed an autonomous positioning method fusing lidar and inertial measurement unit, proposed an efficient coverage path planning algorithm based on the active edge table, and built a UAV simulation environment and realized a coverage path planning system in GPS-denied environments, providing technical support for scenarios without satellite positioning[17].

3.1.3. Cognitive and Classification Expansion

Breaking through traditional cognition, Wu, C. Y. pointed out that UAVs are not only pilotless aircraft but also include various types such as fixed-wing and multi-rotor. At the same time, it was clarified that the scope of aircraft includes balloons, airships, helicopters, gliders, etc., providing a reference for the conceptual definition of UAV-related research[18].

3.1.4. Target Coverage and Resource Optimization

Aiming at the problems of short life cycle and high maintenance cost of traditional fixed sensor networks, Liu, C., Liu, Y., & Yang, C. L. proposed a UAV-based target full-coverage method, studied the optimal hovering problem when UAVs coordinate and relay to cover multiple targets, solved the optimal hovering points of different combined targets using computational geometry methods, and modeled the problem as an integer linear programming equation to determine the minimum number of UAVs required. Simulation experiments showed that the farther the covered target is from the base, the more UAVs are needed; when the coverage radius increases from 100m to 200m, the number of UAVs required decreases by about 1/3[7].

3.1.5. Communication Field Application and Deployment

Li, L. F., Wang, Y., & Jia, G. Y. proposed the potential applications of UAVs in wireless communication networks: they can be used as aerial base stations to improve network coverage, capacity, reliability, and energy efficiency, or as mobile terminals to form large-scale networks in cellular networks to expand real-time video streaming services[6]. Yin, B. N., Peng, M. G., & Liu, C. X. analyzed the challenges in the design and deployment of heterogeneous UAV wireless networks, derived analytical expressions for handover probability, handover error probability, and coverage probability based on stochastic geometry theory. It was found that outdated channel state information will lead to handover errors, and the error first increases and then decreases with the increase of UAV moving speed and base station density; meanwhile, the impact of UAV flight altitude on coverage probability is more significant than that of moving speed[8]. For disaster rescue and temporary sudden hot-spot events, Wang, H. analyzed the air-to-ground channel model for communication between UAV base stations and ground users, discussed the relationship between base station height and coverage radius, proposed a network coverage method based on relative distance to improve coverage rate, and also proposed a 3D deployment method based on cyclic k-means to optimize the number of UAVs and energy utilization[9]. Aiming at emergency communication scenarios, Cui, J. conducted an in-depth study on the impact of UAV position deployment and power-bandwidth resource allocation on the communication coverage of indoor and outdoor users, established a path loss model for UAVs serving indoor users, studied the energy-saving deployment and resource allocation problems when UAVs cover indoor users under the premise of considering user fairness and network stability, and proposed a deployment and resource allocation strategy based on outage probability and a fast coverage overall scheme of "indoor-outdoor-iterative optimization" to achieve maximum coverage of mixed users[19].

3.1.6. Civilian Market and Industry Applications

Shang, X. D., Shen, H. Y., & Wu, W. J. analyzed and pointed out that the application fields of UAVs have expanded from military-specific to civilian and commercial use, covering scenarios such as logistics and distribution, pesticide spraying, video shooting, and advertising promotion. Their

functions have also developed from initial scanning and reconnaissance to photography and videography, load-carrying, inspection and disinfection, etc[5]. Yan, C., Tu, L. H., Wang, Y. H., & Yang, Y. proposed that the civilian UAV market is experiencing explosive growth, outlined the characteristics of civilian UAVs, analyzed their application effects in different scenarios, summarized existing problems and regulatory situations, and predicted future development directions[3]. Liu, L., Wang, T., & Chen, Y. proposed a method of using UAVs to obtain visible light image information, combined with Pix4DMapper and ENVI software for vegetation index analysis and vegetation coverage estimation. This method has reference value in fields such as forestry surveys and agricultural monitoring[2].

3.2. Foreign Cutting-Edge Theoretical Achievements

Foreign scholars have made remarkable progress in expanding UAV application scenarios, optimizing technical details, and analyzing system performance:

3.2.1. Application Scenarios and Social Impacts

Logan Kugler pointed out that unmanned vehicles (including UAVs, unmanned ships, etc.) have many important application cases in the real world, covering fields such as transportation, logistics, agriculture, and environmental monitoring. He believed that with technological progress and cost reduction, unmanned vehicles will play a more important role in the future and have a profound impact on society[10].

3.2.2. Aerial Deployment and Antenna Optimization

Haneya Naeem Qureshi & Ali Imran pointed out that previous studies on UAV aerial deployment (as aerial base stations for air-ground communication) ignored or simplified the impact of actual antenna patterns. This problem was solved by using a 3D directional antenna model, the new trade-off relationships between UAV design space dimensions in different scenarios were revealed and analyzed, the sensitivity of the coverage area to antenna beamwidth and height was compared, the research was extended to multi-UAV scenarios, and a new coverage packing scheme was proposed, which has various advantages over traditional methods[11].

3.2.3. Multi-Rotor Systems and Coverage Control

Huang Sunan, Teo Rodney Swee Huat, & Leong William Wai Lun proposed a new coverage control algorithm, which expands the existing multi-unmanned multi-rotor system (MUM) coverage control technology, introduces a downward-looking sensor model and new constraints such as viewing angle and collision avoidance, studies the mobile network coverage between MUMs, and verifies the effectiveness of the scheme through computer simulation[12].

3.2.4. Path Planning and Hardware Constraints

Anees ul Husnain et al. proposed that efficient and comprehensive regional coverage strategies are crucial when patrol UAVs perform search and exploration tasks. In the ROS-Gazebo simulation environment, various coverage path planning methods were evaluated based on the Hector quadrotor model. It was found that although the optimal coverage path is attractive, more maneuvering operations are usually required to effectively cover the specified area; at the same time, the impact of hardware constraints on coverage area and path was analyzed, their effect on the performance of the Hector quadrotor UAV was discussed, and the importance of considering hardware constraints in path planning and structural design was emphasized[20].

3.2.5. Systems Engineering and Performance Modeling

John MacCarthy proposed using the systems engineering process outlined in the INCOSE Systems Engineering Handbook and ISO/IEC/IEEE 15288:2015 to develop a SysML system architecture starting from the user's requirement statement, and then constructing a mathematical model for the reliability, availability, and maintainability of the UAV system. The Markov analysis model used to determine the operational availability of alternative designs of the UAV system was mainly introduced. This model was used for design performance analysis and trade-off analysis, and the results of the analytical stochastic model and the simple deterministic model were compared[21].

4. Results and Discussion

4.1. Results

Through the collation and analysis of domestic and foreign literature, this review obtained the following core results: (1) Domestic research on UAV coverage rate focuses on practical scenario adaptation, and has formed systematic technical achievements in path planning, special environment positioning, and communication deployment [6,8,9,14,17,19]. For example, Li's hexagonal tessellation path planning method eliminates absolute blind spots, and Ren's GPS-denied positioning scheme provides technical support for complex environments [14,17]. (2) Foreign research emphasizes technical refinement and system modeling, such as Qureshi & Imran's 3D directional antenna model optimizing aerial deployment effects, and MacCarthy's Markov model improving system reliability evaluation accuracy [11,21]. (3) The application fields of UAVs have expanded from traditional military and agriculture to civilian commercial and emergency communication, and the coverage rate requirements show obvious scenario differentiation [5,10]. (4) Simulation data shows that the UAV coverage radius and base station distance have a significant impact on resource allocation: when the coverage radius increases from 100m to 200m, the number of required UAVs decreases by about 1/3 [7].

4.2. Discussion

The research results reflect the characteristics of UAV coverage rate research in different regions: domestic research focuses on solving practical problems, with strong application orientation; foreign research focuses on theoretical depth, providing methodological support for technical refinement [14-21]. However, there are still obvious limitations: first, the research fields are fragmented, domestic research is concentrated in power inspection and agricultural plant protection, while foreign research focuses on military reconnaissance and environmental monitoring, lacking cross-field integration [6-12]. Second, the influencing mechanisms of coverage rate are not clear, and existing studies mostly focus on technical performance rather than in-depth analysis of factors such as operating conditions and data processing capabilities [2,3,5,14-19]. Third, safety research is insufficient, and the adaptability of UAVs in complex environments needs to be improved. In addition, the standardization of UAV technology is lagging behind, which restricts the industrialization development [13]. These problems need to be solved through multi-disciplinary cooperation and cross-regional research exchange.

5. Conclusion

This review systematically summarizes the research status and cutting-edge achievements of UAV coverage rate in different application scenarios. Domestic research focuses on practical technology implementation and scenario adaptation, while foreign research emphasizes technical detail optimization and system performance modeling, jointly promoting the development of UAV from single-function to multi-function and from specific scenarios to full-scenario coverage. Future research should focus on three aspects: in-depth exploration of the influencing mechanisms of coverage rate to provide targeted optimization strategies; expansion of applications in emerging fields such as medical care and education to tap potential value; strengthening safety research and technical standardization to improve adaptability in complex environments and promote healthy industrial development.

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